

Technical Findings, Lessons Learned, and Recommendations Resulting from the Helios Prototype Vehicle Mishap

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Abstract

The Helios Prototype was originally planned to be two separate vehicles, but because of resource limitations only one vehicle was developed to demonstrate two missions. The vehicle consisted of two configurations, one for each mission. One configuration, designated HP01, was designed to operate at extremely high altitudes using batteries and high-efficiency solar cells spread across the upper surface of its 247-foot wingspan. On August 13, 2001, the HP01 configuration reached an altitude of 96,863 feet, a world record for sustained horizontal flight by a winged aircraft. The other configuration, designated HP03, was designed for long-duration flight. The plan was to use the solar cells to power the vehicle's electric motors and subsystems during the day and to use a modified commercial hydrogen-air fuel cell system for use during the night. The aircraft design used wing dihedral, engine power, elevator control surfaces, and a stability augmentation and control system to provide aerodynamic stability and control. At about 30 minutes into the second flight of HP03, the aircraft encountered a disturbance in the way of turbulence and morphed into an unexpected, persistent, high dihedral configuration. As a result of the persistent high dihedral, the aircraft became unstable in a very divergent pitch mode in which the airspeed excursions from the nominal flight speed about doubled every cycle of the oscillation. The aircraft's design airspeed was subsequently exceeded and the resulting high dynamic pressures caused the wing leading edge secondary structure on the outer wing panels to fail and the solar cells and skin on the upper surface of the wing to rip away. As a result, the vehicle lost its ability to maintain lift, fell into the Pacific Ocean within the confines of the U.S. Navy's Pacific Missile Range Facility, and was destroyed. This paper describes the mishap and its causes, and presents the technical recommendations and lessons learned for improving the design, analysis, and testing methods and techniques required for this class of vehicle.

Background

This section of the paper provides a brief overview of the NASA/industry Environmental Research Aircraft and Sensor Technology (ERAST) program from the original Pathfinder vehicle up through the development of the Helios Prototype HP03.

ERAST Program

In 1994, NASA and industry created the ERAST Alliance to further mature High-Altitude, Long-Endurance (HALE) Uninhabited Aerial Vehicle (UAV) technology. The ERAST Alliance was a unique government-industry partnership that was intended to develop both a strong science capability and commercial applications for this class of vehicle. The primary objectives of the ERAST program were to develop UAV capabilities for flying at extremely high altitudes and for long durations, demonstrate payload capabilities and sensors for atmospheric research, address and resolve UAV certification and operational issues, demonstrate the UAV usefulness to scientific, government, and civil customers, and foster the emergence of a robust UAV industry.

Evolution of the Spanloader Configurations to the 3-Point Mass HP03

The HP03 was the fifth generation of all-wing aircraft designed and built by AeroEnvironment Inc. (AV) as technology demonstrators for future solar-powered high-altitude aircraft platforms for science and commercial missions. Figure 1 shows the relative sizes of the 4 spanloader configurations and the 3-point mass HP03 long-endurance configuration. In the next few paragraphs, each vehicle is briefly reviewed to provide a clear understanding of how the HALE vehicles evolved from the 1994 Pathfinder vehicle into the 2003 HP03 aircraft.

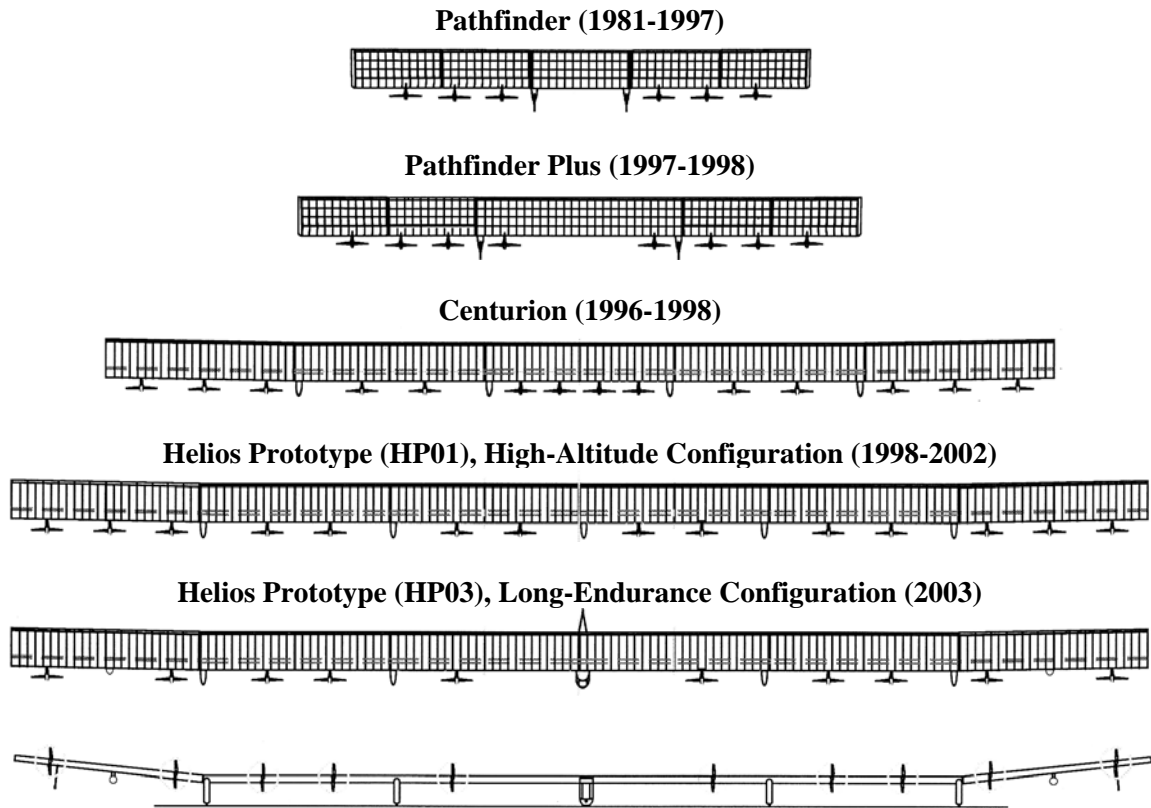


Figure 1: Evolution of ERAST sponsored solar-Powered aircraft.

