P8.3

A REVIEW OF SOLAR-POWERED AIRCRAFT FLIGHT ACTIVITY AT THE PACIFIC MISSILE RANGE TEST FACILITY, KAUAI, HAWAII*

L. J. Ehernberger,† Casey Donohue, and Edward H. Teets, Jr.
NASA Dryden Flight Research Center, Edwards, California

1. INTRODUCTION – THE AIRCRAFT

A series of solar-powered aircraft have been designed and operated by AeroVironment, Inc. (Monrovia, CA) as a part of National Aeronautics and Space Administration (NASA) objectives to develop energy-efficient high-altitude long-endurance platforms for earth observations and communications applications. Flight operations have been conducted at NASA's Dryden Flight Research Center, Edwards CA and at the U.S. Navy Pacific Missile Range Facility (PMRF) at Barking Sands, Kauai, HI. These aircraft flown at PMRF are named *Pathfinder*, *Pathfinder Plus* and *Helios*. Figure 1 shows front (1a) and side (1b) views of *Helios* as it was configured for the 2001 flight. Sizes of these three aircraft range from 560 lb with a 99-ft wingspan to 2300 lb with a 247-ft wingspan. Available payload capacity reaches approximately 200 lb. *Pathfinder* uses six engines and propellers: *Pathfinder Plus* 8; and *Helios* 14. The 2003 *Helios* fuel cell configurations used 10 engines and propellers. The PMRF was selected as a base of operations because if offers optimal summertime solar exposure, low prevailing windspeeds on the runway, modest upper-air windspeeds and the availability of suitable airspace. Between 1997 and 2001, successive altitude records of 71,530 ft, 80,200 ft, and 96,863 ft were established (Dornheim 1998, Teets 2002). Flight durations extended to 18 hours. Table 1 lists the flight date, takeoff time, landing time, flight duration, peak altitude and time of day for each flight at PMRF. Times are given in hours and minutes Hawaiian Standard Time (HST). For the 2003 flight objectives, a primary hydrogen and air fuel cell system was incorporated on the *Helios* airplane. This configuration increased the airplane gross weight from 1500 lb to 2300 lb. This weight addition was primarily in three point masses; the fuel cell at the airplane center span and hydrogen tanks mounted outboard near each wing tip. Highlights of these flights at Kauai, including the peak altitudes and flight durations are listed in Table 1. A low-altitude mishap on the second flight, June 26, 2003, led to loss of the aircraft. The *Pathfinder Plus* continues in use for a series of development flight tests at Edwards this year (2004).

Fig. 1a. Front view of *Helios* on takeoff for altitude record flight August 13, 2001.

Fig. 1b. Side view of *Helios* in-flight, left to right, August 13, 2001.

†L. J. Ehernberger, NASA Dryden Flight Research Center, P.O. Box 273, Edwards, California 93523-0273; e-mail: Jack.Ehernberger@dfrc.nasa.gov

Table 1. Highlights of the solar-powered aircraft flight series at PMRF with maximum altitude, peak wind, and turbulence for flights at Kauai.

Flight date	Takeoff time, HST	Landing time, HST	Flight duration, hrs, min	Maximum altitude, ft	Time reached maximum altitude, HST	Peak winds		Clear air turbulence noted, altitude, ft	Windshear per sec	Inversion rate, °C/1000 ft
						Altitude, ft	Windspeed, knots			
June 9, 1997	08:43	22:22	13:39	67,400	16:11	48,000	39			
July 7, 1997	08:34	23:05	14:31	71,530	15:34	39,000	36			
Aug. 26, 1997	09:12	22:07	12:55	63,400	15:52	48,000	46			
Aug. 28, 1997	08:31	21:20	12:49	32,650	15:47	37,000	46			
Oct. 25, 1997	09:00	20:34	11:34	23,780	14:39	27,000	34			
Nov. 3, 1997	09:07	21:00	11:53	27,000	16:40	28,000	26			
June 17, 1998	08:20	22:32	12:12	53,100	12:12	43,000	64			
June 27, 1998	07:55	22:32	14:37	59,500	14:05	45,000	31	30,000	0.007 to .010 *.01 to .03	*1.0 to 2.2
Aug. 6, 1998	07:58	22:45	14:47	80,201	15:28	40,000	54	34,500 63,000 71,000	.02 to .027 .008 to .028 .017	1.9 to 2.2 1.9
July 14, 2001	08:08	02:08	18:00	76,271	17:30	33,000	50	30,000 50,000	.01 to .03 .0 to 13 .022	2.0 *1.9 to 2.4
Aug. 13, 2001	08:48	01:43	17:55	96,863	16:10	45,000	38		.012 to .025	1.0 to 2.6
June 24, 2002	09:37	23:01	13:33	65,860		20,000	26			
June 28, 2002	08:20	23:22	15:02	65,600		34,000	31			
July 20, 2002	08:29	23:21	14:52	66,140		36,000	33			
Sept. 30, 2002	08:58	20:17	11:19	25,744						
June 7, 2003	08:43	23:37	14:54	52,450	17:33	44,000	59	50,100	.02 to .03	<1.0
June 26, 2003	10:06		00:30	2,800+	10:36					

