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Meteorological Support of the Helios World Record High Altitude Flight to 96,863 Feet

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ABSTRACT

In characterizing and understanding atmospheric behavior when conducting high altitude solar powered flight research flight planning engineers and meteorologists are able to maximize the use of available airspace and coordinate aircraft maneuvers with pilots to make the best use of changing sun elevation angles. The result of this cooperative research produced a new world record for absolute altitude of a non-rocket powered aircraft of 96,863 ft (29,531.4 m). The Helios prototype solar powered aircraft, with a wingspan of 247 ft (75.0 m), reached this altitude on August 13, 2001, off the coast of Kauai, Hawaii. The analyses of the weather characterization, the planning efforts, and the weather-of-the-day summary that led to at record flight are described in this paper.

NOMENCLATURE

dB	decibels
DFRC	Dryden Flight Research Center (Edwards AFB, California)
ERAST	Environmental Research And Sensor Technology
FAI	Fédération Aéronautique Internationale (Lausanne, Switzerland)
GPS	global positioning system
HST	Hawaii Standard Time
km	kilometer
kn	knots
kw	kilowatts
m	meter
m/s	meters per second
PMRF	Pacific Missile Range Facility, (Barking Sands, Hawaii)
SODAR	Sonic Detection and Ranging
TAS	True Air Speed
UAV	Uninhabited Aerial Vehicle

INTRODUCTION

The Helios prototype is the latest in a series of solar powered aircraft designed and built by AeroVironment Inc., (Simi Valley, California). The Helios was built and tested under the Environmental Research And Sensor Technology (ERAST) project, a solar powered aircraft series at the NASA Dryden Flight Research Center (DFRC), Edwards Air Force Base, California. The ERAST project began high altitude flight activity in 1994. Two long-term goals were established for the Helios prototype. First, the *extreme altitude* mission was designed to reach an altitude of 100,000 ft (30,487 m) using only solar power. In 2003, the Helios prototype will be modified for an *extreme duration* mission with the installation of a fuel-cell-based power system. This mission will be an attempt to continuously fly for more than 14 hr at altitudes higher than 50,000 ft (15,240 m)[1,2]. This long duration flight is scheduled to occur at either the U.S. Navy Pacific Missile Range Facility (PMRF), Barking Sands, Kauai, Hawaii or Point Mugu, California.

The 99-ft (30.2 m) Pathfinder[1] configuration, the first aircraft in the series, reached 50,500 ft (15,396.3 m) on September 11, 1995 and, by the summer of 1997 had reached 71,500 ft (21,798.8 m). In 1998, the Pathfinder[3] was modified with a new center wing panel that increased its wingspan to 121 ft (36.9 m). The Pathfinder was renamed the Pathfinder Plus[3] and on August 6, 1998, reached, a then world altitude record for propeller driven aircraft of, 80,201 ft (24,445.0 m). The Helios prototype, a 247-foot (75.0 m) wingspan solar powered electric uninhabited aerial vehicle (UAV) was first flown on September 8, 1999 at the NASA DFRC. On August 13, 2001 at 4:10 pm Hawaii Standard Time (HST) the Helios prototype aircraft ended its climb to altitude and in doing so set a new U.S. national record for absolute altitude (record of 96,863 ft (29,531.4 m). The world record is pending as of March 1, 2002 with Fédération Aéronautique Internationale (FAI)). The current non-rocket powered world absolute altitude record of 85,000+ft (25,914 m) was set by the SR-71 in 1976. The Helios 17-hour flight was conducted at the U.S. Navy Pacific Missile Range Facility (PMRF) at Barking Sands, Kauai, Hawaii. The high altitude UAV flights, since 1997, all took place at PMRF and were made possible because of the available range airspace, planning, favorable atmospheric conditions, and an abundance of solar radiation. This paper discusses the highlights of these attributes as they pertain to the flight operations based at Barking Sands, Kauai, Hawaii. Notice: Use of trade names or names of manufacturers in this document does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

Aircraft Background

The Helios prototype (Figure 1), like its predecessors, has a unique aerodynamic configuration capable of attaining extremely high altitudes and maintaining long duration flight. As a result of the aerodynamic configuration, the Helios is built with an extremely light wind loading 0.835 lbs/ft^2 (0.371 N/m^2) and a long wingspan. These types of UAVs are fragile and travel at slow speeds. When operating or handling the Helios prototype special care is required. Surface winds are a concern to the aircraft, not only during takeoffs and landings, but also during preflight and postflight ground handling. High winds at altitude (higher than the airspeed of the aircraft) during the flight can cause excessive wind drift, making controllability difficult. For this reason, mission rules require the wind speed be less than the aircraft true air speed (TAS). True air speed is the actual air speed a vehicle is traveling through the air mass, determined by knowing the air density at flight altitude, assuming level flight. The Helios minimum TAS required for level flight, is the indicated standard-day sea level TAS of 19 kn (9.7 m/s) multiplied by the square root of the density ratios between the surface standard day density and the actual density at flight altitude.

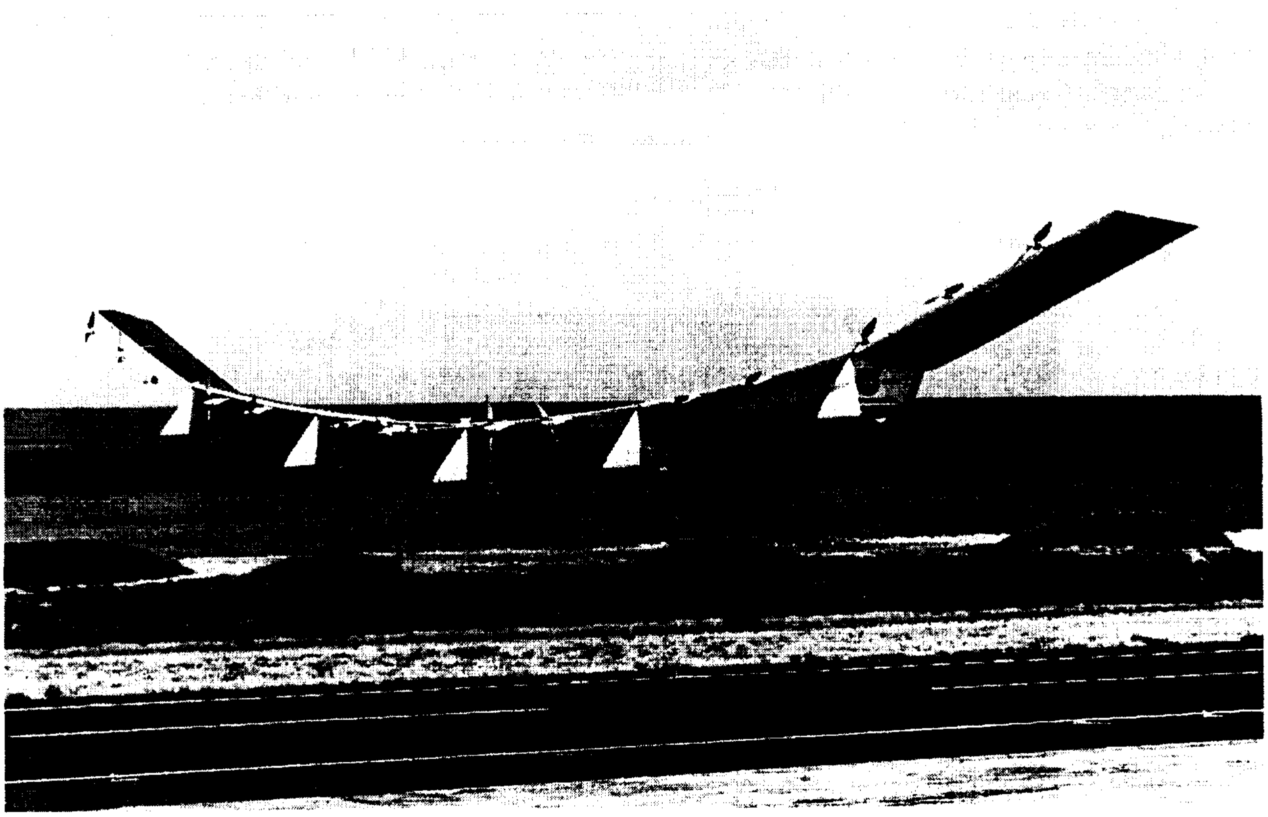


Figure 1. Helios Aircraft at takeoff.