Pathfinder Vehicle: The first generation HALE vehicle was the Pathfinder, a flying wing with a wingspan of about 100 feet powered by six battery-operated electric motors. The vehicle had two underwing pods, which contained the landing gear, the batteries, the instrumentation system, and the flight control computer. The Pathfinder vehicle was the technology test bed for developing many of the enabling technologies and processes for solar-powered stratospheric flight. These enabling technologies included:

- Lightweight composite structures
- Low wing loading flying wing
- Redundant and fault tolerant flight control system
- Lightweight and low power avionics systems
- Low Reynolds number aerodynamics
- High efficiency electric motors
- Thermal control systems for high-altitude flight
- High specific power solar array
- Stratospheric flight operations

With the addition of solar cells covering the entire upper surface of the wing, the Pathfinder vehicle was flown to 50,500 feet at the Dryden Flight Research Center (DFRC) on September 11, 1995 and set a solar-powered, propeller-driven aircraft, altitude record. After a few other modifications, the aircraft was moved to the U.S. Navy's Pacific Missile Range Facility (PMRF) on the Hawaiian island of Kauai. In the spring of 1997, the Pathfinder vehicle was flown to a new altitude record of 70,500 feet. During this flight, the

Pathfinder vehicle carried two lightweight imaging instruments to learn more about the island's terrestrial and coastal ecosystems, demonstrating the potential of such aircraft as platforms for scientific research.

Pathfinder Plus Vehicle: The Pathfinder Plus vehicle was the next step leading to the Helios Prototype. The Pathfinder aircraft was enlarged to a 120-foot wing span aircraft by using four of the five sections from the original Pathfinder wing and a new 40-foot center-wing panel section. This center-wing section was of the same design as the wing section of Pathfinder Plus vehicle's successor, the Centurion, which was being designed to reach 100,000-foot altitude on solar power. In addition, the number of electric motors on the vehicle was increased to eight. The Pathfinder Plus vehicle allowed flights to higher altitudes and was used to flight-qualify the Centurion wing panel structural design, the airfoil shape, and SunPower solar array. Three Pathfinder Plus flights were conducted at the PMRF. The final flight on August 6, 1998 achieved a new record altitude 80,200 feet. These flights validated the power, aerodynamic, and systems technologies needed for the Centurion.

Centurion Vehicle: Development of the Centurion vehicle, the third generation, began in late 1996. Originally, the intent of the ERAST alliance was to build two airframes: one for demonstrating a Centurion high-altitude (100,000-foot altitude) mission and one for demonstrating a Helios long-endurance (96 hours at 50,000-foot altitude) mission. To begin addressing the first goal, a 1/4-scale version of the Centurion vehicle was designed, built, and flight-tested to verify a new high-altitude aerodynamic airfoil design and to evaluate aircraft handling qualities. Also, all of the key technologies that were developed on Pathfinder were further improved into lightweight, more efficient, and more robust subsystems. In 1998, the full-scale Centurion vehicle was built. The vehicle had five wing panels with a total wingspan of 206 feet, 14 electric motors to provide level flight at 100,000-foot altitude, and 4 underwing pods to carry batteries, flight control system components, ballast, and the landing gear. In late 1998 the Centurion flew three development test flights at the DFRC at low altitudes using battery power to verify the design's handling qualities, performance, and structural integrity.

Helios Prototype HP01 (High-Altitude Configuration): In early 1999 under the constraint of a reduced budget that could fund only one aircraft, NASA and AV agreed the best way to proceed was to use a single airframe to demonstrate both of the ERAST goals. Based on this plan and to demonstrate the ERAST goal of sustained flight near 100,000 feet, the Centurion was modified from a 5-wing panel to a 6-wing panel aircraft by replacing the center-wing panel with two new stronger center-wing panels and by adding a fifth landing gear. This change resulted in the wingspan being increased to 247 feet. The aircraft continued to use 14 electric motors, with the four center motors redistributed on the new center-wing panel. Following these modifications the name of the aircraft was changed from Centurion to the Helios Prototype, thus becoming the fourth configuration in the series of solar-powered flying wing demonstrators.

Using a traditional incremental approach to flight testing, the Helios Prototype HP99 (the number indicating the year of the flight, and later for the HP03, the year and flight number) was first flown in a series of six battery-powered, low altitude, development flights in late 1999 at DFRC to validate the longer wing's performance and the aircraft's handling qualities. Various types of instrumentation required for the planned solar-powered high-altitude and long-endurance flights were also checked out and calibrated during these initial low-altitude flights. Four flights were conducted to assess the high-altitude configuration and two flights, with the aircraft ballasted for the "then" planned regenerative fuel cell system (RFCS) hardware and the solar array needed for the long-endurance flight, were conducted to assess the performance of the heavier configuration. At this time the long-endurance configuration was intended to use only eight electric motors.

Through 2000 and 2001, the HP99 was upgraded with new avionics, high-altitude environmental control systems, and a new SunPower solar array (62,000 solar cells) and renamed the HP01 (Figure 2). On August

13, 2001 flying out of the PMRF, the aircraft reached an altitude of 96,863 feet, a world record for sustained horizontal flight by a winged aircraft.



Figure 2: HP01 vehicle flying near Kauai.

Fuel Cell Development: In late 1998, NASA and AV started the preliminary design and development of the RFCS for the long-endurance demonstration planned for 2003. However by 2001, it was clear that designing, building, and testing two flight weight RFCS pods for the long-endurance demonstration would not be possible with the time and budget remaining to the program. During late 2001, NASA and AV agreed to change from a RFCS to a consumable Primary Fuel Cell System (PFCS) using hydrogen and air. The primary motivation for the change was two-fold: 1) the PFCS, derived from existing fuel cell components in the automotive industry, could be designed, built, and tested within the current schedule and budget constraints; and 2) a Helios UAV with a PFCS would have a 7-14 day duration capability. Also contributing to the decision to switch to the PFCS was that 2003 was the last year of the ERAST program. It was important to the program that a major milestone be accomplished without schedule or budget relief.

Helios Prototype HP03 (Long-Endurance Configuration): The primary objective of the 2003 flight test program was to use a hydrogen-air fuel cell, the PFCS, to sustain flight overnight at 50,000 feet. The aircraft to be used for the long-endurance demonstration in 2003 was designated the HP03.

Based on recommendations during the HP03 Preliminary Design and Critical Design Reviews, a decision was made to strengthen the wing tip spars so that their structural margins would be consistent with the structural margins along the rest of the wing spar under the design load conditions. NASA and AV also recognized that the structural, stability and control, and aeroelastic margins of safety were less on the HP03 than on the HP01. However, these margins were still sufficient to conduct the 2003 long-endurance flight demonstration. It was also recognized that the mass distribution for HP03 was significantly different than the mass distribution of the initially proposed demonstrator with a RFCS system. The aircraft with the RFCS would have required two regenerative fuel cell pods located at about 1/3 the distance from the vehicle centerline to the wing tip. The HP03 vehicle, with the PFCS installed, was more point loaded in that 3 pods were required. The heavy primary hydrogen-air fuel cell pod (520 lbs) was located at the centerline of the aircraft and the 2 high-pressure hydrogen fuel tanks (165 lbs each) were located at the center of each wing tip panel. A schematic of the PFCS is provided in Figure 3.

