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Atmospheric Considerations for Uninhabited Aerial Vehicle (UAV) Flight Test Planning

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ATMOSPHERIC CONSIDERATIONS FOR UNINHABITED AERIAL VEHICLE (UAV) FLIGHT TEST PLANNING

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Abstract

Atmospheric considerations are a key element in support of uninhabited aerial vehicle (UAV) flight testing. The local atmospheric environment (wind speed and direction, wind shear, temperature, precipitation, and turbulence) must be characterized and understood. The primary objective is to ensure safety of the vehicle, test range, and ground assets. The generalized atmospheric behavior for any potential flight operations site is best described by combining the local seasonal climatology, daily upper atmospheric wind and temperature profiles, and hourly surface and low-level wind observations. This paper describes a continuous forecast update process based on monitoring atmospheric turbulence with surface and low-level wind for the support of UAV flights. Updates ensure the most current available data needed for mission planning. Each mission plan is developed so as not to exceed operation limits because of weather conditions. This paper also discusses climatology, weather forecasts, and day-of-flight weather monitoring for planning of uninhabited aerial vehicle missions.

Nomenclature

dB	decibels
DFRC	Dryden Flight Research Center, Edwards, California
EAFB	Edwards Air Force Base, Edwards, California
FTS	flight termination system
GPS	global position system
PMRF	Pacific Missile Range Facility, Barking Sands, Kauai, Hawaii
RCC	Range Commanders Council
RMS	root mean square
SODAR	sonic Doppler acoustic radar
UAV	uninhabited aerial vehicle

Introduction

Uninhabited aerial vehicle (UAV) flight tests are being conducted at the NASA Dryden Flight Research Center (DFRC), Edwards Air Force Base (EAFB), Edwards, California and the Naval Pacific Missile Range Facility (PMRF), Barking Sands, Kauai, Hawaii in support of NASA's Environmental Research Aircraft and Sensor Technology (ERAST) program. Currently these subsonic vehicles are designed to operate at altitudes above 60,000 ft. The UAV vehicles are characterized by long wingspans, light wing-loading (less than 20 lb/ft^2, similar to those of sailplanes), and are powered by solar-electric motors or super turbocharged internal combustion engines (fig. 1). These vehicles are being developed for environmental studies and sensor development programs.

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Special care is needed to operate UAV's. Meteorological conditions that can effect them, and must be accounted for, include winds, turbulence and cold temperatures at designated altitudes. Most UAV's are fragile and travel at relatively slow speeds.

In general, the most important meteorological consideration is wind speed and wind direction (both surface and upper levels). Conditions such as clouds, precipitation, and icing are also important, but if these conditions prevail the flights are usually canceled. Surface winds can affect the aircraft, not only during takeoff and landing, but also during the preflight and postflight ground handling. For this reason light winds are the most favorable. High winds during flight can cause excessive aircraft drift, making position controllability of the aircraft much more difficult. This can make a mission profile unattainable and result in the flight being canceled. High winds can also produce a large flight termination system (FTS) drift footprint,[1] which may require flight cancellation. Experience has shown that regardless of an airplane's mode of propulsion, the most important operational consideration for flight has become the weather.

To consider the suitability of a site for UAV flight test activity, a detailed study of the site climatology and local atmospheric behavior must be undertaken. This study will determine the probability of meeting requirements set forth by the aircraft limitations. A good understanding of atmospheric behavior provides information which determines whether a site is suitable for flight test or not. The primary goal of this paper is to discuss the use of climatology, surface and upper atmospheric observations, weather forecasts, real-time weather data, and equipment in the planning and operational process for flight tests. In particular, focus will center on the process development for the Pathfinder solar-powered UAV.

Climatology

Climatology is the statistical collective of weather conditions for a given spatial and temporal reference. Official climate data, known as *Surface Observation Climate Summaries* and the *Range Reference Atmosphere*, are generally available from the Range Commanders Council (RCC) for specific sites. It is important to understand the local seasonal and monthly climate (the surface and upper air weather statistics or climatology) to be able to establish times when weather conditions are favorable to fly UAVs. Acceptable minimal conditions are determined using established operational limits,[2] which are established to minimize the risk to the vehicle and to enhance the probability of a safe recovery. Climatology is also useful in enabling efficient flight scheduling so as to minimize cancellations caused by weather. The surface weather parameters considered most important are winds, cloud cover, and precipitation; while the upper-level parameters are primarily temperature and winds.

