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DEVELOPMENT OF A USEFUL MARS AIRPLANE EXPLORATION CONCEPT AT NASA / AMES RESEARCH CENTER

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ABSTRACT

An airborne platform is well suited to exploration of planetary bodies with atmospheres, such as Mars, Venus, and possibly Titan. Unmanned Aerial Vehicles (UAV's) are a high growth terrestrial technology area applicable to planetary science missions. An airplane's range for exploration is greater than for surface platforms. Due to closer surface proximity, the resolution for airplane mounted instruments is greatly improved over orbiter mounted instruments. The variety of terrain accessible to an airplane is greater than for most surface platforms. An airplane is capable of correcting for atmospheric entry errors. The public outreach potential for an airplane mission is also very high. Airplane concepts have risks associated with deployment, flight conditions, and data return. These risks are being addressed through aggressive testing and technology development work, including flight tests in Mars-like conditions. The Mars airplane concept began in 1977 as a follow-on to the Viking project. Studies and tests were conducted at the Jet Propulsion Laboratory (JPL) and NASA / Ames Research Center's (ARC) Dryden Facility. During the last seven years, the pace of development has accelerated rapidly due to work by an ARC team including Cal Poly, San Luis Obispo (SLO), and the Naval Research Laboratory (NRL). These efforts have resulted in two Discovery Mission proposals from ARC and have spawned efforts from other teams, resulting in additional testing and mission proposals. The work has focused on four areas: 1) flight in severe and demanding aerodynamic conditions, 2) packaging the airplane for space travel, atmospheric entry, and deployment, 3) mission performance, and 4) data return. ARC has extensively studied the close interrelationship between these factors. Continued development of Mars airplanes at ARC and other locations, including more flight tests, will provide a useful tool for extraterrestrial robotic exploration and can provide capability augmentation for future human Mars exploration.

INTRODUCTION AND BACKGROUND

An airborne platform is well suited to exploration of planetary bodies with atmospheres, such as Mars, Venus or other places. Michael Pidwirny describes remote sensing Earth applications using a variety of techniques and platforms, including airplanes (Introduction to Remote Sensing).

The United States Geological Survey (USGS) has used aerial mapping for many years and produce many products for government and private use (USGS and Remote Sensing). The same techniques that have been used on Earth in many applications can be applied to planetary studies as well.

In order to fly, an airplane's weight, which depends on the local gravity field as shown in Equation 1, must be balanced by lift. Lift is the force produced perpendicular to the flow of a fluid as derived from Bernoulli's law and stated in Equation 2.

$$F_{\text{Lift}} = mg = L \qquad 1$$

$$L = \frac{1}{2}\rho V^2 S_{\text{reference}} C_L \qquad 2$$

where:

m is the system mass
g is the gravitational constant that is unique to each planet
C_L is the lift coefficient of the airplane
ρ is the density of the planets atmosphere at the flight altitude
V is the relative velocity between the atmosphere and the airplane
$S_{\text{reference}}$ is the platform area of the airplane's wing

For a given airplane $S_{\text{reference}}$ remains constant. For a given location, ρ and g vary. Density varies with altitude and although g can varies slightly with altitude, it is generally assumed as a constant value for each planet or body. The airplane lift coefficient, C_L, varies only with the wing angle-of-attack, α. Within a given mission, V and α will vary with each mission segment. Also for a given mission, an airplane with an electrical power train will maintain constant mass; this is not true of power trains using consumable fuels.

In order to achieve higher lift an airplane experiences more drag, the force tending to impede the airplane's forward motion. Equation 3 gives the drag force. Also, as seen with the lift in Equation 2, the more thrust or faster the airplane goes the more lift that is achieved. There are therefore four basic balancing forces on an aircraft, as shown in Figure 1, the lifting force counteracts the weight and the thrust counteracts the drag.

$$D = \frac{1}{2}\rho V^2 S_{reference} C_D \qquad 3$$

where:

C_D is the drag coefficient that depends on various factors, including airplane configuration and angle of attack.

Consider an electrically powered airplane designed for flight on Earth. For this example, the shape, size, and mass of the airplane are not changed when it is flown over various places. If the airplane is taken to a place where either the atmospheric density or the gravitational constant is different, or both, the flight velocity will be different to maintain the same C_L. In the case of Mars, the difference is significant and has a large impact in the design and test of the airplane. On Mars, the gravitational constant is 0.377 (about three-eighths) that of Earth's, which is good news since a given airplane will fly as if it were three-eighths its weight on Earth. The bad news is that the Mars atmosphere is much less dense than Earth's; at the nominal atmospheric datum elevation on Mars—conceptually equivalent to mean sea level on Earth—the Martian atmosphere is about one percent as dense as Earth's. Sherman Wu reports that Mars datum is taken where the mean pressure is 6.1 mbars -- the triple point pressure of water at 273° K (131). The mean radius for the datum is 3382.9 km. Going back to Equation 2, in order for an airplane to fly at the same lift coefficient on Mars as on Earth, it must fly much faster.

In order to determine how much faster an airplane must fly over Mars, we start by combining Equations 1 and 2, then re-arrange and eliminate common terms, in Equations 4a through 7, in order to arrive at the Mars to Earth flight velocity ratio found in Equation 8. This method can be used for transformations between any two sets planetary bodies and altitudes.