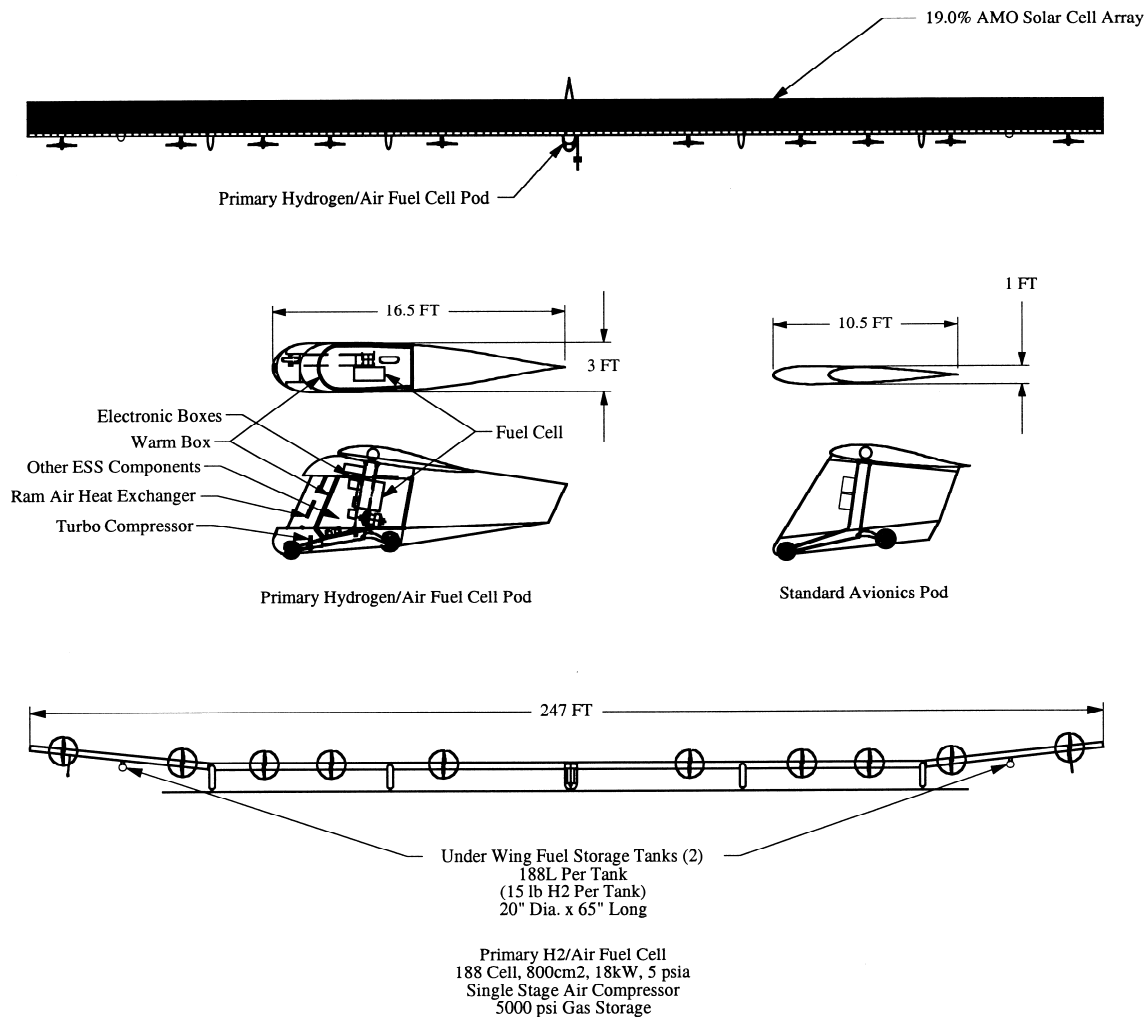


Figure 3: Schematic of HP03 hydrogen-air fuel cell configuration.

Aircraft Modifications Following HP01 Flights: By the end of 2002, the PFCS was designed and fabricated. The primary modifications to the aircraft included:

- Center pod was replaced with a fuel cell pod weighing approximately 520 lbs
- Two hydrogen fuel tanks (165 lbs each) were added at motor pylon locations #2 and #13
- Hydrogen supply lines were added between hydrogen tanks and the fuel cell pod
- Motors on pylons #2, 6, 9, and 13 were removed resulting in 10 motors
- Spar strengthener in the form of a concentric tubular inner spar was added to the tip panel spars
- Aluminum center joiner tube was replaced with a lighter weight carbon fiber tube
- Propellers optimized for flight at 65,000-foot altitude were installed
- Tip panel incidence was reduced from 1 degree to 0 degrees of incidence
- Front row of solar cells on center-wing panels and the first two front rows from mid and wing-tip panels were removed
- Servos from wing tip panels were removed and the wing tip panel elevators were fixed at -2.5 degrees offset (trailing edge up)
- Wing tip landing gear was installed
- Three battery packs were reconfigured into pod 2 and pod 4 to mass balance the aircraft

By April 2003, testing of the PFCS was completed and integrated into the aircraft, and all combined systems tests were accomplished. The final gross weight for the HP03 was 2,320 lbs as compared to the 1,585 lbs gross weight of HP01 during its altitude record flight in 2001, an increase of 735 lbs.

The HP03 load carrying structure was constructed mostly of composite materials. The main wing spar was made of carbon fiber, was thicker on the top and bottom to absorb the bending that would occur during flight, and was wrapped with Nomex and Kevlar to provide additional strength. The wing ribs were made of epoxy and carbon fiber. The wing leading edge consisted of aerodynamically shaped Styrofoam, and the entire wing was wrapped with a thin, transparent plastic skin. As described earlier, the aircraft consisted of 6 panels for a total wingspan of about 247 feet. Aerodynamically shaped underwing pods were attached at each wing panel joint to carry the landing gear, the battery power system, the flight control computers, and flight instrumentation. The wing had no taper or sweep, an 8-foot wing chord (aspect ratio of 31) with a maximum thickness of 11.5 inches (constant from wingtip to wingtip), and 72 trailing-edge elevators spanning the entire wing.