***** Indicates wind shear or inversion rate layer is above the turbulence altitude.

2. PAYLOAD DEMONSTRATIONS

In addition to setting altitude and endurance records, payload applications for science, communications, and crop monitoring were demonstrated. During the first flight season at PMRF in 1997, the *Pathfinder* airplane attained an altitude of 71,530 ft to set a record for propeller-driven as well as solar-powered aircraft. This flight also demonstrated the ability to control speed, altitude, and ground track as needed for science observations. A high spectral resolution digital array scanned interferometer (DASI) payload acquired hyperspectral images of several science targets. In addition, a high spatial resolution airborne real time-imaging system (ARTIS) acquired and transferred images to the Internet within minutes. Both systems were developed at NASA Ames Research Center. These systems applications include detecting forest nutrient status and regrowth (after damage by Hurricane Inike in 1992), coastal water algae, sediment concentration, and coral reef health. Researchers from the University of Hawaii and the University of California participated.

In 1998, the *Pathfinder Plus* airplane demonstrated solar powered flight to 80,201 ft and in 2001 *Helios* achieved a record altitude of 96,863 ft.

In 2002, the *Pathfinder Plus* airplane was used by AeroVironment and NASA Dryden Flight Research Center to demonstrate a variety of payloads in collaboration with the Japan Telecom Ministry, Clark University, and NASA Ames Research Center. On June 24, 2002, a digital television (DTV) broadcast demonstrated the first telecom repeater application for a commercial customer, as well as the first relay platform operation in the stratosphere. On June 28, 2002, a cellphone payload demonstrated use of a mobile phone wireless repeater link at altitudes of 24,000 and 65,600 ft during four hours of station keeping. An Internet service link was successful at an altitude of 18,000 ft.

On July 20, 2002, the world’s first high-speed Internet link demonstration through a stratospheric aircraft was accomplished for cellphone and videolink, attaining rates of 24 Mbps.

Remote sensing of coffee fields was demonstrated on Sept. 20, 2002, with imaging payloads at an altitude of 21,000 ft (Herwitz 2003). Maximum observed operating range of the wireless local area network (WLAN) telemetry link was 15 nmi line-of-sight with image data downlink rates of 3 to 4 Mbps. Best system throughput of more than 6 Mbps was achieved with the aircraft flying tangential to the antenna at a range of 3 to 5 nmi. Error-free 16-MB digital images were transmitted with no data dropouts to a ground-based laptop computer in less than 35 seconds at transfer rates ranging from 3 to 6 Mbps.

3. ATMOSPHERIC PERTURBATION RISK MANAGEMENT

Primary meteorological sensitivities are associated with cloud cover, runway winds, excess wind drift at altitudes aloft, and atmospheric turbulence (Donohue 2001; Teets 1998, 1999). Cloud and precipitation avoidance is largely enabled by direct observations at low altitude, by onboard video, and by weather satellite monitoring at high altitudes. The requirements to have relatively clear skies for the solar-powered aircraft and windspeeds less than the maximum flight speed at most levels, has likely biased the atmospheric perturbations experienced at PMRF to more benign conditions. Never the less, about 30 percent of the flights have penetrated or deviated away from clouds or rain. Frequent wind profile forecast updates and rawinsonde observations help manage exposure to wind and turbulence aloft. Windspeeds aloft are generally limited to the airplane true airspeed, which is expressed most simply in terms of equivalent airspeed for the operational airplane configuration. Equivalent airspeed is related to the true airspeed by the square root of the ratio between the ambient atmospheric density at flight altitude and the standard day density at sea level (Gracey 1980). For reference purposes herein, a nominal equivalent airspeed value of 20 knots is used. A comparison of upper-air PMRF windspeed climatology for the months when high altitude flights were accomplished; June, July and August; with the true airspeed as a function of a constant 20-knot equivalent airspeed with altitude is shown in Fig. 2 and listed in Table 1. Climatology curves depict the monthly mean windspeed values and the monthly mean speeds plus one standard deviation (σ). During these months the monthly mean windspeeds are generally less than, or approximately equal to the true airspeed for a 20-knot operational equivalent airspeed. The peak flight day windspeeds with respect to the reference true airspeed curve are shown with symbols on Fig. 2 at their respective altitudes. On four of the