$$L = mg_{\text{Earth}} = \frac{1}{2}\rho_{\text{Earth}}V_{\text{Earth}}^2 S_{\text{reference}}C_L \tag{4a}$$

$$L = mg_{\text{Mars}} = \frac{1}{2}\rho_{\text{Mars}}V_{\text{Mars}}^2 S_{\text{reference}}C_L \tag{4b}$$

$$m = \frac{\rho_{\text{Earth}}}{2g_{\text{Earth}}}V_{\text{Earth}}^2 S_{\text{reference}}C_L \tag{5a}$$

$$m = \frac{\rho_{\text{Mars}}}{2g_{\text{Mars}}}V_{\text{Mars}}^2 S_{\text{reference}}C_L \tag{5b}$$

$$m = \frac{\rho_{\text{Mars}}}{2g_{\text{Mars}}}V_{\text{Mars}}^2 S_{\text{reference}}C_L = \frac{\rho_{\text{Earth}}}{2g_{\text{Earth}}}V_{\text{Earth}}^2 S_{\text{reference}}C_L \tag{6}$$

$$\frac{\rho_{\text{Mars}}}{g_{\text{Mars}}}V_{\text{Mars}}^2 = \frac{\rho_{\text{Earth}}}{g_{\text{Earth}}}V_{\text{Earth}}^2 \tag{7}$$

$$V_{\text{Mars}} = \sqrt{\frac{\frac{\rho_{\text{Earth}}}{g_{\text{Earth}}}V_{\text{Earth}}^2}{\frac{\rho_{\text{Mars}}}{g_{\text{Mars}}}}} = V_{\text{Earth}}\sqrt{\frac{\rho_{\text{Earth}}\,g_{\text{Mars}}}{\rho_{\text{Mars}}\,g_{\text{Earth}}}} \cong V_{\text{Earth}}\sqrt{\frac{0.377}{0.01}} = V_{\text{Earth}}\sqrt{37.7} = 6.14V_{\text{Earth}} \tag{8}$$

As flight velocities and atmospheric conditions become vastly different, aerodynamic parameters combine in ways that are not usually encountered over Earth. As can be seen in Equation 8, Mars airplanes need to fly over six times as fast on Mars to generate the same lift as on Earth. This translates to a need for Mars airplanes to fly closer to the speed of sound, or Mach 1, than comparable terrestrial airplanes do. The speed of sound (a), is calculated by Equation 9. Another piece of bad news enters the picture here because the different composition of the Mars atmosphere lowers the speed of sound relative to comparable Earth altitudes. Operation of NASA / Glenn Research Center's Atmosphere Simulator shows that, at likely flight altitudes on Mars, the speed of sound will be 80% of that on Earth, as shown in Table 1 (Interactive Atmosphere Simulator). Close to the speed of sound, shock waves begin to form on localized areas of the airplane, which have the effect of limiting the maximum C_L the airplane can attain.

A further piece of bad news enters the picture, which is a result of the Mars atmospheric density being so low. Aerodynamicists use a non-dimensional number as an indicator of the relative viscosity of an atmosphere. The number is a ratio of the atmosphere's inertial forces to its viscous forces and is called the Reynolds number (R), as given by Equation 10. R indicates whether the airplane skin friction coefficient is laminar (smooth and streamlined) or turbulent. Laminar flow numbers are lower than turbulent flow numbers. Laminar is usually better, but when Reynolds Numbers drop below about 150,000, it becomes more and more difficult for an airplane to produce lift. Unfortunately, an airplane flying close to Mars datum at high enough subsonic speed to produce the C_L required will be at a Reynolds Number of around 150,000 at best. The combination of all these effects means that designing an airplane to fly in a subsonic regime on Mars is an aerodynamic challenge and must be done very carefully with frequent tests to assure the consistency of theory with reality.

$$a = \sqrt{\frac{\gamma P}{\rho}} \qquad 9$$

$$R = \frac{\rho V x}{\mu} \qquad 10$$

where:

a is the speed of sound
P is the gas pressure
R is the Reynolds number
x is a characteristic length (i.e. the chord length of the wing)
γ is the heat capacity of the gas
ρ is the density of the atmosphere
μ is the gas viscosity

Flight above a surface of a planetary body other than Earth is possible, although difficult, as long as the body has a definable atmosphere. Places with a dense atmosphere and a low gravity field would be a good place to fly.

THE MARS AIRPLANE CASE.

An airplane has advantages over traditional types of planetary exploration platforms. Michael Malin reminds us that large-scale geophysical observations require traverses on the order of tens of kilometers (6). In order to obtain a complete dataset, data with a resolution intermediate between data acquired from orbit and data obtained on the ground is required. Ronald Greeley also observes that trying to unravel Earth's history using only orbital data and ground truth from less than a dozen stations would be extremely difficult (2).

A variety of non-contact instruments can be carried by an airplane platform. Examples of such instruments are a camera (CAM) for context and detailed imagery; a magnetometer (MAG) to search for remnants of the ancient Martian magnetic field; a miniature thermal emission spectrometer (mini-TES) to study the mineralogy of Mars; and a neutron spectrometer (NS) to search for hydrogen which is a constituent of water, although finding hydrogen with a NS does not guarantee that water is present. The range of an airplane exploration is greater than for surface platforms. A modest Mars airplane should be able to cover 500 km. The range goal for the Mars exploration Rover (MER) reported by the Jet Propulsion Laboratory (JPL) is a total distance of one km (summary). The resolution obtainable from a given instrument configuration is greater for an airplane flying four km above the surface than for an orbiter at 400 km above the surface. An airplane can fly over terrain that is too rough for a safe landing. On the other hand, topographic data, such as those available from the Mars Orbiting Laser Altimeter (MOLA) needs to be carefully considered in order to plan a flight traverse (topography of Mars). Mars airplanes do not have large ceiling margins. An altitude of three to five km above Mars datum is probably a reasonable design assumption. Airplanes can also fly adjacent to a vertical canyon wall or near the edges of craters. Such flight operations can be used to directly observe geologic horizons or, for example, to investigate the evidence for gullies described by Malin and Edgett.

Imagery provides the context for the science investigation and is always of high interest to the general public. The public outreach potential for images taken from an airplane is very high. Malin points out that a Mars airplane mission will capture the public's attention and will return valuable data that can be correlated with other observations (1).

Any planetary probe has a targeting error associated with it. Uncorrected trajectory errors that may accumulate during interplanetary cruise and deviations which occur in the atmosphere of Mars during entry of the aeroshell combine to cause dispersions from the ideal target. The locus of dispersions from the target point is an ellipse with the long axis parallel to the entry path. A unique capability of an airplane is the ability to null out entry errors and fly back within the error ellipse to the area of interest.