Being a solar powered aircraft, clouds that block the sun can be a significant obstacle during takeoff; however, the aircraft is equipped with batteries that may be used for limited takeoff power. These batteries power the aircraft control and navigation systems during the long nighttime descent and go-around capability. During the year 2000, more than 65,000 solar cells in 1,800 groups were mounted on the upper surface of the Helios' wing. These solar cells are about 19-percent efficient in converting solar energy into electrical current. The entire array is capable of producing a maximum output of about 35 kW at high noon on a summer day. As a result of the entire wing having an airfoil shape and the aircraft maintaining a positive angle of attack for best performance, the solar array faces somewhat aft of the direction of flight. Therefore the aircraft must continuously fly away from the sun in order to receive optimum solar energy on the array. While clouds are not particularly desired for takeoff, they are desirable once above them at high altitude because of reflected solar energy. Reflected energy is captured by these silicon cells which are bifacial, meaning the cells can convert solar energy into electricity when illuminated from either above or below.

Test Range

The PMRF is situated on the western shore of the island of Kauai. The island is split in two by a large north-south oriented ridge, ranging from 2500 to 5000 ft (1067.0 m), which creates two unique climates on an island just 30 miles (48 km) across (fig. 2). The eastern side (or Lihue side) is wetter and windier than the western side as a result of direct impact from the trade winds. This trade wind system occupies most of the tropics with winds blowing from the subtropical high toward the equatorial low pressure centers. In the Northern Hemisphere Pacific region, these winds are northeasterly and are concentrated to the eastern half of the ocean. They are primarily surface winds, their usual depth being 3,000 to 5,000 ft, although they sometimes extend to much higher levels. "The trades," as they are called, are characterized by being very moist with great consistency of direction; these trade winds are the most consistent wind system on earth[4]. Kauai's western side rests in a wind and rain shadow created by the ridge that diverts the wind and moisture around the island. This wind shadow scenario creates a region of light winds and precipitation during the strong tradewind season (summer). One of the reasons Hawaii's PMRF was chosen as the Helios flight location was because of the light surface and upper level wind conditions that exist during the summer.

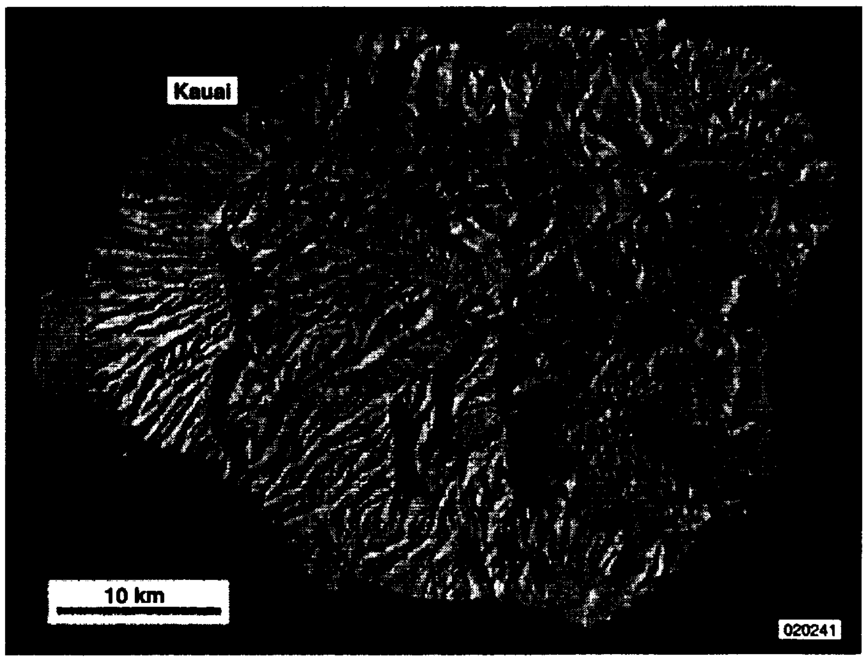


Figure 2. Map of Kauai's topography.

Another advantage to conducting operations from PMRF is the ample airspace. PMRF controls and operates an airspace of over 42,000 square miles that extends out nearly 150 miles to the west and arches northward to the northeast with nearly all this airspace being over water. The Helios has been given authority to operate in warning area W-188 outlined on figure 3. However, because of the high terrain to the northeast of PMRF, the actual operating area within W-188 is slightly reduced. This high terrain obscures the line-of-sight of the tracking antenna when the aircraft travels into the eastern edge of warning area W-188 or into W-189 (not accessible by Helios). The blocked airspace is indicated on figure 3 by the hatched region to the east and north of the island.

Located on the westernmost major island of the Hawaiian archipelago the PMRF is at a latitude of 22° 02' N. As a result of this latitude, the sun elevation angle changes very little over the course of the summer between June 1 and August 1, and the sun actually passes overhead in mid June and on June 21, is positioned slightly north (1.5°) of Kauai. This situation provides the opportunity to have high sun angles throughout most of the summer. A high sun angle allows the Helios prototype to effectively fly in any direction because the sun is high overhead from late morning to early afternoon.

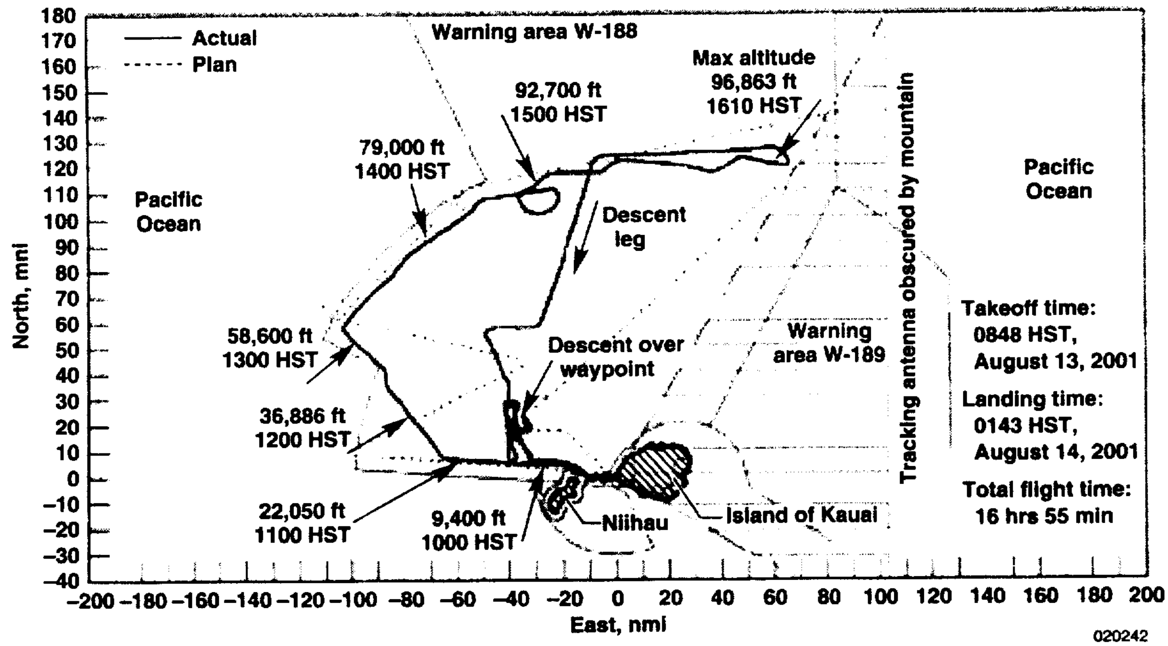


Figure 3. Flight track of Helios prototype during the record-breaking flight.