Surface Climatology

The surface climatology describes the behavior of the atmospheric boundary layer (the lowest 100 meters of the atmosphere). The affects of surface conditions are of primary importance during takeoff, landing, and ground handling. Vehicles with light wing-loading (<20 lb/ft^2) are extremely sensitive to surface winds. At EAFB, for example, understanding the hourly atmospheric behavior enables wind-sensitive aircraft to conduct and complete operations by late morning, before the thermally induced afternoon winds arrive. It is important to know the hourly surface behavior in the event of an early return to base for some unexpected reason during long flights. At EAFB the afternoon summer winds increase during the day to about 12 kn[3] while at PMRF the afternoon winds increase to about 8 kn[4] Figure 2 shows the monthly trends and frequency of winds observed less than 5 kn and less than 15 kn at EAFB during the early morning, forenoon, and late afternoon.

Upper-Level Climatology

The upper-level winds impose significant restrictions for UAV flight test operations. These operations require light winds at all levels of the atmosphere in which the aircraft operates. The best conditions usually exist when a weak pressure gradient is associated with a high-pressure system. Figures 3 and 4 show a representation of the upper-level winds for each month at EAFB and PMRF. These data are best used to quantify the effect of climatological winds to project wind drift estimation for FTS and mission planning. To show what a possible FTS drift profile may look like using the EAFB data, two months were chosen to represent wind profiles from strong and calm wind months. The months chosen were February (a climatologically high-wind month) and August (a climatologically low-wind month) shown in figure 5. The drift estimation plot shows the path the vehicle would follow if the FTS chute is deployed at a given altitude. The estimation is computed with a chute fall rate of 30 ft/sec. Because February is a high-wind month, the drift distance is greater in comparison to August. A UAV such as Pathfinder, which uses a chute with a 3-ft/sec fall rate, would travel one order of magnitude farther.

The atmospheric profile is important to the operation of UAV’s primarily because of thermal limits on the avionics and other hardware. Cold temperatures are a concern to most UAVs. Cold temperatures can affect critical aircraft components, such as battery power efficiency for vehicles using batteries (like Pathfinder), and general system failure due to cold soak.

The coldest temperatures are observed at or above altitudes where the tropopause is located. The tropopause is the boundary between the troposphere and the stratosphere. There is a large difference in temperature between EAFB (mid-latitude) and PMRF (tropics) shown in figure 6. In the tropics, the tropopause is located at a much higher altitude because the atmosphere is warmer. Because the tropopause is at greater altitudes in the tropics (as at PMRF), the temperature lapse rate continues to decrease in altitude, allowing the minimum temperature to get much colder. Another difference between EAFB and PMRF is the time of year at which the minimum cold temperature is observed. At EAFB, the coldest temperatures occur in early- to mid-summer when the tropopause is at the greatest altitude, while at PMRF they occur in January. Along with the mean temperature, standard deviations (or sigmas) are used to examine extreme cold temperature conditions. Extreme temperatures are based on a 3-sigma value. The 3-sigma value for the January minimum temperature at EAFB is 12.0° C. At PMRF the 3-sigma value is 9.7° C. Therefore, the extreme cold temperatures at EAFB and PMRF for January are –78° C (–108.4° F) and –86.4° C (–123.5° F) respectively.

Because aircraft limitations differ, it is important to plan flight tests when the vehicle has the best opportunity to fly. At EAFB and PMRF, there are climatologically favorable months to fly UAV’s and then there are unfavorable months, when acceptable flight conditions are not frequently experienced. Based on the climatology of both EAFB and PMRF, UAVs would have the best flight conditions during the summer and early autumn months.

Forecast and Expected Variability

Probabilities for light wind conditions are enhanced when there is a fair weather high-pressure system. However, when weather conditions are dominated by strong disturbances the task becomes much more complicated. A climate forecast can be quite reliable if stable air masses are in firm control, otherwise, predictions for low winds may be difficult as weather systems pass through the region. In general, the civil aviation need for light winds is not as critical as it is for UAV operations, in which forecasting light wind conditions is a special challenge to the meteorological staff. Depending on the operational characteristic of the UAV and the desired mission profile, some months are statistically better than others for flight tests. Models such as the Nested Grid Method, the Aviation Model, and the Medium Range Model provide very good information that allow the meteorologist to provide reliable weather data in a timely manner, enhancing the probability of mission success. However, these models are used as general guidance rather than the final word, since they do not cover smaller-scale weather features that may influence local winds at the flight operation site.