There are disadvantages to an airplane. Instruments that require long duration contact with the surface are not appropriate for use in a flight traverse. JPL describes such instruments, as carried on the MER rover arm (instruments). Examples of such instruments are an Alpha Particle X-Ray

Spectrometer (APXS) for elemental analysis of Martian soil and a Mössbauer Spectrometer (MB) to determine the composition and abundance of iron-bearing minerals. Global coverage of a planet can only be provided by an orbiting platform.

Certain key guiding principles have resulted from the development of useful Mars Airplane Concepts at NASA / Ames Research Center (ARC). The first is:

> **Principle 1. Integration of the science objectives and the observation platform is an important element of mission planning**.

Landers and rovers are riskier than orbiters because of the deployment and landing operations that must occur. In order to fit into the payload shroud of a launch vehicle and survive atmospheric entry at Mars, the airplane's wings and fuselage must be folded into a compact volume, then stowed in an aeroshell (entry capsule). Before it can even begin a flying mission, a Mars airplane must first emerge from its aeroshell and deploy itself from its stowed configuration, in mid-atmosphere. This deployment sequence is the most challenging flight segment of the mission. Figure 2 shows the sequence of events from interplanetary traverse to deployment and, finally, to free flight. After the atmospheric entry phase is complete, the airplane must emerge from the capsule, deploy its wings and fuselage, and begin flying.

Communications have a direct bearing on the amount of data returned from a Mars airplane mission and therefore take on added importance. A Mars flight traverse will be short, typically about an hour. The airplane will gather and store more data in-flight than it can transmit back to Earth while aloft. A large portion of the data must be transmitted from the surface after the airplane has run out of energy and come to ground. ARC has considered options such as providing a hardened data box; targeting the Mars airplane carrier spacecraft as a relay station; taking advantage of orbiters in place from other missions as relays; and using modified landing techniques. Certainly technologies both inside and outside of the discipline of aerodynamics need additional development for a useful Mars airplane.

DEVELOPMENT

The Mars airplane concept began in 1977 as a follow-on to the Viking project. JPL produced a Technical Report describing studies and tests that were conducted there and at then ARC's Dryden Flight Research Center (DFRC) (contract report). Dale Reed's Mini-Sniffer airplane was an early high-altitude, remotely piloted vehicle (RPV) (Mini-Sniffer). Engineers at NASA / Ames Research Center (ARC) have studied this work and have been developing and testing Mars airplanes since 1996. A team consisting of ARC, Cal Poly San Luis Obispo (SLO), Naval Research Laboratory (NRL), and Global Solutions for Science and Learning (GSSL) has developed a variety of designs and extensively tested two variants of one of these designs. A description of the team is provided in the acknowledgements and contributions section below.

Two Principal Investigator (PI) led proposals for NASA Discovery planetary exploration missions have been prepared with the assistance of the ARC team. Greeley's Airplane for Mars Exploration (AME) and Malin's Mars Airborne Geophysical Explorer (MAGE). These proposals sparked renewed interest in Mars airplanes. The work done at ARC has defined the aerodynamic and non-aerodynamic technologies that need to be developed; developed the guiding principles described herein; and spawned intense competitive development work from other teams.

AME-1, NASA 721, a rigid, non-folding model, investigated the problems of low Reynolds number flight. This model was 22% of the size of a contemplated Mars airplane design. Scale model radio controlled (R/C) airplanes commonly fly at Earth sea level at Reynolds numbers similar to those that will be experienced at Mars. These types of models are simple to build and fly by experienced modelers. The ARC team is fortunate to have several such modelers. In addition even the most costly R/C type models are relatively inexpensive to build compared to traditional flight investigation models. These factors greatly facilitated the entire Mars airplane testing program. The actual performance of AME-1 equaled or exceeded predictions. David Hall provides a summary of the design and testing of AME-1 and recommendations for further development and testing.

The next early study area was the challenge of packaging a useful airplane in an aeroshell. Earlier attempts to approach the aerodynamic problem was to use very long wings in order to maximize the planform area. This approach required that the wings have several folds and resulted in a complex deployment sequence as indicated in Figures 3a through 3d. Shortening the wing reduces the planform area that causes the flight velocity to increase. This has an impact on flight power, which in turn affects the fuel mass fraction. This study provided a second guiding principle to Mars airplane design:

Principle 2. Packaging drives configuration and constrains all other design parameters.

In November of 1996 through February of 1997 the ARC Mars airplane team conducted several low altitude (sea level) tests of AME in support of Greeley's Discovery proposal. AME-2, NASA 722 is a near twin of AME-1, except that it can be folded and packaged in a mock entry capsule or aeroshell as shown in Figure 3a. Figures 3b through 3d show various stages in the deployment sequence, which include a total of 6 wing joints, one fuselage joint, and a tail boom release. The mock aeroshell was carried aloft by a large radio controlled mothership airplane (NASA 720) and dropped from altitudes between 300 and 500 m. These tests indicated that a much simpler deployment scheme was needed. Hall also reports on the design and testing of AME-2 and makes additional recommendations.