In support of the test range weather, several meteorological instruments are employed to monitor upper- and lower-level atmospheric conditions. Upper atmospheric range data of wind pressure, and temperatures are provided by the NASA-DFRC balloon-borne Global Positioning System (GPS)-tracked radiosonde package, launched periodically from an established location at PMRF. The GPS system is a Vaisala DigiCORA III (MW21) sounding system (made by Vaisala, Oyj (Helsinke, Finland)). The data collected include thermodynamic data (temperature and relative humidity) and GPS position every 1-sec. Position is determined by real-time code correlating differential computations. The receiver-processor produces wind vector data by real-time derivatives of position; final wind data represents a 20-sec moving average. One disadvantage to using the GPS radiosonde system is that balloons are only launched every few hours and thereby do not continuously observe the changes in the lower atmosphere. Surface winds are provided by a NASA-owned MetOne, Model 034A wind anemometer (made by MetOne Instruments, Inc. [Grants Pass, Oregon]) that provides instantaneous wind information of both speed and direction. All wind data is archived for postflight analysis averaged in 1-, 5-, or 15-minute intervals. Additional wind sensors with similar options, owned and operated by the U.S. Navy, were available. These sensors are located at strategic locations around the facility, such as runway thresholds, landing zones, hilltops, and buildings.

To obtain detailed low-level (less than 1 km above ground) wind and turbulence data, meteorologists and planners have enlisted the use of sonic Doppler acoustic radar (SODAR) or wind profilers. Two SODAR systems were used: both models from AeroVironment, Inc. (Monrovia, California) the model 2000 and the model 4000 (or miniSODAR). The model 2000 operates at an acoustic frequency in the 2000-Hz range (Aerovirnonment, Inc. [1993]).[5] This system uses three acoustic-speaker, parabolic-dish configuration antennas. These three independent beams are employed to measure a three-dimensional wind field. For higher resolution near the surface, the miniSODAR operates at a frequency of approximately 4500 Hz using a 32-element speaker array antenna (AeroVirnonment, Inc. [1996]).[6] These SODAR systems are placed near the landing threshold and provide updated wind information at user-selected intervals from 1 minute for the model 4000 and from 10 minutes for the model 2000. The

SODAR altitude levels range from 65 to 4,921 ft (20 to 1,500 m) with reporting intervals of 65 ft (20 m) for the model 2000; and 49 to 656 ft (15 to 200 m) with a reporting interval of 16 ft (5 m) for the model 4000. These SODAR systems provide the meteorologist with information as to the current structure of the lower atmosphere, and trends that are occurring over time. By observing these changes, the planners are able to modify takeoff and landing times, to cancel or postpone the flight, or to change the takeoff and landing and choose the desired runway. The SODAR has a few advantages; it is self-sufficient and requires little attention to operate, and it provides constant updates of wind and turbulence, information.

Climatology

The Hawaiian Islands lie neither in the tropics nor within the belt consistently influenced by mid latitude atmospheric systems. As a result, a combination of methods and techniques must be used to forecast changes in weather. Climatology is the statistical representation of the atmospheric environment for a given spatial and temporal reference. The planning for any UAV activity, especially the Helios prototype, requires a comprehensive understanding of the local seasonal climate (such as the surface and upper air climatology). This understanding minimizes risks by establishing periods and intervals of favorable weather conditions. Operational weather limits establish minimal risk to the vehicle and enhance the probability of a safe return. Climatology can also be extremely useful in efficient scheduling and minimizing cancellations that may result from unacceptable weather. The surface weather parameters considered most important are winds, cloud cover, and precipitation; while the upper-level parameters are primarily temperature and winds.

The upper level winds impose the greatest restrictions for UAV flight operations. Figure 4 highlights the upper level winds at PMRF from the surface to 100,000 ft for each month of the year[7]. These data are used to simulate the effects of wind on aircraft behavior during flight. The highest mean wind speed is in February, with wind speeds in excess of 60 kn (30 m/s). In contrast, the lightest mean wind month is June with speeds of 25 kn (12 m/s). Both maximums are observed at 45,000 ft (13,720 m). In the summer, Hawaii's weather features are better represented by the tropics than by midlatitude features. As a result, the upper level features will closely model the mean conditions of that month. In the stratosphere, the wind directions are strongly dependent on season. Figure 4, also shows the wind field in the stratosphere (55,000 ft) (16,764 m). For example, in February the stratospheric winds are westerly (moving from west to east) and generally light at all levels, while in July the winds are easterly (moving from east to west) and increase steadily in speed with altitude peaking at approximately 50 kn (25 m/s) at 100,000 ft (30.5 km). The seasonal direction reversal at stratospheric levels is a result of pressure gradient forcing. During the spring and summer the stratospheric pressure gradient increases from north to south, initiated by the continuous heating in the northern polar stratosphere as a result of the 24-hour a day sun.

Surface climatology describes the behavior of the atmospheric boundary layer, the lowest 100 meters of the atmosphere. The surface conditions are of primary importance during takeoff, landing, and ground handling. For these periods the desire is to operate during light wind conditions. The winds are most favorable during evening and morning hours. Based of these data similarly, on the Lihue side of the island, time of day also influences the speed of the surface winds even though they are under constant impact of the generally steady trades. The wind difference between PMRF and Lihue is the result of the high terrain deflection of the trade winds. (For detailed analysis regarding the PMRF climatology see *Atmospheric Considerations for Uninhabited Aerial Vehicle (UAV) Flight Test Planning* NASA/TM-1998-206541).[8]