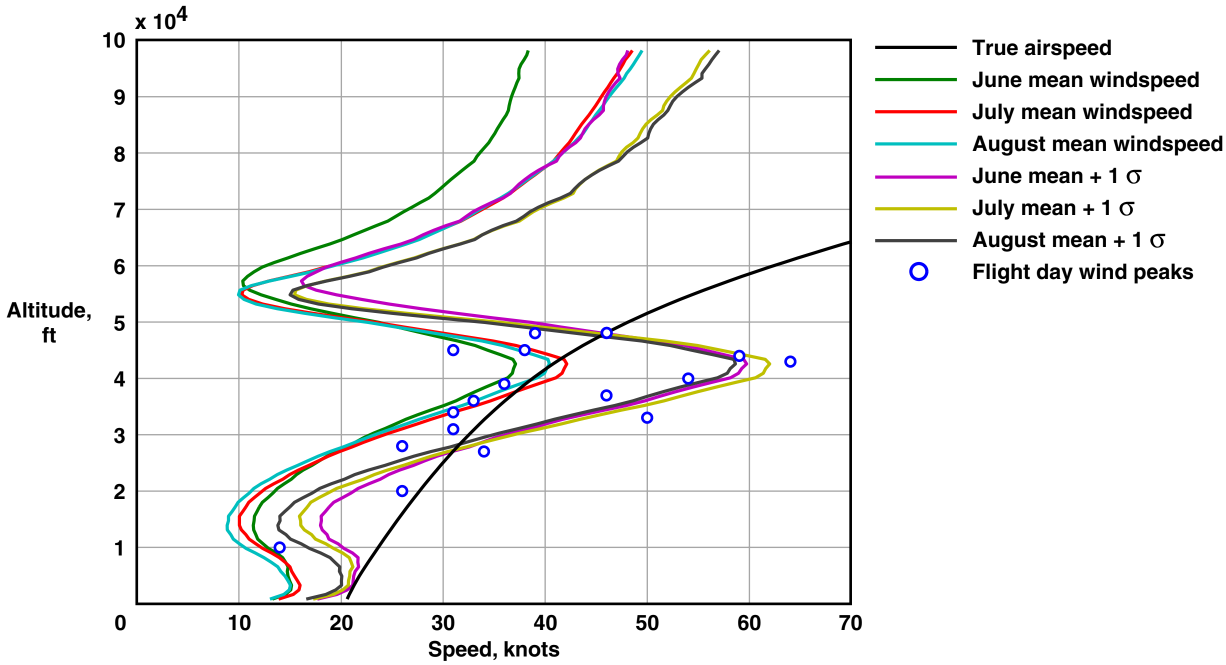

Fig. 2. Reference true airspeed, PMRF windspeed, climatology, and flight day wind profiles peak values.

flight days peak winds exceeded the speed envelope of monthly mean speed plus one standard deviation. On five of the flight days peak wind layers exceeded the reference flight true airspeed by 5 to 22 knots. In these cases flight plans were modified to keep the flight track within approved air space and to manage the potential impact footprint in case the flight termination system use was needed (Bauer 1997; Teets 1998; Underwood 1996).

Weather was monitored to minimize risks associated with clear air turbulence. Weather monitoring included the conservative use of “rules of thumb” derived from previous literature for passenger aircraft and high altitude flight, pilot reports, advisories from forecast offices, and centralized aviation weather forecast products. Several source materials are listed in the bibliography (Ehernberger 1981; Hopkins 1977; Incrocci 1971; Scoggins 1975).