The aircraft was powered by 10 brushless direct-current electric motors rated at 2 hp or 1.5 kW each. The two-bladed propellers were 79 inches in diameter, made of composite materials, and designed for high efficiency at high altitudes. To turn the aircraft in flight, differential power was applied to 8 of the 10 motors (power to the outboard 4 motors on one wing was increased while power to the 4 motors on the other wing was decreased). Servomotors commanded by the aircraft's flight control computer drove the trailing edge elevators for pitch control. To provide adequate lateral stability, the outer wing panels had a built-in 10-degree dihedral (upsweep), and to prevent wingtip stall during the slow landings and turns, the wing tip had a slight upward twist.

Straight Line Flight: On May 15, 2003 a successful straight-line flight test of the HP03 vehicle was conducted. This flight was a mission dress rehearsal in preparation for the first long-duration flight in June. The primary objectives of the straight-line flight were to verify the proper wing dihedral distribution, and to conduct all of the necessary preflight assembly and test procedures required for a high-altitude mission. The aircraft was flown at an altitude of 2 feet above the runway for about 10 seconds. The assessment of the flight results indicated the aircraft had approximately the correct wing dihedral distribution, and that all of the aircraft systems, the fuel cell pod, and the ground support equipment were working well with the exception of the solar array (broken bus bars on the solar array). Test data from this flight allowed for fine-tuning the aircraft's mass distribution, wing tip panel incidence, elevator settings, and flight control system gains to help establish a safe operating envelope for long-duration flight investigations. After this flight some minor modifications to the vehicle, including repairing the solar array bus bars, were completed.

First Flight (HP03-1): On June 7, 2003 the first flight of the aircraft, designated HP03-1 was accomplished. The objectives of this flight were to:

- Demonstrate the readiness of the aircraft systems, fuel cell systems, flight control system, flight support equipment, range support instrumentation, and procedures required for a long-duration flight
- Validate the handling and aeroelastic stability of the aircraft with its fuel cell system and gaseous hydrogen storage tanks installed
- Demonstrate the operation and the performance of the fuel cell system in the stratosphere
- Provide flight, fuel cell pod, and ground crew qualification training for the additional personnel required to staff future multi-day flights

Performance pre-flight analyses estimated that the HP03 was capable of approximately 30-hour flight duration at 50,000 ft altitude. During the flight, data were measured in real-time to validate the predicted aeroelastic characteristics of the aircraft and to demonstrate that the vehicle was aeroelastically stable at the flight conditions expected for the long-endurance flight demonstration. The aircraft flew flawlessly thus

validating the handling and aeroelastic stability of the aircraft. However, the flight was aborted about 15 hours after takeoff because of some leakage associated with the coolant system and compressed air lines that feed the PFCS. Because of this leakage, the fuel cell system could not be started.

The turbulence levels and winds during this first flight were uncharacteristically light. As a result there was concern that the airspeed variations in turns, the high sideslip at low-power/low-altitude conditions (i.e. landing), and the sensitivity of wing dihedral to power setting over the entire flight envelope would make the aircraft more difficult to handle and to land safely under the more normal weather conditions that would be present in the flight test area. As a result the HP03-1 aircraft was modified to improve the aircraft handling qualities, to reduce wing dihedral sensitivity to power setting, and to increase wing dihedral at low power. These modifications included:

- Propeller pitch was flattened from -5.5 to -8 degrees
- Power throttle scaling on the two outboard motors was reduced to 50 percent of the center motors
- Drag mode on the tip motors was eliminated
- Wing-tip panel incidence angle was increased from 0 to 0.5 degrees
- Flight control system autopilot longitudinal gains were increased by 3db, the ratio of the airspeed hold gain to the pitch attitude damping gain was increased by a factor of 2, the longitudinal gain switch on the pilot's controller multiplier was reduced, and the limiter on the value of the airspeed error integral was increased

Second Flight (HP03-2): The second flight of the aircraft was designated as HP03-2 and took place on June 26, 2003. The objectives of the test were to:

- Clear the aircraft flight envelope for the new aircraft configuration changes, and for the 50,000 feet to 60,000 feet altitude climb/glide needed for the planned long-duration mission
- Verify stable operation of the fuel cell and compressor at an altitude of 50,000 feet
- Achieve fuel cell pod rated flight power of 18.5 kW at 50,000 feet
- Run the fuel cell pod system for at least 2 hours to develop confidence that it can run all night
- Develop a modest fuel cell performance sensitivity matrix
- Demonstrate a rapid shutdown of the fuel cell pod and night restart on battery power

Description of the Mishap

On June 26, 2003 at 10:06am local time, HP03-2 vehicle took off from the PMRF under the guidance of the Mobil Pilot (MP) located in the front vehicle shown in Figure 4. At that time the wind conditions were within an acceptable envelope, and consisted of a wind shadow over and offshore from PMRF, bounded to the north, south, and above by zones of wind shear and turbulence separating this region from the ambient easterly trade-wind flow.



Figure 4: HP03-2 on takeoff.

At 10:19am, the Stationary Pilot (SP), located in a trailer near the runway, noted that instrumentation and the aircraft were behaving as though it was in turbulence (noted later as the 1st encounter with turbulence). At 10:22am and again at 10:24am the aircraft again encounter some turbulence. The aircraft's wing dihedral became larger than normal and mild pitch oscillations occurred; the wing dihedral during both events returned to normal without any pilot inputs, and the oscillation damped out. These events both occurred during the time when the Stationary and Mobil crews were focused on the handoff procedure. Neither crew was aware of the high wing dihedral or the pitch oscillations. At 10:35am, at approximately 2,800 feet altitude, the aircraft began experiencing airspeed excursions of around ± 2 ft/sec. The persistent high wing dihedral (Figure 5) and the subsequent loss of pitch control, the aircraft became very unstable in a highly divergent pitch mode in which the airspeed excursions from the nominal flight speed about doubled every cycle of the oscillation. During the final nose down dive (approaching 90°) the aircraft exceeded the maximum allowable speed by over a factor of two. The resulting high dynamic pressures caused progressive failure of the wing leading edge secondary structure on the outer wing panels. Soon thereafter, the solar cells and skin on the upper surface of the wing began to rip off. These failures destroyed the aircraft's ability to generate lift and sustain flight; as a result, the aircraft fell into the ocean (Figure 6). The aircraft impacted the ocean within the confines of the PMRF test range and was destroyed.



Figure 5: HP03-2 with high wing dihedral.

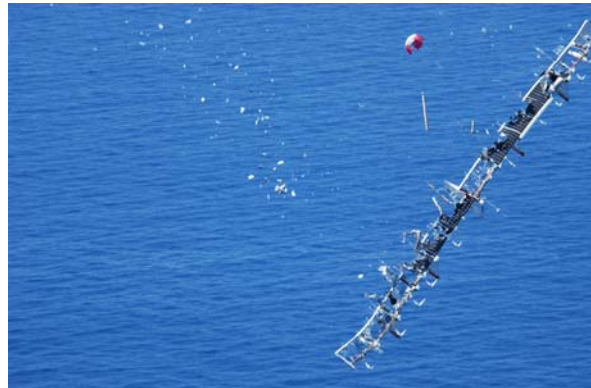


Figure 6: HP03-2 falling towards the Pacific Ocean.