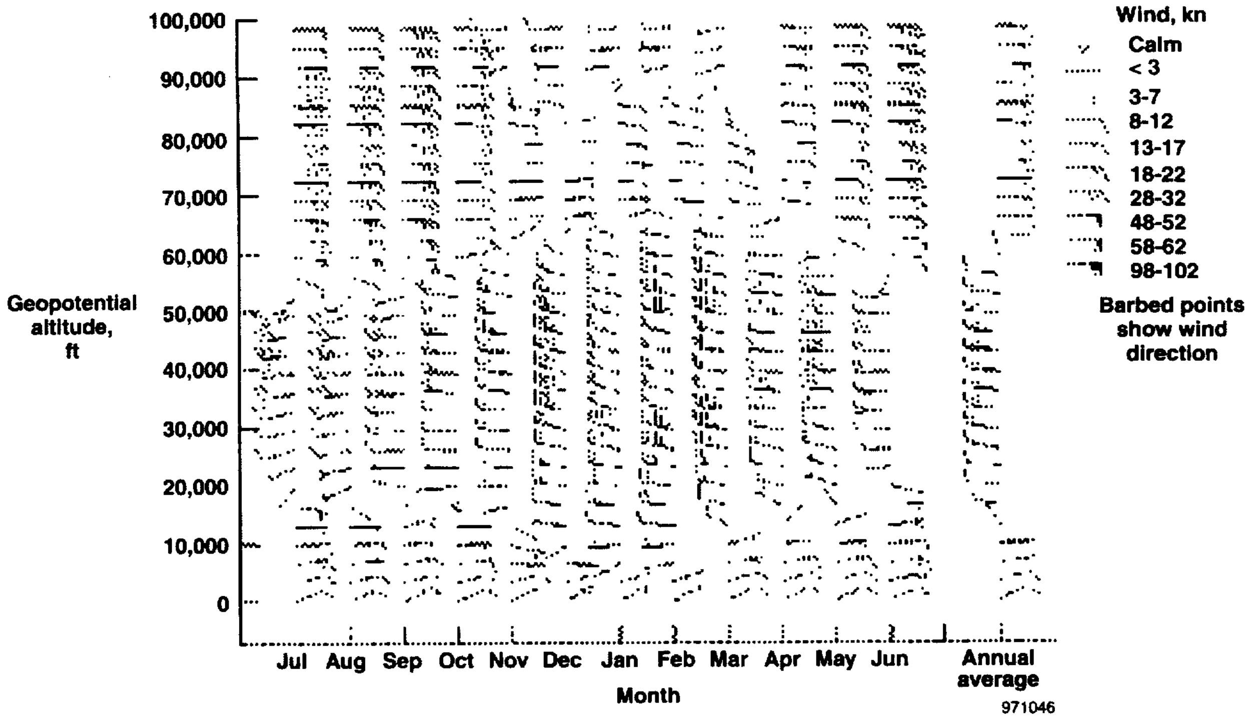


Figure 4. Monthly mean, upper atmospheric wind speed and direction for Pacific Missile Range Facility, Barking Sands, Kauai, Hawaii.

Flight Planning

The primary use of climatology data was to quantify the effects of wind as related to mission planning[2]. Mission planning involves every detail of the flight timeline including: preflight ground handling, preflight, takeoff, in-flight activity, landing, and postflight ground handling.

For the UAV, weather limits differ greatly depending on the type of mission and the UAV itself. The Helios prototype for example; has a 12 kn peak limit for ground operations, while for takeoff and landing the Helios is limited to a 7 kn peak. Ground crew control becomes especially difficult in strong winds, and the airplane could be damaged by strong gusts that lift and drop the airframe. In support of the planning activity, SODAR and wind towers were used to construct a coarse surface or boundary layer wind model highlighting the hourly wind behavior, including the diurnal transition periods of early morning and early evening (offshore to onshore and onshore to offshore). While these preliminary observations were not methodically documented, the timing of the change has been fairly consistent. Nominally, the morning transition begins around 0730 HST with the shift of winds from offshore to onshore. The reversal then occurs around 2200 HST with winds shifting offshore once again. The peak wind of the day nominally occurs between noon and 1300 HST, at 10 kn (observed in the 20-day wind average). The surface winds at Lihue are much more predictable. These winds, unless driven by large-scale bad weather features, will nearly always be east-northeast in direction and with speeds of 8-14 kn. The historical wind data will be further discussed later.

As a reminder, the climatology winds (figure 4) show that during summer, the tropospheric winds are the most favorable for flight activity. The best conditions usually exist with weak pressure gradients associated with a high-pressure weather system. To be considered highly favorable, the wind speeds must be less than the aircraft TAS and the wind direction must result in the airplane sensing head winds at all altitudes, during each leg of the flight. This is required so that positive ground speed can be maintained. In some cases, there are exceptions to this rule. One such example: a strong jet exists that exceeds the TAS by 10 kn for only a few thousand feet. This situation may be acceptable provided predictions can ensure the aircraft is able to return to base at any time throughout the mission regardless of location. Each case for exception is thoroughly reviewed.

A unique challenge presented to the flight planners was to optimize the flight plan, by balancing the sun position, the winds of the day, and the established airspace. For optimum lift, the aircraft maintains an angle of attack such that the solar arrays face somewhat aft of the direction of flight. Optimizing the climb means the vehicle must orient itself away from the sun during the morning and afternoon. This means the aircraft is always flying away from the sun. The large amount of available airspace permits flight planners and meteorologists to efficiently develop a flight plan that permits the pilots to safely maneuver the vehicle, keeping the sun on the solar array. As mentioned earlier, it is desired to have the aircraft always flying into a head wind. At lower levels of the atmosphere the climb rate of the vehicle is not very good, by having a headwind the forward movement of the vehicle is reduced. The advantage of a slow forward ground speed is increased airspace management and vehicle tracking. Headwinds keep the vehicle close to base while allowing the climb to continue. At low altitude, wind speeds can be equal to or greater than the aircraft TAS, making ground speed zero or negative. This situation is not significant provided the aircraft can maintain a climb rate and the atmosphere is not turbulent. The prepared flight plans take into account the sun elevation and location of the aircraft. Depending on atmospheric conditions, it is sometimes necessary to deviate from the flight plan in order to make minor heading adjustments or to reposition the aircraft in preparation for the next leg. Making these corrections at specific times minimizes any lost climb time.

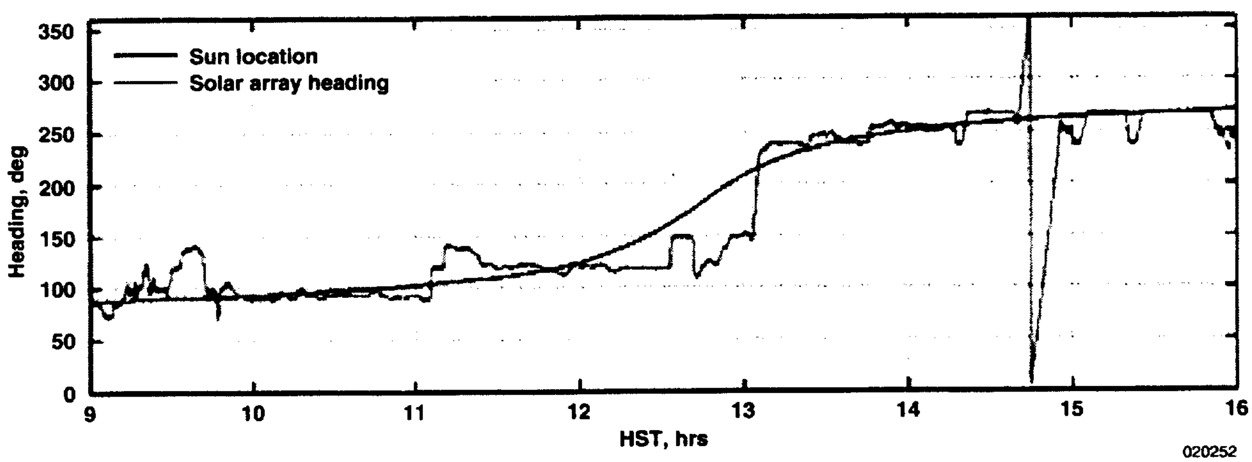
Combining airspace management, sun position, and the weather is also very important during the final climb to altitude. The Helios, as it enters the tropical stratosphere (~55,000 ft (16,768 m)), should begin to encounter easterly winds that steadily increase with altitude. At this point, the aircraft is at the furthest point west of the base. The Helios also makes its final turn towards the east, traveling away from the sun on the final climb to altitude. During this final climb to altitude, higher wind speeds are actually desired. The increasing stratospheric winds that accompany increased altitude slowly decrease the forward speed of the vehicle, keeping the aircraft inside the established airspace. At these altitudes the aircraft TAS is considerably higher than the wind speed.

Finally, clear skies and light winds are always desired for takeoff. Once the aircraft climbs above the trade wind layer, low clouds are usually no longer a problem. The solar arrays are bifacial, so they can continue to produce power whether illuminated from above or below. The clouds below the aircraft reflect solar energy back up into the sky that can be used to generate more power, increasing the climb rate. Precipitation of any kind is not desired. Fortunately, the vast majority of the precipitation for the Hawaiian Islands occurs during the months of December to February. On the island of Kauai, Mt Waialeale, one of the wettest spots on earth (more than 600 inches a year), lies on the ridge that separates the island. This ridgeline wrings out most of the moisture before it reaches PMRF. Lihue on the eastside receives more than twice the amount of precipitation PMRF receives in a given year.