The packaging lessons learned from AME led to a much simpler wing unfolding scheme for Malin's proposal. The Kitty Hawk 2, NASA 725, model of ARC's family of Mars airplanes features only two wing hinges, between the outer tip panels and the inner wing sections, and no fuselage folds. This tradeoff increases flight velocity and, since the airplane is a tailless design, introduces control issues. Kitty Hawk 2 is shown in Figure 4. The Kitty Hawk 2 aircraft was smaller than the AME aircraft and was therefore less capable. Kitty Hawk 2 was designed to fly a shorter traverse than AME and carry fewer instruments. This study provided another key guiding principle of Mars airplane design:

Principle 3. Airplane configuration and mission performance are tightly coupled

In 1999, ARC's work in the development of Mars airplanes was sharply focused by a call from the NASA Administrator for proposals for a "Micro-mission" which would fly an airplane over Mars on December 17, 2003, the 100th anniversary of the Wright Brother's first flights at Kitty Hawk. The size of the airplane was highly constrained so as to fit as a secondary payload on an Ariane 5 mission. Several teams within NASA responded with concepts. ARC studied two concepts. The first concept was a conventional aircraft, shown in Figure 5, packaged in an aeroshell as in the previous Discovery proposals. The second concept was a delta-winged vehicle, shown in Figure 6, that required no aeroshell because it used a direct entry -- a true aerospace plane. The chosen concept was the conventional design depicted by Figure 5 showing the full scale Kitty Hawk 3, NASA 726, in a partially folded configuration. This design is very conventional, more like the AME aircraft, with a low forward wing and a large tail. There are six hinge joints, one for the tail boom, one center pivot for the middle wing section, two for the tip panels, and two for the propeller. The wingspan of 2.6 m, overall length of 1.5 m, and gross mass of 40 kg likely makes this model a prototype of the smallest practical Mars airplane. The folded configuration of the Kitty Hawk 3 class Mars airplanes is very compact.

Propulsion for Kitty Hawk 3 is via a propeller, driven by either an electric motor or a hydrazine heat engine similar to the power plant used for the Mini-Sniffer. Advanced electrical power systems such as fuel cell designs using Lithium-Hydrogen Peroxide (Li-H_2O_2) are reported in Hall. Propellers for Mars flight will have high tip speeds, introducing potential Mach number effects.

The aerospace plane, NASA 728 concept, entered the Martian atmosphere directly from space without benefit of a protective aeroshell. Propulsion was a hydrazine rocket and cruise speeds were in excess of Mach One throughout its flight. The name "super cruiser" was also applied to this design. If a significant portion of the entry trajectory is counted, the flight traverse is a large fraction of the circumference of Mars. Due to the high speed and altitude of the traverse, the science is limited to instruments that can adapt to high-speed passes. Image smear for camera is a typical instrument adaptation issue. This is in accordance with the third guiding principle of Mars airplane design.

CONTROL AND DAMPING

After the basic problems of making lift and overcoming drag, control and damping is the next most important issue. Control of a Mars airplane is complicated by the lack of aerodynamic damping due to the low atmospheric density. A stable airplane acts like the classic mass and spring systems that are studied in basic physics class. The airplane will try to stay in one attitude, but if disturbed, will oscillate around a stable position. The stabilizing force is a function of the flight velocity of the airplane and the air density. For good behavior, and in particular for an airplane carrying imaging sensors, we need that oscillation to be well damped. The tail surfaces of an airplane provide that damping, by creating a force that is a function of the tangential velocity, due to airplane rotations, and the atmospheric density. For airplanes operating at low altitude on Earth, the stabilizing and damping forces almost always work out with an appropriate relationship. However, as the atmospheric density decreases, we have to increase the flight velocity of the airplane to make enough lift. The stabilizing forces remain about constant; however, the damping forces are greatly reduced. At 30 km altitude on Earth, an airplane tends to have a lot of oscillation. One cure for this is to greatly increase the length of the tail moment arm, but this adds a lot of mass and is hard to package in an aeroshell. The best solution is to use angular rate gyros and the flight computer to drive the control surface servos to provide artificial damping. This system has been in common use on jet airliners to provide passenger comfort for many decades. Since any Mars airplane is going to have the required sensors, computers, and servos anyway, the artificial damping can be implemented by then. Once the Mars-specific behavior is understood, appropriate control software, can be developed to manage stability. The resource cost is additional electrical power.

MANUEVERABILITY

In low-density atmospheres, the maneuverability of an airplane is decreased. This happens for two reasons. First of all, to make a turn, we bank the airplane to redirect the wing lift to produce a horizontal component, as given by Equation 11. This horizontal centripetal force accelerates the mass of the airplane around the turn. Equation 12 shows the reduced available lift for an aircraft in a turn. Centripetal force is given by Equation 13. Recalling Equation 1, which shows the relationship between density and velocity, we see that, for a given bank angle, the turn radius is inversely proportional to atmospheric density. At 30 km on Earth, where the density is about 1% of sea level density, our turning radius is 100 times larger than at sea level. Note that increasing speed, while it means we can make more lift, also means that we NEED more side force to hold a given diameter turn, so the two effects tend to cancel each other.

$$F_h = L\sin(q) \tag{11}$$

$$F_v = L\cos(q) \tag{12}$$

$$F_h = \frac{mV_t^2}{r} \tag{13}$$

where:

F_h is the horizontal centripetal force
F_v is the reduced vertical lift
L is the lift
m is the mass
q is the bank angle
r is the radius
V_t is the tangential velocity (normal to the radius vector)

A more basic issue is in low-density conditions where not very much lift is available. For efficiency and packaging reasons, the airplanes are designed to cruise close to their maximum lift angle of attack. When we bank the airplane to get centripetal force, we lose vertical lift, as given by Equation 12. If we are already operating close to the maximum lift, we can only have shallow bank angles without stalling, meaning even larger diameter turns.

Finally, there is yet another constraint on the integrated mission performance for Mars airplanes. A critical issue is the ability to send all the collected scientific data off planet before the airplane comes to ground at the end of the flight. This usually means sending the data to a relay spacecraft. The narrower the beam angle of the antenna on the airplane, the faster it can send the data. More maneuvers and steeper bank angles make it much more difficult to transfer the data. This issue has been discussed earlier so a fourth guiding principle of Mars airplane design should now be stated:

> **Principle 4.** **Data preservation is constrained by airplane performance, flight duration and landing**

FLIGHT TESTING

Aircraft must be tested in conditions that are as close to the expected flight conditions as possible. All of the issues regarding lift, control, damping, and maneuverability described above, and other issues regarding propulsion described below, need to be brought together in integrated tests. Numerical analysis techniques can be validated by wind tunnel tests; however, if the model is not full scale, then the usual approach is to adjust the parameters in Equation 10 to produce similar flow conditions as characterized by R. If the test occurs at too high a density, then the size and/or the test velocity must be reduced. Recalling the impact of Mach effects, and Equation 9 it can be seen that reducing velocity means that important effects may not be fully captured. As noted earlier, g is different on Earth and on Mars and ρ appears in the denominator of Equation 9 and the numerator of Equation 10. This means that Equations 8, 9, and 10 must also be used to both design the airplane and define appropriate test conditions.