The aircraft impacted the ocean in mile-deep water 10 miles off the coast of Kauai. The vehicle structure including the main load carrying composite wing spars were severely damaged. The elapsed time from the first effort to diagnose and correct the high wing dihedral condition to the point at which the airplane began to break up in the air was 91 seconds. Figure 7 provides time histories of the aircraft's pitch rate and airspeed, and the wing dihedral for the 30-minute flight.

Helios Flight H03-2

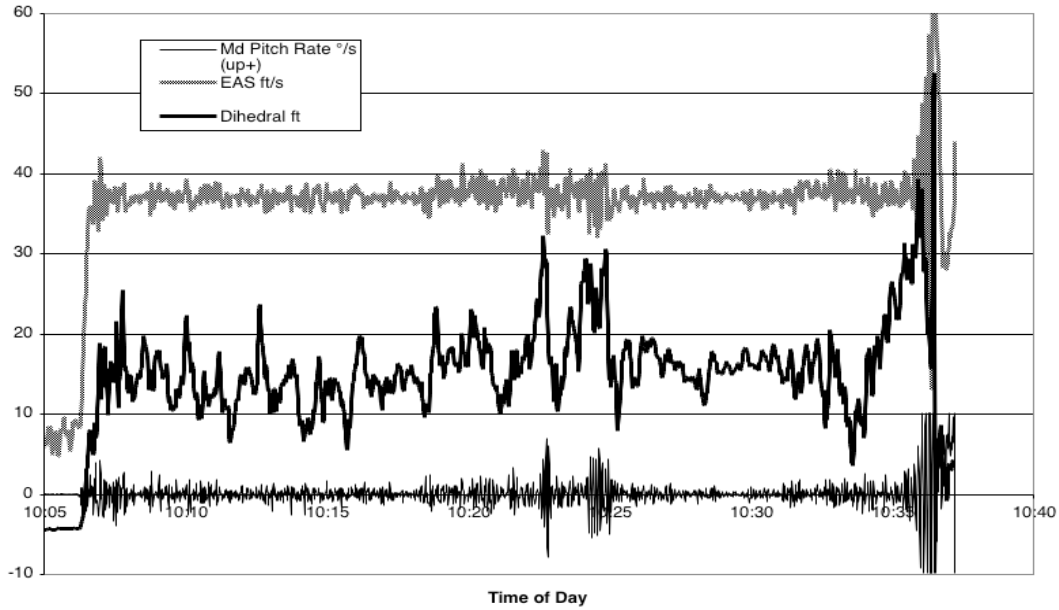


Figure 7: Wing dihedral, pitch rate, and airspeed history during mishap.

Observations Concerning the Mishap and Analysis Results

Weather Environment

In earlier years the strategy on climb-out for the Helios vehicles was to avoid the shear lines until the airplane achieved sufficient altitude to get above the most significant turbulence. Aircraft measurements and flow simulations in the area of the mishap indicated that this altitude is about 4000 to 5000 feet. Because HP03-2 flew at a somewhat higher equivalent airspeed than previous solar-powered configurations without an increased rate of climb, the slope of the climb-out trajectory was lower than previous flights. This meant a longer flight trajectory over which the airplane was exposed to the greater turbulence at lower levels, and at the same time, trying to avoid the north and south shear lines (Figure 8). Regardless of these concerns, the weather conditions on July 26, 2003 were within the bounds required for performing flights from the PMRF.

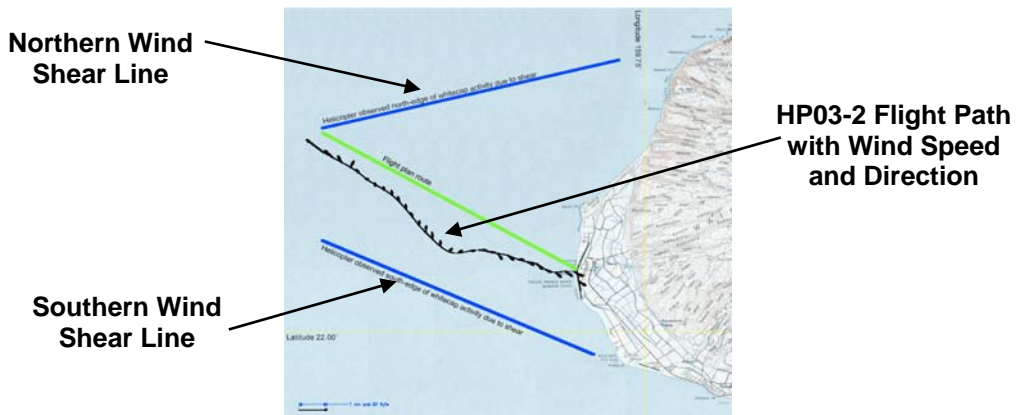


Figure 8: Helicopter observed turbulence shear line.

The 1st encounter with turbulence did not cause high wing dihedral. The next two encounters occurred in the space of three minutes. The aircraft developed high dihedral deflections of about 30 feet, began to oscillate in pitch, and then recovered on its own without pilot interaction. Since this type of pitch oscillation was a known flight dynamic characteristic of the Helios class of vehicles that had been predicted, observed, and controlled several times in prior flights with predecessor configurations, the MP and SP pilots and flight crews did not interpret the airspeed variations associated with the events as serious periodic oscillations, but rather as typical responses due to turbulence. On the 4th encounter with turbulence (Figure 9), the dihedral increased to an even higher magnitude of about 40 feet, and the pitch oscillation diverged rapidly.