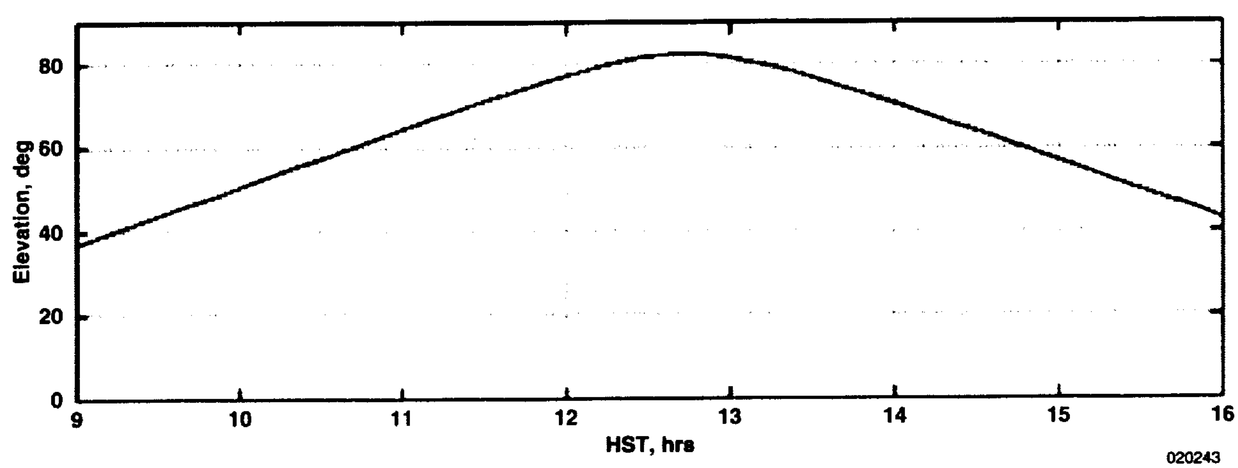
Day of flight

On August 13, a building high pressure system dominated the Hawaiian Islands, in particular, the region above 30,000 feet, where days before an upper level low pressure center had been located. The upper level winds at PMRF were typical of the season on the day of flight. The desired flight plan for August 13, based on the prevailing winds (dots) and the actual ground track (solid line), is shown in figure 3. The significant difference between the predicted flight plan and the actual flight plan is two-fold, (1) the result of a 36-minute weather hold; and (2) changes in the wind field over a 17-hour period. Because of the hold, certain planned maneuvers were eliminated in order to make up for lost sun time. The two tracks to altitude are relatively close, showing just how benign the weather was this day.

In figure 3, the actual flight path loosely overlays the predicted flight path, which keeps the sun on the array. Sun azimuth and aircraft aft heading as well as the sun elevation angle for August 13 are shown in Figure 5(a,b). Notice the heading curves briefly separated between 1100 and 1300 HST. This separation is planned during high sun elevation angles. At high sun elevation angles the energy received by the solar array is nearly equal regardless of the aircraft heading.



a. Sun azimuth and solar cell heading.



b. Sun elevation angle.

Figure 5. Sun location and solar array heading, and sun elevation angle.

The upper altitude wind speed and direction profiles are shown in figures 6 and 7. In order to show aircraft wind sensitivity, the Helios TAS curve and the climatological mean wind for August are added to figure 6 and only the mean wind direction for August is added to figure 7. The maximum wind speed for the day was 38 kn (19.5 m/s), reported on the last weather balloon launch of the day at 45,000 ft, 1913 HST (balloon #6). From figure 6, a positive forward velocity is maintained when the winds are oriented

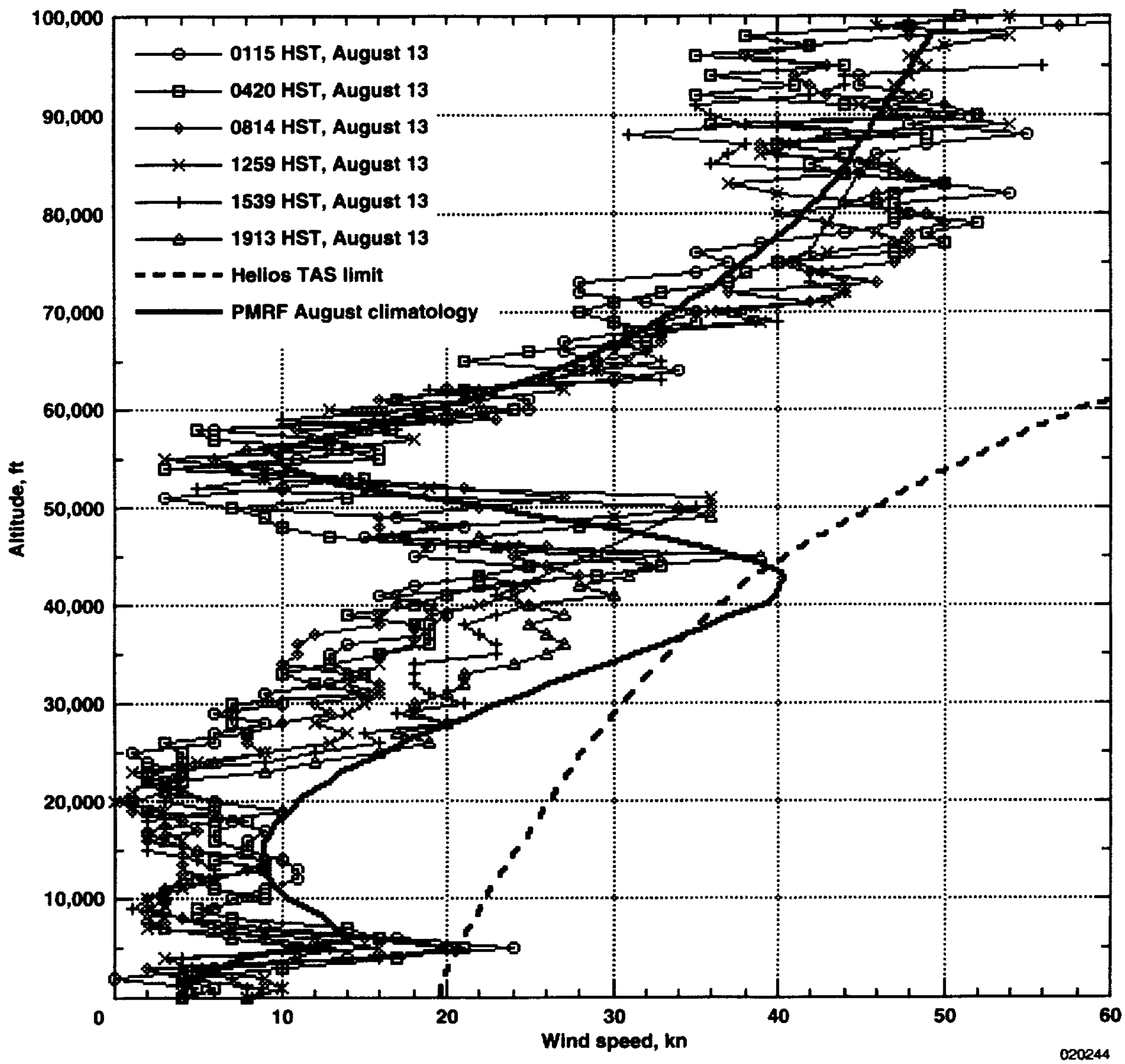


Figure 6. Wind speed profiles from August 13 with Helios TAS limit and PMRF August wind climatology.