Clear air turbulence at middle and high altitudes was encountered as high as 73,000 ft with intensities termed as strong as “moderate.” Shallow layers with enhanced wind shears, temperature inversion rates, or both, were noted in rawinsonde data for nearby altitudes. In general, enhanced values of wind shear, .010 to .03 per sec, were noted in layers near the reported turbulence altitudes. Shallow layers of enhanced temperature inversion rate were also observed with values ranging from 1.0 to 2.6 °C per 1,000 ft altitude. The altitudes of reported middle and high altitude clear air turbulence (CAT) on individual flights are listed in Table 1 along with values for the predominant shear layers and inversion layers. In some cases significant wind shear or inversion rates were noted in high altitude layers above the turbulence, these are designated with an asterisk (*) in the table. These encounters are not known to have induced any marginal effects with respect to the airplane structure or control system flight worthiness.

Table 2. Log of weather event encounters.

Flight date	Maximum altitude, ft	Notes
June 9, 1997	67,400	Low-altitude turbulence and vertical drafts on descent below 8000 ft.
July 7, 1997	71,530	Nil
Aug. 26, 1997	63,400	Low-altitude turbulence between 4000 and 7000 ft on climb, smooth on descent
Aug. 28, 1997	32,650	Turbulence on climb to 6000 ft. Moderate on descent between 3000 ft and 2500 ft.
Oct. 25, 1997	23,780	Flew through rain on descent. Also turbulence between 6200 ft and 500 ft, with “sinking air” at 1000 ft.
Nov. 3, 1997	27,000	Climb encountered updraft, smooth above 7000 ft. Descent had moderate turbulence below 6500 and 4500 ft.
June 17, 1998	53,100	Nil
June 27, 1998	59,500	Bumpy takeoff and turbulence near 4,500 and 30,000 ft on climb. On descent 300–400 ft/min sink noted near 11,000 ft altitude.
Aug. 6, 1998	80,201	Low-altitude turbulence layers below 11,000 feet on climb. Middle and high-altitude turbulence layers to 73,000 ft.
July 14, 2001	76,271	Takeoff delayed by low altitude cloud deck. Thermal, up-down draft turbulence noted on takeoff. Light turbulence noted in jet stream wind shear and at low altitude, turbulence at 400 to 500 ft on descent.
Aug. 13, 2001	96,863	Takeoff delayed until cloud shadow on airplane cleared. Cloud layer between 4200 and 5000 ft had strong turbulence. Turbulence below 7000 ft on descent.
June 24, 2002	65,860	Ground level wind speeds marginal 20 minutes before takeoff. Wind subsided before clouds closed in on runway.
June 28, 2002	65,600	Inadvertently penetrated cirrus clouds.
July 20, 2002	66,140	Cumulus blocked the normal flight path. Thin cirrus clouds were present.
Sept. 30, 2002	25,744	Light to moderate turbulence on climb near 1600 ft. Stronger low-altitude turbulence on descent.
June 7, 2003	52,450	A quiet “benign” flight day with broken cumulus and cirrus observed. Light turbulence near 50,000 ft.
June 26, 2003	2,800+	Light low-altitude turbulence.

On four flights atmospheric wave motions, either sinking (downdrafts) or rising (updrafts) had some noticeable effect on airplane performance. The *Helios* airplane (Fig.1) aeroelastic motion response to a very low altitude perturbation experienced on takeoff may be viewed by a Weblink at http://www.dfrc.nasa.gov/Gallery/Movie/Helios/HTML/EM-0046-04.html. Low-altitude turbulence was noticed on both climb and descent on about 30 percent of the flights. Overall, low-altitude turbulence encounters on climb during the morning hours were experienced on 9 days, while 7 flights encountered low-altitude turbulence on descent for landing during the evening or night hours. Table 2 notes pertinent weather events for each flight date.

4. DISCUSSION

State-of-the-art advances in airframe design, solar cell efficiency, batteries, and fuel cells are demonstrating new approaches to high-altitude long-endurance aircraft for applications to earth observations, communications, and atmospheric science. Significant payload capacity for both remote and in-situ sensors is practical, and also serves well for missions combining telecom and atmospheric sensors (Hunley 2002). Flight speeds in the stratosphere are modest and when combined with station keeping for communications applications would provide Eulerian sampling of atmospheric variations. Present solar-powered aircraft have accomplished flight durations of over 10 hours at high altitude and more significantly have validated design technologies for high-altitude flight durations of several days. Use of such modest low-speed platforms in science field experiments could compare the Eulerian data with Lagrangian measurements from constant level balloons to investigate the limits of the “frozen field” assumptions generally invoked with respect to aircraft measurements of turbulence and wave perturbations. Two additional attributes of the solar or hydrogen fuel-cell-powered airplane configurations flown are the minimal influence on in-situ sampling. First, potential interference to chemical species measurements is minimal from both the standpoint of aerodynamic compression effects and potential contamination from fuel exhaust products. Second, low aerodynamic distortion is also an asset for accurate airspeed and ambient pressure data, which are significant to accurate turbulence motion measurement and to evaluation of pressure field effects on the high altitude turbulence process energy budgets.