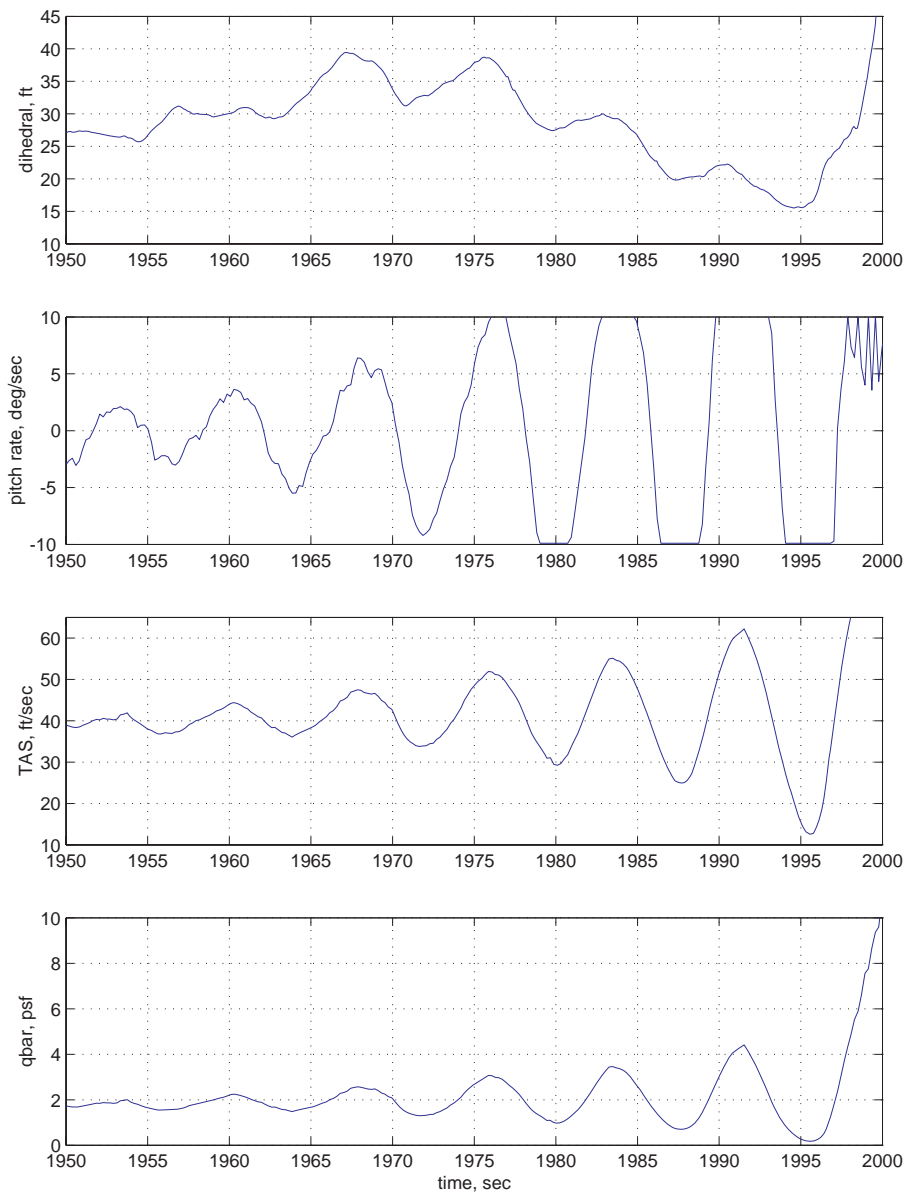


Figure 9: Dihedral, pitch, vehicle airspeed, and dynamic pressure for mishap event.

Pre-Mishap Analyses

Analyses performed prior to the mishap accurately predicted the wing dihedral shape in smooth air. These analyses also predicted that the aircraft would be unstable for a wing dihedral greater than about 30 feet. However, these analyses did not predict the degree of aircraft's increased sensitivity to disturbances like turbulence, the inability of the aircraft to restore itself to some nominal dihedral after being disturbed, or the highly divergent nature of the unstable pitch mode.

For the HP03-2 flight, it was surprising just how strong the dihedral response to turbulence was compared to the HP03-1 flight on June 7, 2003. In the smooth air (an unusual condition for the area) observed on June 7, 2003, the aircraft dihedral shape was well predicted, as mentioned above, and within acceptable levels. On June 26, 2003 the trade winds veered slightly more southerly than the typical east-northeast direction. In addition, the shear lines from the island's wake boundaries were converging near the aircraft. These weather conditions created a stronger gust environment than on June 7, 2003. Under these conditions, the aircraft morphed to large dihedral deflections (2nd and 3rd events), sustained them for tens of seconds, and then abruptly returned to normal.

It was also observed that the aircraft dihedral shape in turbulence was not robust, that is, the aircraft was slow to restore to a more classical and stable shape. Although analyses performed before the mishap flight showed this fact, the first flight on June 7, 2003 appeared to confirm that the less robust configuration could be made acceptable with appropriate control system gain changes. This may have been false confidence in that flight HP03-1 was flown in one of the most benign turbulence conditions encountered during solar-aircraft flights from PMRF.

As mentioned above, the rapid divergence of the pitch oscillation when the dihedral reached 40 feet (4th event) was not expected. Analysis had predicted that the aircraft was not stable in pitch for dihedral greater than 30 feet, but it was not anticipated that the divergence would be so rapid. Pitch oscillations encountered in previous flight tests of vehicles of the Helios class were mild, giving the crew time to deliberate on a course of corrective action. For all of the past events, the pitch oscillations quickly damped out when the corrective action was taken. The predicted pitch instability was considered acceptable, because there was no history (or prediction) of large, sustained dihedral deflections.

Post-Mishap Analyses

It was known that the aircraft with a persistent high dihedral above 30 feet would be unstable. It was determined that a combination of weather, aeroelastic, flight control system (FCS), and point mass effects initiated and/or caused the persistent high dihedral, which in turn caused the pitch instability. It was also determined that the propulsion systems did not contribute to sustaining the persistent high dihedral observed.

Turbulence Effects: In terms of the environmental effects, turbulence was determined to have initiated the high wing dihedral, however it was also determined the turbulence was not necessary to maintain it. Post mishap analysis revealed that spanwise lift redistribution (from the center of the aircraft to the outboard wing panels) was very sensitive to small amplitude gusts (Figure 10). It had been the experience of the Helios type aircraft that its dihedral varied as local airflow varied along the wingspan. Figure 11 provides a comparison of the wing spanwise lift distribution for the HP01 and HP03-2 aircraft configurations with a superimposed 0.5 ft/sec gust. For this study, it was assumed that the aircraft encountered a gust exhibiting a 0.5 ft/sec downward flow at the centerline and 0.5 ft/sec upward flow at the wing tips. Although the probability of the aircraft encountering such a gust is very low, the intent of the analysis was to show the sensitivity of the aircraft to gusts, even small gusts. The HP03-2 configuration has noticeably more lift outboard and less lift inboard. The increased lift outboard would be expected to lead to considerably increased dihedral. It is important to remember that the modeled sensitivity to local variations in sectional airflow is primarily a consequence of the aircraft's reactions to increasing dihedral, trailing edge up elevator,

and wing tip leading edge twisting up, not the first-order effects of airflow change. The airflow variation is only the transitory force. It was determined that elevator response and the change in wing twist contributed to the wing's slow return to nominal dihedral conditions. In the absence of a gust that flattens the wing (for example, a momentary gust having relative downward air motion on the tips and upward near the airplane centerline), these aerodynamic effects slowed the return to nominal dihedral.