to the left of the TAS curve. In addition, the winds at most altitudes this day were less than mean August speed, which is below the aircraft TAS. The lightest wind of the day was reported at less than 5 kn (2.6 m/s) at an altitude of approximately 10,000 ft. Light winds, less than 10 kn (5.2 m/s), dominated the profile between 8,000 ft (2,439.0 m) and 25,000 ft (7,.622.0 m). Wind directions remained consistent

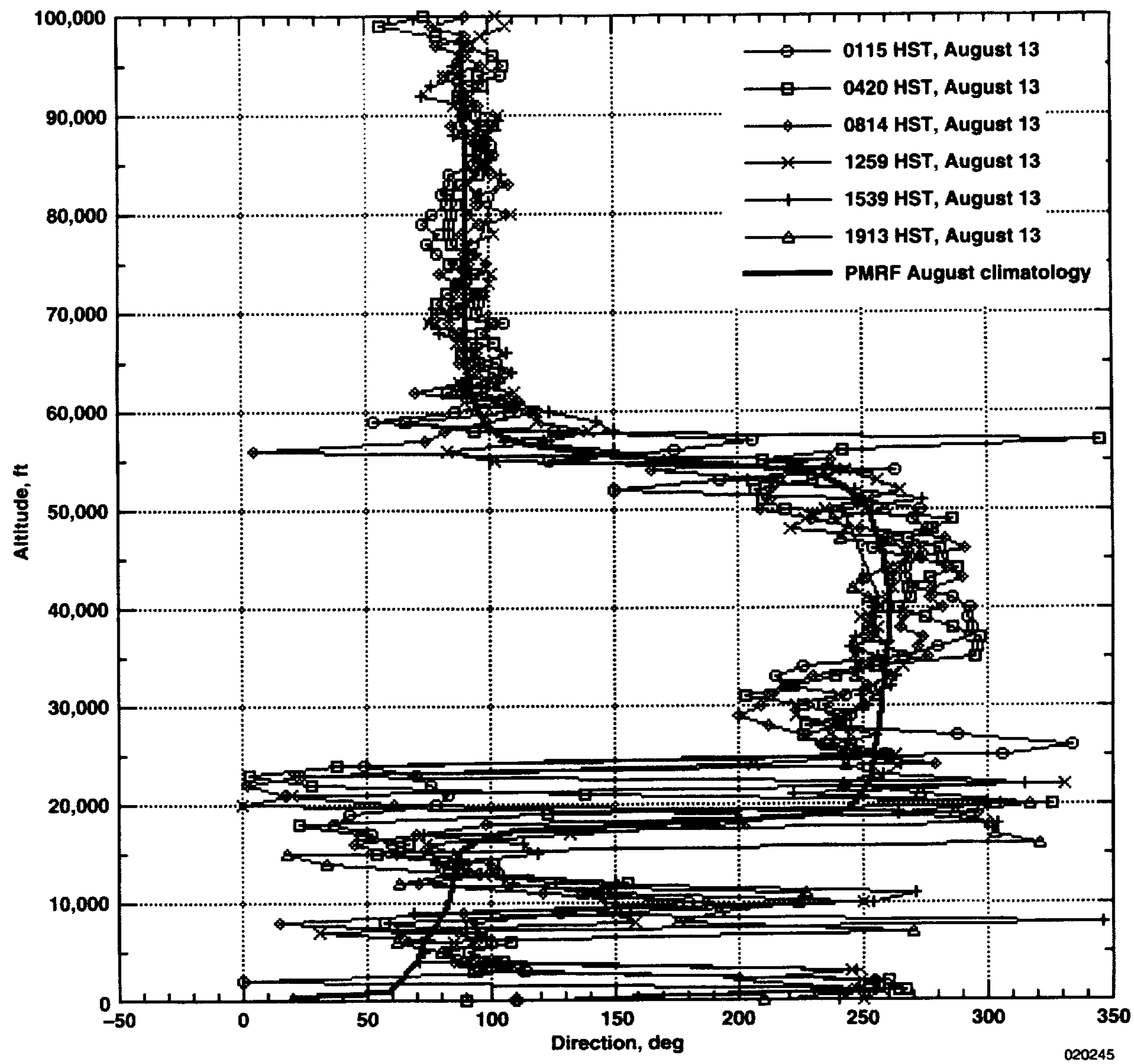


Figure 7. Wind direction profiles from August 13 with PMRF August wind direction climatology.

over the period matching very well to the climatology for August, this is evident in figure 8. Some slight veering (clockwise turning of the winds) was observed from 220 deg at 30,000 ft (9,146.3 m) to 280 deg at 45,000 ft (13,719.5 m). At 57,000 ft (17,378.0 m) and entering lower stratosphere the winds began their switch to the east with 074 deg at 13kn (6.7 m/s) increasing to 64 kn (32.9 m/s) at 100,000 ft (30,480.0 m).

The surface and boundary layer conditions on the island were strongly influenced by high pressure to the north and the trade wind layer it produces. This trade wind layer was unusually thick, more than 8,000 ft (2,439 m) and very moist. When thick trade wind layers exist, the island's mountain range does little to block and divert the winds and clouds above, which pass over the mountain unaffected. Just prior to the scheduled takeoff, a large cloud mass moved over the base from the east. A hold was issued until the cloud either dissipated or moved on, which it did 36 minutes later. The wind passing over the mountain will, in many cases, mix with the relatively calm air in the lee of the ridge, producing a shear line. In some cases the shear lines may mix to the ground. This shear line then travels downwind and out to sea, embedded in the trade wind flow, producing isolated pockets of turbulence. This shear turbulence was detected above the base by the (SODAR) wind profiler as seen in figure 8. The time height series shows the period and randomness of the shear lines and how close to the ground they mix. The darker patches, in figure 8, between 984 and 2,296 ft (300 and 700 meters) represent turbulence. The SODAR turbulence mode relies on the strength of the returned signal, thus the greater the turbulence intensity the stronger the signal returned (reflected).