NASA has several powerful and complex wind tunnels but even these may not fully capture all of the relevant test parameters. For a full-scale model, designed to fly in a low-density environment, a wind tunnel would have to operate at a near vacuum. The alternative is to conduct tests with a free flying model in an appropriate location in the Earth's atmosphere. These tests are riskier than traditional flight testing which does not usually occur until traditional analysis and wind tunnel tests are completed. The point is, existing design codes and facilities are either not adequate or uncalibrated so early flight testing is a must. The risk is mitigated since producing a model, using high quality R/C material and equipment, and outfitting it with industrial and military grade electronics can be undertaken as an affordable option. One of the key goals of Mars airplane flight testing is, in fact, to calibrate the design and analysis tools that do exist. Mars-like conditions in the Earth's atmosphere exist at altitudes above 30 km. A High Altitude Flight Test (HAFT) program was therefore initiated. The Kitty Hawk 3 (KH3) project was organized at ARC.

The KH3 project defined three goals and twelve objectives for the HAFTs as listed in Tables 2 and 3. On August 9, 2002, NASA 731, Wilbur, was launched from a helium balloon over Tillamook, OR and released from an altitude of 31.4 km during HAFT1. This test, achieved all of the tabulated goals and objectives and established for the first time that flight in Mars like conditions was possible. The model transitioned from a nose down launch attitude and entered a stable descending glide at just under 30 km. The wings were fixed out and not unfolded for this test.

Based on the analysis of HAFT1 data, calibrations were made to prediction and analysis tools and a second test, HAFT2, was planned for a higher drop altitude. For this test an ambitious effort to design and add a propeller was initiated. The proven airframe would be used as a flying test bed for an advanced propeller design. An efficient propeller will increase flight time for a given amount of power available. The simulations and performance predictions used for HAFT2 were based on information obtained from HAFT1.

Adding a propeller required modification of the basic airframe to accommodate an electric motor, additional batteries for the motor and the propeller itself. Orville was rebuilt and became NASA 731A. A comparison between Orville as 731 and 731A is shown in Table 4. Additional details of the propeller design are provided below.

The final events associated with the performance of a HAFT occur over a one-week period and involve the usual activities associated with any flight test project. Final integration, which has been extensively rehearsed, is performed on-site. Systems checks and needed fixes are also made on-site. Figures 7a through 7d show key events during a HAFT. In Figure 7a, 731A is shown on a test stand undergoing radio communications and interference tests with the balloon avionics adjacent and active. Figure 7b shows the moment of launch as 731A is gently pushed away from the ground handlers underneath the rising balloon. The ascent takes just under two hours, a successful "pullout" requires about 45 seconds, and the descent requires approximately two and one-half hours. The attitude of 731A just before release from the balloon is shown in Figure 7c, from an altitude of 32.9 km (108,000 ft.). In Figure 7d, 731 is "Flying on the Edge of Space at approximately 30 km.

The initial results from HAFT2 did not meet the optimistic expectations generated by HAFT1. Unexplained dynamics, possibly attributable to the propeller, caused the model to depart from its planned trajectory, over speed, and breakup. Continuing analyses taught us more about Mars flight than we learned from HAFT1. Additional information from the HAFT1 data has been discovered by re-examining this dataset. It is encouraging to note that the early portions of both HAFT1 and HAFT2 were very similar. If dynamic effects caused HAFT2 to end early it demonstrates that the low damping and inertial effects discussed earlier are very real and need to be carefully considered. Mars flight is possible, but only within a very narrow corridor. The envelope has been pushed and its limits are now becoming clear.

Shortly after HAFT2, a team from Langley Research Center (LaRC) completed another HAFT and demonstrated a scheme for unfolding the airplane's wings. The configuration of the LaRC model was different than the Kitty Hawk model, being a blended wing/body delta shape. The power for this model will be a rocket motor rather than a propeller. It may be the case that for small airplanes, and the Kitty Hawk model was likely the smallest feasible model, rockets may have the advantage over propellers.

PROPELLER

The propeller was designed to match the KH3 cruise flight conditions at 30 km altitude on Earth, with a flight Mach number of 0.55. While an actual propeller designed for a Mars airplane would be somewhat different, this condition is a good test of the basic concept and the design methods. The propeller was sized to produce thrust equivalent to level flight on Mars. Because Earth has about three times the gravity as Mars, the airplane was three times heavier, and has three times as much drag. This means that we would not have enough thrust for level flight on Earth, but we could still measure the performance of the propeller. The propeller was designed to produce about 5N of thrust, and with a shaft power input of 1kW, with an efficiency of about 75%.

Previous propeller designs for this size airplane had kept the tip speed subsonic. To produce the needed thrust, a very large diameter was needed (about half the wingspan of the airplane), with very high pitch angles, and low shaft speeds. While predictions indicated that efficiencies of over 70% were possible, the large props were heavy and hard to package in the aeroshell. The very high pitch meant that off design performance (i.e. at higher power for climbing) was poor. The low shaft speed also meant a heavier gearbox, and very high torque complicated the airplane design. (An asymmetric wing with more span and area on one side to counteract the propeller torque was needed).

The KH3 propeller took a different approach, and used modern computer programs to design airfoils with good performance at low Reynolds Numbers and transonic to supersonic speeds. These airfoils are very thin. The thickest section was only 5% of the chord width, while the tip airfoils were 1%. The thin sections and the need to have a precise propeller shape under its operating loads meant that we had to design the desired shape, create a structural model of it with the estimated loads, determine the deflection of the propeller under those loads, and then adjust the shape of the mold so that the propeller would twist to its proper shape when operating.