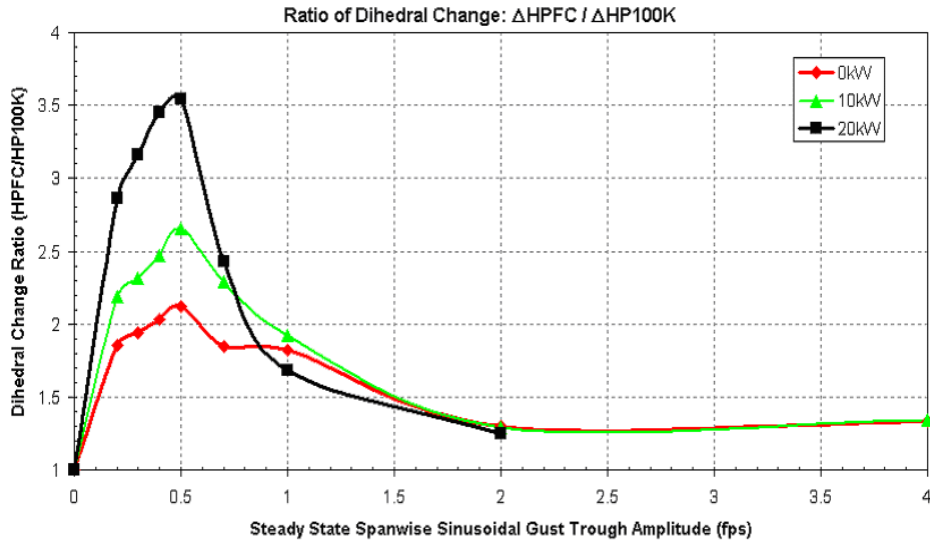


Figure 10: HP03-2 increased sensitivity to small gusts.

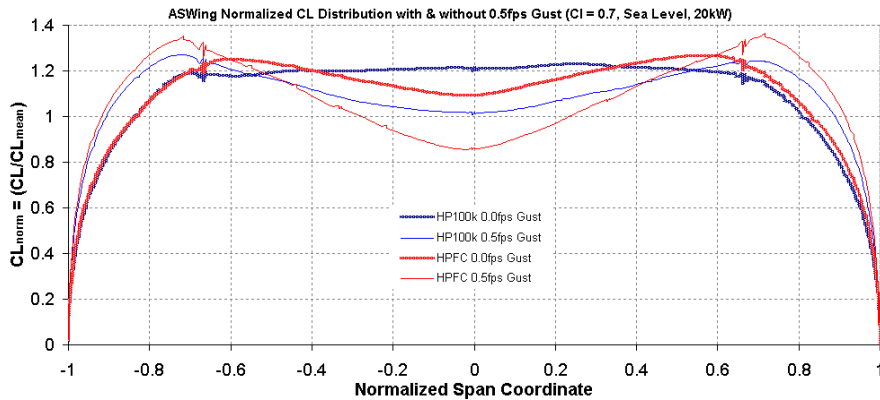


Figure 11: Variation of spanwise lift distribution with gust velocity.

Aeroelastic and FCS Effects: It was determined that wing twist and lift loss due to elevator deflection, consequences of the aeroelastic characteristics of the aircraft and the FCS, contributed to causing the persistent high wing dihedral. It was also determined that the FCS's response and the wing's aeroelastic response to perturbations were found to not only increase wing dihedral, but also to sustain the dihedral. These two effects oppose the wing's return to lower, wing tip deflections. The FCS reacts to the wing dihedral increase by deflecting the elevators trailing edge up. The elevators on the outer 40 feet of each wing are fixed. For any control law command requiring an elevator trailing edge up response, more lift is lost in the center of the aircraft than at the wing tips.

The quantification of the primary effects of dihedral on elevator position and twist is best illustrated by analyzing the spanwise lift distribution. For a given airspeed and motor power setting, the predicted spanwise distribution of lift is provided in Figure 12. The spanwise redistribution of lift from the center of the aircraft to more outboard panels is the primary cause of the unexpectedly slow return to lower dihedral after any perturbation.

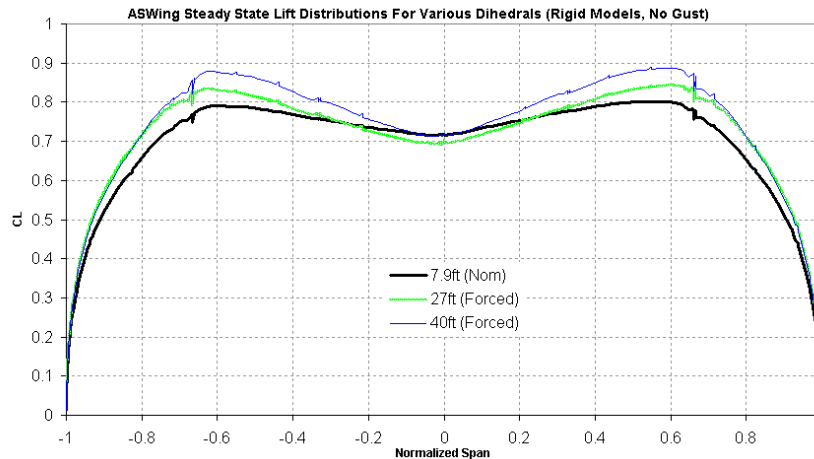


Figure 12: Spanwise lift distribution for various wing dihedrals.

3-Point Mass Effects: It was also determined that adding 3 point masses to the HP01 configuration contributed to causing the persistent high dihedral. Although the Helios Prototype aircraft was conceived as a very simple aircraft design for high-altitude solar flight, the structural flexibility and the large masses associated with the fuel cell system introduced substantial complexity into the aircraft's flight dynamics. The subset of complexities, which are relevant to understanding the mishap, is the relationship between wing dihedral, the addition of 520 lbs to the aircraft's centerline, the addition of 165 lbs near each wing tip, and the FCS. The large center mass required that the 165 lb hydrogen fuel tanks be placed outboard on the wing to prevent excessive wing dihedral. For the HP03 configuration at normal airspeeds and no turbulence, the wing dihedral varied on an average from about 11 feet to about 17 feet tip deflection during the first flight on June 7, 2003.