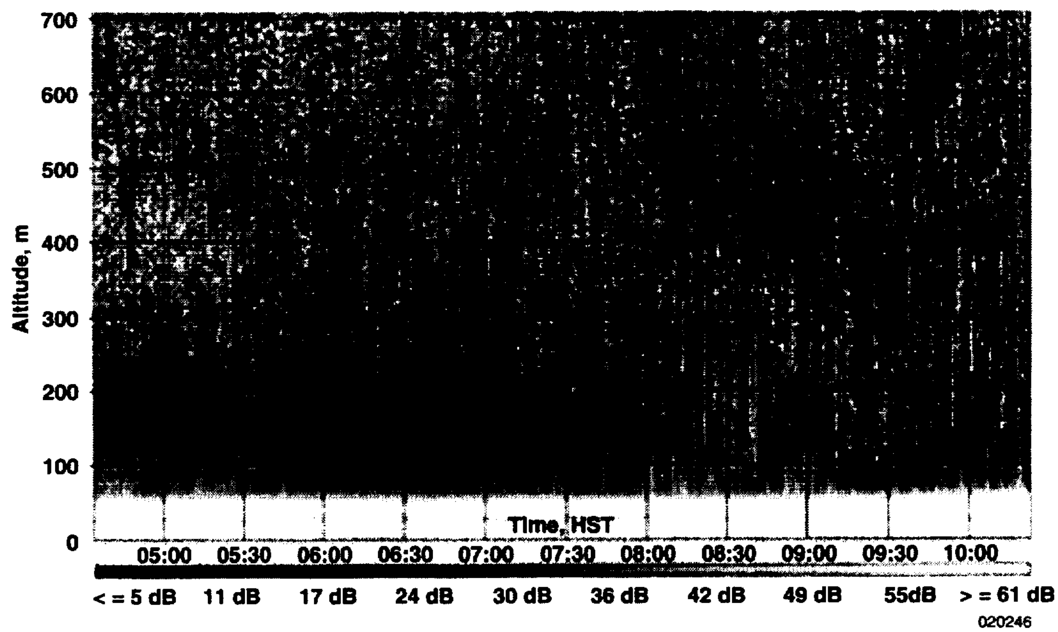
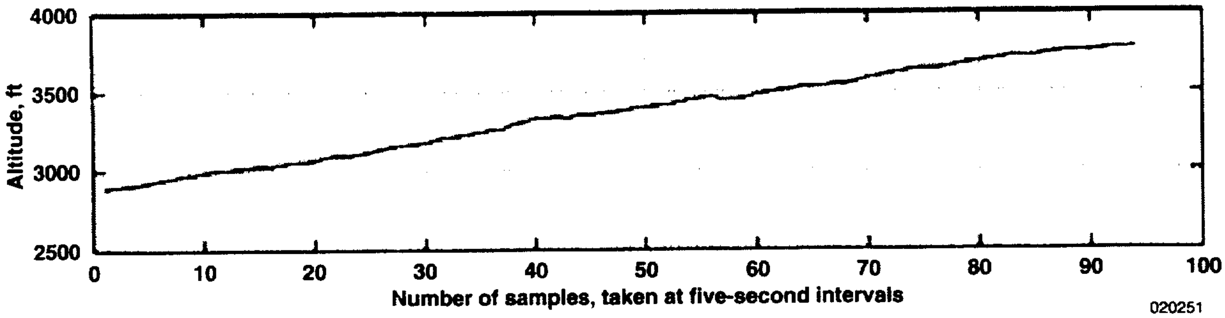


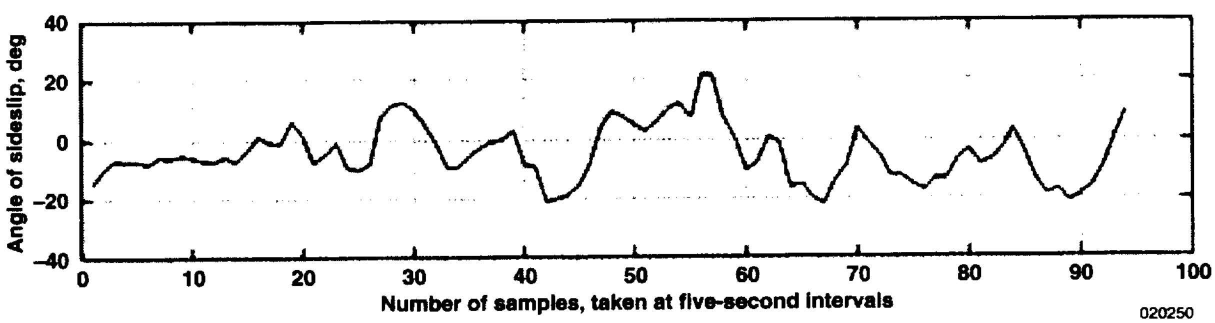
Figure 8. Trade wind shear observations by SODAR.

Out over the water, the aircraft passed through the strongest shear zone between 3,000 and 4,000 ft (900 and 1200 m), indicated by the abrupt changes in the angle of attack and angle of side slip, shown in figure 9 (a,b,c). Turbulence predictors in the upper-air profile (wind shear and low level instability), visual observations of clouds, and SODAR measurements all indicated that turbulence would be encountered. The indicators suggested the expected turbulence would be in the light to moderate category and would be confined to a shallow layer (~1,500 feet) that contained the majority of the clouds.

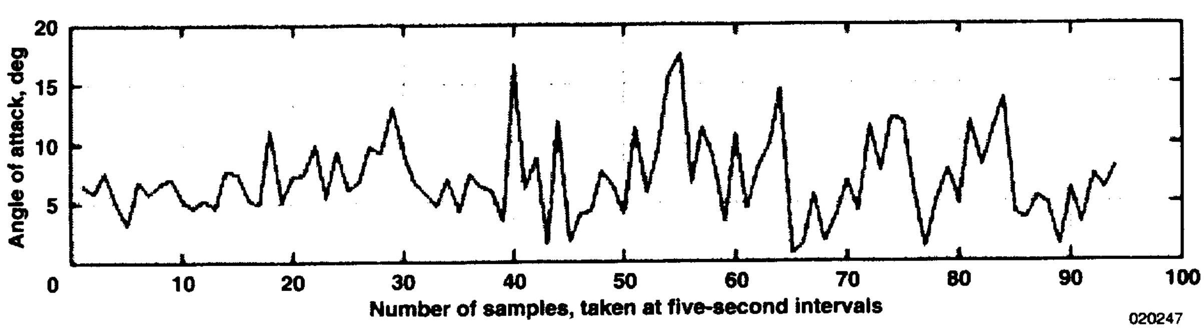
Surface wind (speed and direction) time histories for the flight, the surface climatology for Lihue[10], and a 20-day wind average from PMRF (produced by the author) are shown in figures 10 and 11. The surface winds at PMRF, as mentioned before, are not controlled by the trade wind flow but by the local daily pressure changes from surface heating. However, regardless of location, the winds on both sides of the island do tend to show influence from heating as observed by the matching wind trend from Lihue. The observed activity in the surface wind behavior on day of flight was a direct result of the shear layers periodic mixing towards the ground.



a. altitude



b. angle of sideslip



c. angle of attack

Figure 9. Turbulence encounter by aircraft during climb out over water.