The resulting propeller was about half the diameter of the subsonic props, only 60 cm, and operated at roughly 10,000 RPM. The tips are at a Mach number of 1.08, and the Reynolds Numbers vary from 17,000 at the tip to a peak of 35,000 in the middle of the blade.

TERRESTRIAL ANALOGS

An airplane designed for exploration of Mars and other planetary bodies belongs to a large class of aircraft called Unmanned Aerial Vehicles (UAV's). Technology and capabilities for terrestrial and extraterrestrial UAV's overlap and the work on each type can be complementary. Research by Frost and Sullivan has been reported in industry sources predicting that the world market for UAV's is expected to grow following recent successful military and civil operations that have proliferated during the last decade (Industry news). Recent events appear to reinforce that notion. This Journal goes on to note that the inclusion of advanced technology is a given in the design of these vehicles. The parallel development of UAV's for advanced uses in planetary exploration and terrestrial applications will distribute the technology development burden and strengthen the result of each effort.

CONLUSIONS

We have seen that in addition to the usual design space dimensions of range and payload, the design space for Mars, and other extraterrestrial airplane missions includes dimensions of atmospheric density, packaging, and data return. A series of four guiding principles for Mars airplane design are now available. Density, which is a function of altitude, is more of a limitation over Mars, with its sparse atmosphere, than it is over Earth or other planets with relatively dense atmospheres.

Continued development of Mars airplanes by the KH3 project at ARC, and projects at other locations will include more flight tests, and can provide a useful tool for robotic exploration of Mars. When human exploration of Mars becomes a reality, airplanes may augment the effort by scouting the way for the astronauts to follow. Such a scenario is depicted in Figure 8.

ACKNOWLEDGEMENTS AND CONTRIBUTIONS

The KH3 project at ARC is a small group with members from four organizations.

The ARC portion of the team, consisting of Lawrence Lemke and co-authors Gonzales and Corpus, provided overall project management, component and system testing, and systems integration. Use of the Moffett Airfield was also arranged by ARC. R/C aircraft consultation and piloting assistance was provided by Robert Hogan, Division Chief of the Advanced Projects Division in which the KH3 team is located.

The SLO contingent, consisted of David W. Hall and Robert W. Parks, who have teamed for many years to develop unusual, special purpose aircraft for a variety of military and civilian

customers. Hall and Parks were responsible for the overall definition, design, and analysis of airplane configurations and fabrication of test articles. Parks provided day-to-day consultation on a variety of issues including aerodynamic performance, test requirements, test hardware, and the simulation and integration efforts. Manual piloting of the low-level portion of test flights not under autopilot control was also performed by Parks.

The NRL group, consisted of Richard Foch, Gregory Page, Peter Chaplin, Steven Tayman, Michael Baur, and Nandy Pizzaro, who are part of a larger group that develops UAV's for use by the military. NRL has a large experience base in simulation and wing unfolding techniques and also consulted on the design of aircraft, provided expertise in the application of folding wing technology, performed mission simulations, and developed flight software. NRL also provided the autopilot, a control station and associated communications equipment, and personnel to support the launch efforts

GSSL was the contractor for the helium balloon flights and provided assistance with integration and communications activities. GSSL launches large high altitude tow balloons to support a variety of scientific and engineering investigations. GSSL also provided weather briefings and co-ordination with the FAA and the military for airspace use. Use of the Tillamook Airport for launch and recovery was arranged by GSSL who also assisted with post-flight tracking and recovery after HAFT1 and HAFT2. Timothy Lachenmeir and Robert Moody were the primary individuals who performed this work. Also participating from GSSL were Craig Brunson and Koh Murai.

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FIGURES

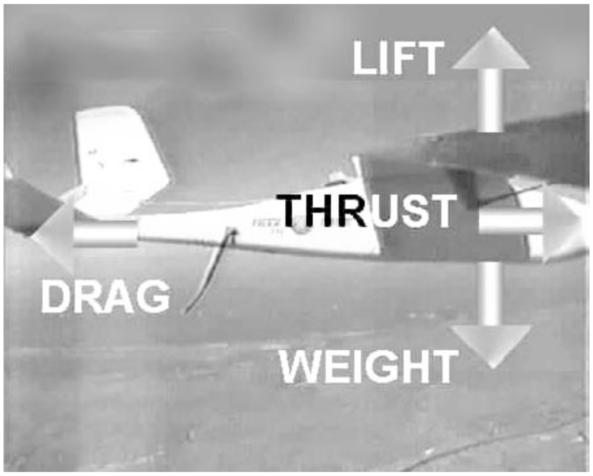
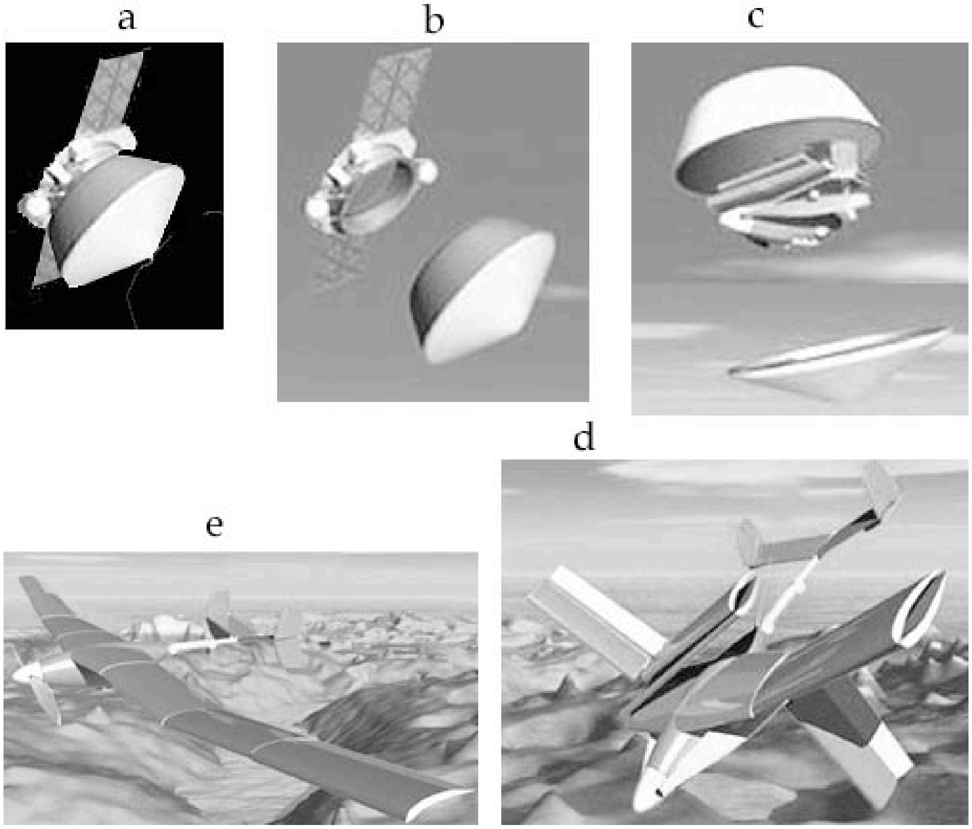