Unstable Phugoid Mode: It was concluded that the persistent high dihedral caused the pitch instability. The pitch oscillation shares many characteristics with a traditional neutrally damped phugoid response of conventional fixed wing aircraft. For the Helios Prototype vehicle, the period of the neutrally damped pitch oscillation was about 8 to 9 seconds and the pitch rate was about 5 degrees/second. The stability of the oscillation was predicted and observed to be proportional to the wing dihedral of the aircraft. For wing dihedrals of about 30 feet wing tip deflection, the pitch oscillation became dynamically unstable.

The underlying physics of the phugoid mode and its potential instability is thought to be a consequence of two primary factors. The first factor involves the large longitudinal static stability that results from a high aerodynamic pressure relative to center of mass as the wing tips bend up. As the dihedral increases, the center of aerodynamic force moves further above the center of gravity. This increasing static stability is believed to increase phugoid instability. The second factor involves the pitching inertia of the aircraft which increases dramatically with wing dihedral. The pitching inertia, a dominant effect to this flight mode, grew by a factor of five over the dihedral range seen on the HP03-2 flight.

Proximate and Root Causes

This section of the paper provides the proximate and root causes for the mishap. Definitions for these terms are provided below.

Proximate Cause: The event that occurred, including any condition that existed immediately before the undesired outcome that directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.

The investigation determined that as the aircraft configuration evolved from a spanloader configuration to a configuration involving 3 large point masses, existing design and analysis tools failed to predict the vehicle's increased sensitivity to external disturbances. On the day of the mishap, the aircraft was perturbed by turbulence, morphed into an unexpected, persistent, high dihedral configuration that caused an unstable, highly divergent, pitch oscillation to occur from which vehicle recovery was not possible. During the pitch oscillation the aircraft experienced a high-speed dive that significantly exceeded the aircraft's design airspeed resulting in failure of secondary structure, and subsequently loss of lift. The Proximate Cause for the loss of the HP03-2 was the high dynamic pressure reached by the aircraft during the last cycle of the unstable pitch oscillation leading to failure of the vehicle's secondary structure.

Root Causes: One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome.

There were two factors that were considered root causes for the accident:

- Lack of adequate analysis methods led to an inaccurate risk assessment of the effects of configuration changes.
- Configuration changes to the aircraft altered the aircraft from a spanloader to a highly point-loaded mass distribution on the same structure significantly reducing design robustness and margins of safety.

Technical Recommendations and Lessons Learned

Reference 1 provides a complete list of the contributing factors, significant observations, findings, recommendations, and lessons learned associated with the mishap. Below is a list of just the technical recommendations and lessons learned from that report:

- Develop more advanced, multidisciplinary (structures, aeroelastic, aerodynamics, atmospheric, materials, propulsion, controls, etc) "time-domain" analysis methods appropriate to highly flexible, "morphing" vehicles.
- Develop ground-test procedures and techniques appropriate to this class of vehicle to validate new analysis methods and predictions.
- Develop multidisciplinary (structures, aerodynamic, controls, etc) models, which can describe the nonlinear dynamic behavior of aircraft modifications.
- Provide for more incremental flight-testing when large configuration changes significantly deviate from the initial design concept.

- Implement mitigations or hardware systems for returning a vehicle back into a safe flight envelope when performing hazardous or envelope expansion testing.
- Develop a method to measure wing dihedral in real-time.
- Develop manual and/or automatic techniques to control wing dihedral in flight
- Develop capability to perform simulations of the vehicle's response to disturbances.
- Apply advanced atmospheric models that better predict conditions.

The technical lessons learned from extracted from Reference 1 are summarized below:

- Including large point masses on this type of airframe should not be attempted without optimizing the design of the primary load carry structure.
- Measurement of wing dihedral in real-time is necessary with a visual display of results.
- Procedures to control wing dihedral in flight are necessary for the Helios class of vehicle.
- Time domain design and analysis tools for examining the effects of disturbances on the behavior of highly flexible vehicles are required.
- Model fidelity and validation, as well as time domain simulation, can significantly reduce technical risk where the complexity and nonlinearity of subsystem interaction is significant.
- Using numerical simulation models it is possible at modest cost to gain useful meteorological information that highlights the regional weather peculiarities to assist in preparing for flight-testing.
- Design and analysis tools applicable to large, lightweight flexible wing aircraft require better space-time domain models of atmospheric disturbance

Summary

The Helios Prototype vehicle was one of several remotely piloted aircraft funded and developed by NASA under the Environmental Research Aircraft and Sensor Technology project. This vehicle was a proof-of-concept, propeller-driven, flying wing built and operated by AeroVironment, Inc. The vehicle consisted of two configurations. One configuration, designated HP01, was designed to operate at extremely high altitudes using batteries and high-efficiency solar cells spread across the upper surface of its 247-foot wingspan. The other configuration, designated HP03, was designed for long-duration flight. For the lon-duration flight, the plan was to use the solar cells to power the vehicle's electric motors and subsystems during the day and to use a modified commercial hydrogen-air fuel cell system for use during the night.

On the day of the HP03 mishap, the vehicle took off mid morning from the Navy's Pacific Missile Range Facility located on the island of Kauai, Hawaii. The aircraft was under the guidance of ground-based mission controllers. At that time the environmental wind conditions were within an acceptable test envelope. This environment consisted of a wind shadow over and offshore from the facility, bounded to the north, south, and above by zones of wind shear and turbulence that separate the region from the ambient easterly trade-wind flow. At about 30 minutes into the flight, the aircraft encountered turbulence and morphed into

an unexpected, persistent, high dihedral configuration. As a result of the persistent high dihedral, the aircraft became unstable in a very divergent pitch mode in which the airspeed excursions from the nominal flight speed about doubled every cycle of the oscillation. The aircraft's design airspeed was subsequently exceeded and the resulting high dynamic pressures caused the wing leading edge secondary structure on the outer wing panels to fail and the solar cells and skin on the upper surface of the wing to rip off. The aircraft impacted the ocean within the confines of the Pacific Missile Range Facility test range and was destroyed.

It was determined that the aircraft stability and control problem was caused by the complex, nonlinear, interactions involving the flexible structure, the unsteady aerodynamics, the flight control system, the environmental conditions, and vehicle flight dynamic characteristics. It was also determined that the available analysis tools and solution techniques were constrained by conventional and segmented linear methodologies that did not provide the proper level of complexity to understand the technology interactions on the vehicle's stability and control characteristics.

References

- [1] Noll, Thomas E.; Ishmael, Stephen D.; Henwood, Bart; Perez-Davis, Marla E.; Tiffany, Geary C.; Madura, John; Gaier, Matthew; Brown, John M.; and Wierzbanski, Ted: "Investigation of the Helios Prototype Aircraft Mishap", Volume I - Mishap Report, January 2004.