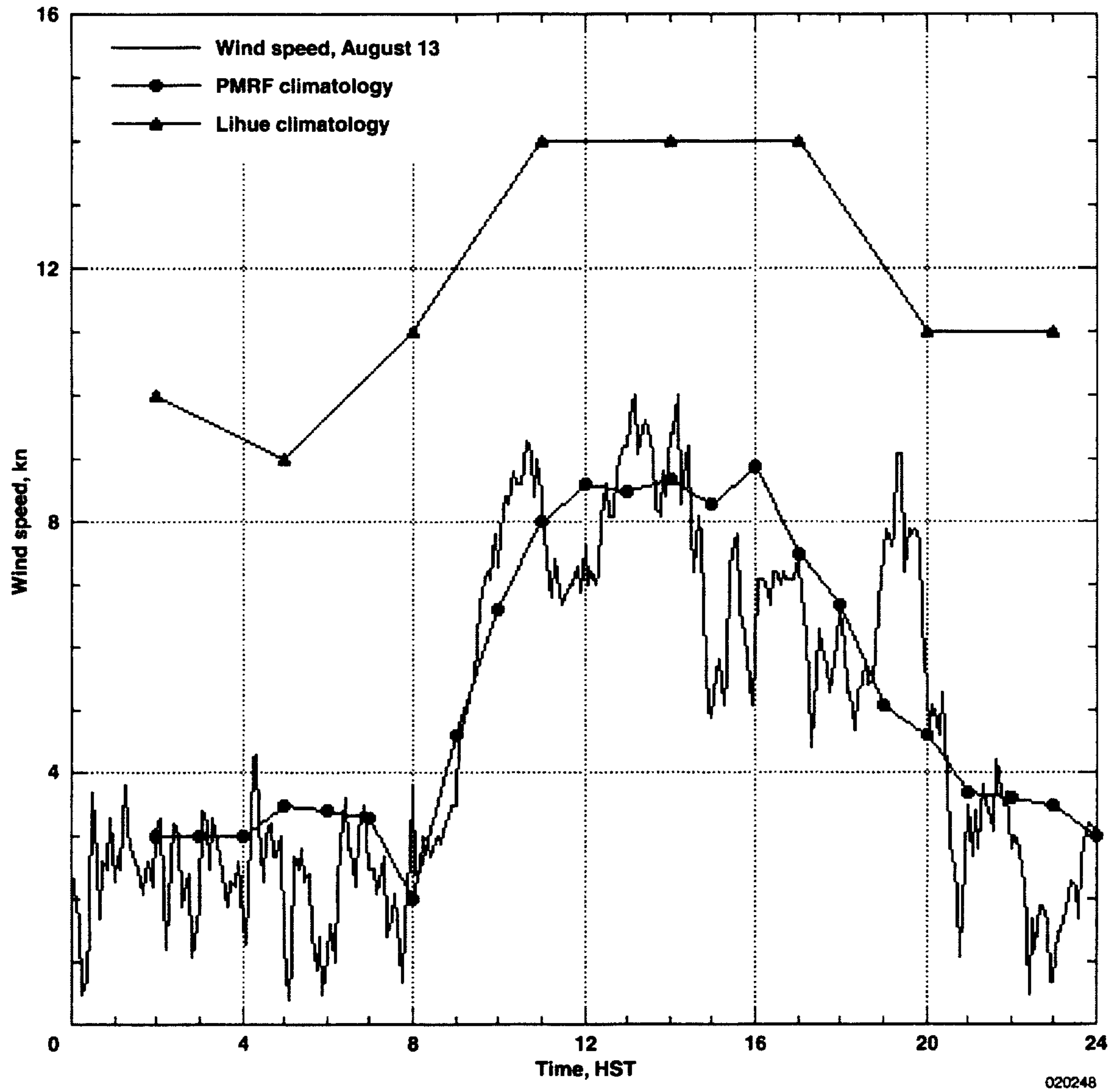


Figure 10. PMRF surface wind speed history for August 13 with PMRF and Lihue surface climatology.

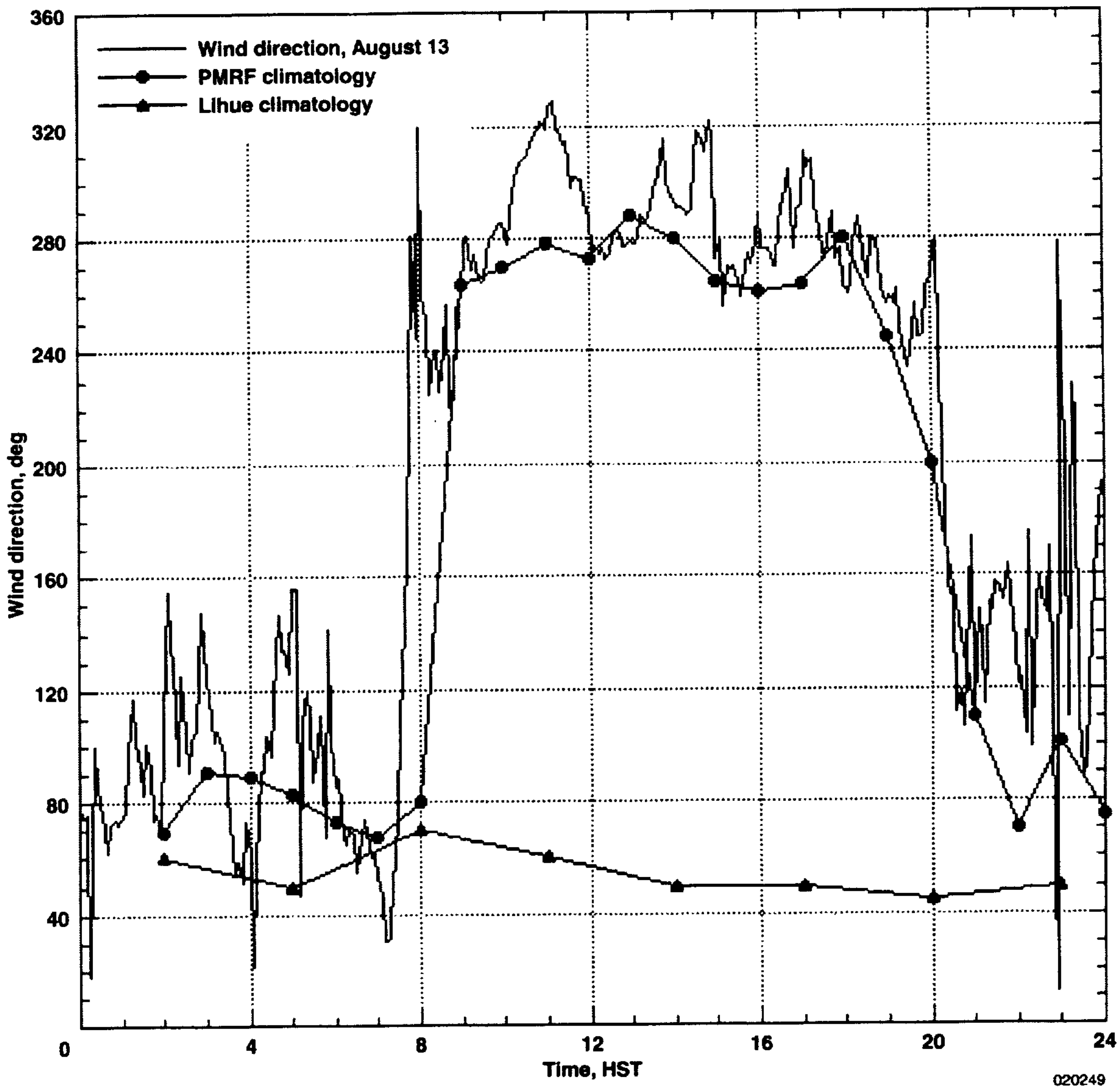


Figure 11. PMRF surface wind direction history for August 13 with PMRF and Lihue surface climatology.

CONCLUDING REMARKS

A world altitude record was achieved off the island of Kauai, Hawaii, in part, facilitated by the extensive evaluation of the local meteorology, detailed flight planning, a large amount of available airspace, and an aircraft designed and equipped for the extreme conditions. Each of these elements made a significant contribution to the success of this mission. Pacific Mission Range Facility (Barking Sands, Hawaii) is in an ideal location on the Island of Kauai, whereby the terrain acts as a natural wind and rain deflector. During the summer season, climatology can be used based on reasoning that day-to-day tropical weather change differs little from the monthly mean, and being such can be forecasted based on historical values. Flight plans had a strong bias to the upper level conditions and sun elevation angle; however, without the 42,000 square miles of airspace in which to operate, the record altitude may have been lower. The airspace provides a perfect setting to constantly fly away from the sun and yet never deviate from the air space. The ability of the flight planners, meteorologists, and pilots to prepare and adjust the flight plans real-time, ensures the best possible outcome. And finally, the aircraft was designed and equipped for high altitude flight that can accommodate for the long duration exposure to extreme cold, strong winds, turbulence and the ability to operate at night.

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In characterizing and understanding atmospheric behavior when conducting high altitude solar powered flight research flight planning engineers and meteorologists are able to maximize the use of available airspace and coordinate aircraft maneuvers with pilots to make the best use of changing sun elevation angles. The result of this cooperative research produced a new world record for absolute altitude of a non-rocket powered aircraft of 96,863 ft (29,531.4 m). The Helios prototype solar powered aircraft, with a wingspan of 247 ft (75.0m), reached this altitude on August 13, 2001, off the coast of Kauai, Hawaii. The analyses of the weather characterization, the planning efforts, and the weather-of-the-day summary that led to at record flight are described in this paper.

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