Figure 1 - *Forces Acting on an Airplane*

Figure 2 - *Mars Airplane Transport and Deployment Stages*



In view **a**, the complete spacecraft (S/C) and aeroshell stack is shown in interplanetary cruise. View **b** shows the aeroshell separating from the spacecraft. The aeroshell is opening and the airplane is emerging in view **c**. Right after emergence from the aeroshell, the tail boom has unfolded and the wings are driven open by aerodynamic forces in view **d**. Finally, in view **e**, the airplane is in free flight.

Figure 3a - *Airplane Stowed in Aeroshell*

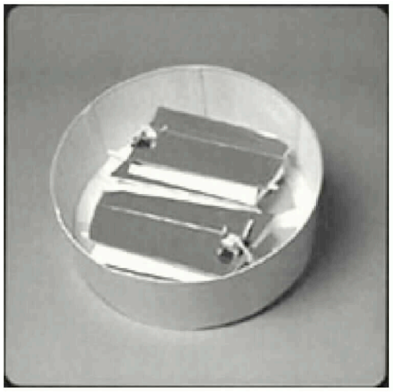
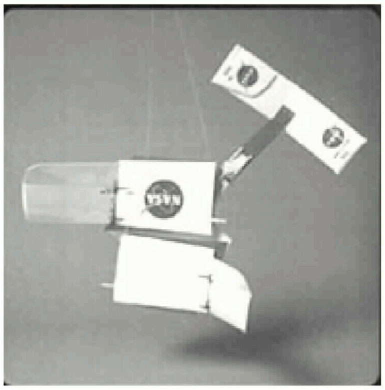


Figure 3b - *Initial Deployment*



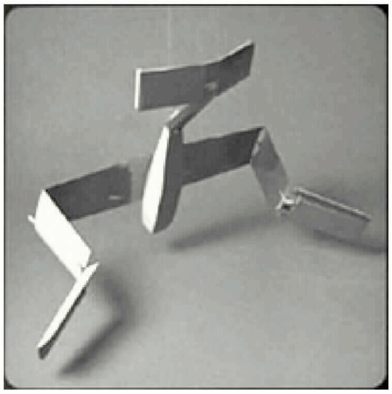


Figure 3c - *Wings 50% Out*

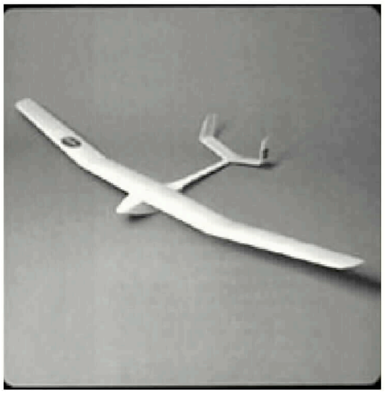


Figure 3d - *AME-2, NASA 722,Ready to Fly*

Figure 4 - *Kitty Hawk 2, NASA 725*

Figure 5 - *Kitty Hawk 3, NASA 726*

Figure 6 - *Mars Aerospace Plane, NASA 728*

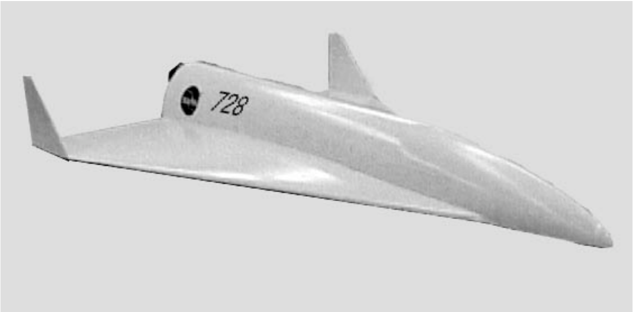
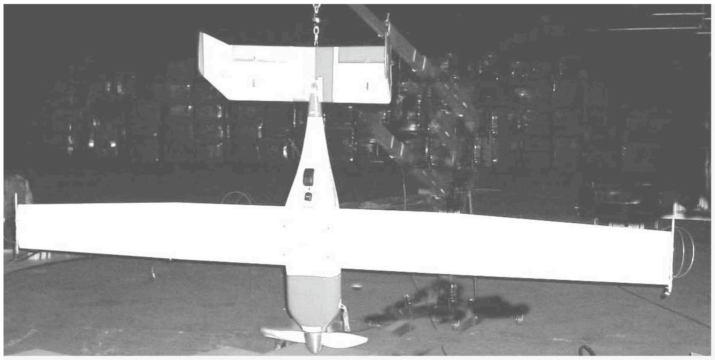