5. CONCLUDING REMARKS

The *Pathfinder*, *Pathfinder Plus* and *Helios* aircraft flights have demonstrated development evolution of lightweight high-altitude aircraft. Using solar power a record altitude of 96,863 ft was established in 2001. Payloads for crop and ecological monitoring as well as telecom relay demonstrated capabilities for remote flight control, science measurements, and communications relay at high altitudes. Flight track management achieved successful trajectory control when maximum windspeed peaks exceeded true airspeed. In addition, turbulence and updraft-downdraft perturbations experienced aloft were within the airplane design and operational envelope. These flight accomplishments demonstrate important accomplishments in high-altitude aircraft design capability for applications to telecom, earth resources monitoring, and atmospheric dynamics documentation.

6. BIBLIOGRAPHY

Bauer, J. E., and E. H. Teets Jr., 1997: An impact-location estimation algorithm for subsonic uninhabited aircraft. NASA-TM-97-206299, 28 pp.

Donohue, C. J., K. Underwood, and D. G, Bellue, 2001: Use of acoustic wind profilers for uninhabited aerial vehicle flight test activities. Preprints, *Seventeenth International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology,* Session 1, Albuquerque, NM, Amer. Meteor. Soc., P1.5.

Dornheim, M. A., 1998: “Pathfinder Plus exceeds 80,000 ft.; Centurion assembled.” Aviation Week & Space Technology, **149**, 7, 33.

Ehernberger, L. J., and N. B. Guttman, 1981: Climatological characteristics of high altitude wind shear and lapse rate layers. NASA TM-81353, 101 pp.

Gracey, W., 1980: Measurement of aircraft speed and altitude. NASA RP-1046, 208 pp.

Herwitz, S. R., J. G. Leung, M. Aoyagi, D. Billings, M. Y. Wei, S. E. Dunagan, R. G. Higgins, D. V. Sullivan, and R. E. Slye, 2003: Wireless LAN for operation of high resolution imaging payload on a high altitude solar-powered unmanned aerial vehicle. *Proc. International Telemetering Conference*, Las Vegas, NV, International Foundation for Telemetering, **XXXIX**, ISSN 1546-2188, 03-08-02.

Hopkins, R. H., 1977: Forecasting techniques of clear-air turbulence including that associated with mountain waves. World Meteorological Organization. WMO No. 482, Technical Note No. 155, 31 pp.

Hunley, J. D., and Y. Kellogg (compilers), 2000: ERAST: Scientific applications and technology commercialization. NASA CP-2000-209031, 203 pp.

Incrocci, T. P., and J. R. Scoggins, 1971: An investigation of the relationships between mountain-wave conditions and clear air turbulence encountered by the XB-70 airplane in the stratosphere, NASA CR-1878, 34 pp.

Scoggins, J. R., T. L. Clark, and N. C. Possiel, 1975: Relationships between stratospheric clear air turbulence and synoptic meteorological parameters over the Western United States between 12-20 km altitude. NASA CR-143837, 161 pp.

Teets, E. H., Jr., and N. Salazar, 1999: Wind and mountain wave conditions for the Pathfinder Hawaiian flight test operation. NASA CR-1999-206571, 10 pp.

Teets, E. H., Jr., C. J. Donohue, and P. T. Wright, 2002: Meteorological support of the Helios world record high altitude flight to 96,863 feet. NASA TM-2002-210727, 20 pp.

Teets, E. H., Jr., C. J. Donohue, K. Underwood, and J. E. Bauer, 1998: Atmospheric considerations for uninhabited aerial vehicle (UAV) flight test planning. NASA/TM-1998-206541, 18 pp.

Underwood, K. H., and E. H. Teets Jr., 1996: Pathfinder: upper-air climatology and real-time wind prediction for flight test. AIAA-96-0398, 5 pp.