Figure 7a - *731A Orville on Test Stand*



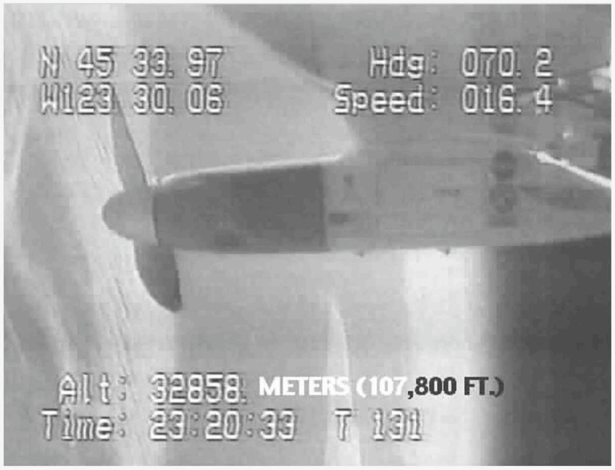


Figure 7c - *Orville Poised for Release*

Figure 7b - *Orville Takes Flight Again*

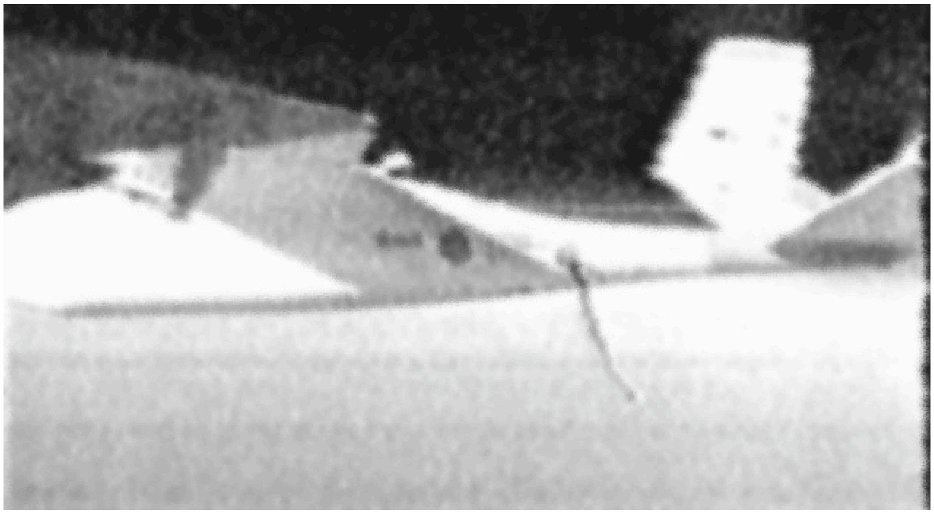


Figure 7d - *Flying on the Edge of Space*

Figure 8 - *Airplane as Advance Scout*

TABLES

Table 1 - Mach Number Variation

Parameter	Earth high altitude	Earth middle altitude (jet liner regime)	Earth low altitude	Mars
Altitude in kilometers	30.5	10.0	1	4.0
Temperature in degrees Centigrade	-41	-50	15	-35
Mach Number	1.00	1.00	1.00	1.00
Speed of sound in meters per second	305	300	340	244
Ratio of localized speed of sound to Mars speed of sound	0.80	0.81	0.72	1.00

Table 2 - *HAFT Goals*

Goal 1:	Demonstrate gliding flight over Earth in aerodynamic conditions similar to those found over Mars and which have not yet been experienced in terrestrial flight. Achievement of this goal will establish the level of difficulty for Mars flight.
Goal 2:	Validate analytical performance predictions made for the designed airfoil. Determine Airfoil C_L and overall lift to drag (L/D) ratio. Determine overall power requirements for power plant and propeller design. Analytical tools that are currently available have not yet been calibrated for flight in the required regime. Achievement of this goal will provide data for improved designs of Mars airfoils and propellers.
Goal 3:	Establish and understand procedures for future high altitude tests of airplanes of a small size in support of future Mars Airplane missions and their proposals. Achievement of this goal will sets a precedent and establishes the capability for using high altitude balloons as a launch platform for future flight tests.

Table 3 - *HAFT Objectives*

Objective 1:	Update and analyze the design of the Kitty Hawk 3 class of Mars airplanes and produce two copies, NASA 729 and 731. NASA 729 and 731 differ from NASA 726 in the tail volume and changes from a low wing configuration for 726 to a high wing for 729 and 731. In honor of the Wright brothers, 729 is named Wilbur and 731 is named Orville.
Objective 2:	Use the NASA 720 mothership to launch Wilbur and Orville for low altitude test flights (at 500 m) to validate general flying characteristics and to checkout avionics system performance.
Objective 3:	Define an overall avionics and power system architecture that allows the

model to fly autonomously under control of an autopilot to a recovery area while acquiring, logging, and transmitting data, including control signals from, and telemetry and video to, a control station.
Objective 4: Qualify avionics and components for flight above 30 km by engineering analyses and environmental tests.
Objective 5: Perform an overall thermal analysis of high altitude flight conditions.
Objective 6: Bench test the integrated avionics package.
Objective 7: Outfit Wilbur, NASA 731 with the high altitude avionics package.
Objective 8: Establish the radio range of the control, telemetry, and video equipment.
Objective 9: Establish a test altitude window, plan maneuvers, and perform a numerical simulation to predict performance. Use the results to program the autopilot.
Objective 10: Use a high altitude helium balloon to take the model to the test altitude window and release it.
Objective 11: Collect performance data.
Objective 12: Compare actual and predicted performance and refine analysis and prediction techniques.

Table 4 - Orville as 731 / 731A

Parameter	731	731A
Overall length (m)	1.50	1.65
Wingspan (m)	2.60	3.66
Wing area (m^2)	0.77	1.12
Mass (kg)	12.7	15.9
Planned drop altitude (m)	30,800	32,600
Actual drop altitude (m)	31,400	32,900