Each candidate site needs to have forecast information available which is specific to itself, or sufficient data that allows forecasts to be made on a regular basis. In evaluating a site for flight operations an evaluation of upper air forecast reliability and daily changes must be conducted. One such evaluation was conducted for EAFB, in which days were randomly selected that had wind and temperature forecast data available. Each forecast was then compared to the 24-hour validation time, when such information was available. The forecast errors are presented in an east and north component reference (generally used in meteorology) and plotted as a function of altitude (fig. 7(a) and 7(b)). The variability of the data shows errors ranging from little or no change (<5 kn) to days where as much as 68 kn (55 kn west-east and 40 kn south-north) wind error was observed with little warning. The primary interest in this evaluation is to determine the reliability of the model data for specific sites.

Day-of-Flight Observations

Rawinsonde balloon[5,6] data produces the basic atmospheric observations of temperature, pressure, relative humidity, and wind speed and direction. These data are analyzed to ensure a valuable data set. The rawinsonde data is not perfectly accurate, and in some cases it may appear valid but actually be misleading. Balloon inaccuracies have been experienced from time to time. These inaccuracies could be caused by either a loss of signal in the tracking systems through the base receiver or global position system (GPS), or they could result from a bad temperature and pressure sensor. At first look, any day may appear perfect for flight with clear skies and light surface winds, however, a further analysis of weather conditions could reveal that the mission objectives cannot be met based on operational limitations of wind and temperature. Other important information obtained from the balloon data relates to the stability and turbulence properties of the atmosphere.

The turbulence data are most difficult to forecast and become a significant problem when working with lightly wing-loaded aircraft. Conditions associated with turbulence vary widely, however some simple indicators such as strong vertical wind shears, unstable temperature lapse rate, and upper altitude trough lines may be used to indicate the presence of turbulence. In preparation, early morning rawinsonde balloons should be launched within three to six hours before takeoff to allow ample time to examine the current state of the atmosphere. The mission objectives and the vehicle will determine the number of rawinsondes needed during the test. For example, the Pathfinder aircraft with a wing-loading of <1 lbs/ft^2, normally uses between five and seven balloons during a mission. Other aircraft such as ALTUS, which have higher wing loads and a higher true airspeed, may require only one balloon before flight. Surface anemometers are used to observe wind changes that appear during ground and flight operations. Persistent wind features (such as the trade winds) are modified by local terrain-induced wind flows and can produce erratic behavior. The use of anemometers placed in various locations provide monitoring capability to detect the onset of these conditions, so that corrective action can be taken in time to prevent potential mishaps.

Real-Time Data and Nowcasting

Early morning balloon data and the latest weather forecasts provide the mission planners with the wind profiles needed to simulate and schedule flights. Depending on the vehicle and flight duration, updates to the forecast, or nowcasts, are presented to mission planners and pilots. A nowcast is a forecast based on current observation in the local area that is valid for only a few hours and are frequently updated. The new or updated forecasts allow mission planners an opportunity to amend flight plans based on the latest data.

To provide the meteorologists and mission planners with the data needed to make nowcasts, and to incorporate this information into a flight plan, many sources of data are required. For example, surface wind anemometers located at several sites around the facility are used, especially for the most sensitive vehicles. These anemometers are placed at strategic locations (opposite runway thresholds, approximate landing zone, hill tops, and buildings). To measure low-altitude winds (<1 km above ground) the use of sonic Doppler acoustic radar (SODAR)[7] (or some other wind profiler) is enlisted. These wind profilers constantly sample the atmosphere at various levels in height, ranging from 15 to 1000 meters. The SODAR, as an example, emits a low-frequency sound pulse, and receivers then listen for reflected sound signals. The SODAR computer compares the initial signal to the returned signal and computes a frequency shift and range. This frequency shift is directly related to the radial wind speed. The turbulence is related to the intensity of the returned signal. This tool provides near real-time updates to the changing atmosphere. Updates from these instruments are produced at user-selected intervals of from 1 to 60 min. The structure of the changing boundary layer helps to provide planners an opportunity to modify the time of takeoff or landing, cancel or delay a flight, and to change which runway to use for takeoff and landing. In contrast to the rawinsonde which are launched every few hours and require several persons to launch, the SODAR is self-sufficient; it provides constant updates of wind and turbulence data within the lowest thousand meters of the atmosphere. Figure 8(a) is a sample of the time-height wind cross section using conventional wind barbs for speed (in knots) and direction. Figure 8(b) shows the facsimile display for returned signal strength. In this figure the darker grays refer to the strength of the returned signal. Figure 9 shows the weather clearance flow chart used by Pathfinder in determining whether the meteorological conditions support a flight.

Experiences

On July 7, 1997 the Pathfinder solar-powered aircraft reached an altitude of 71,500 ft above the Pacific Ocean off the coast of Hawaii. This record flight began at 08:30 hours (local time) with a picture-perfect mission ending, landing at around 23:00 hours (local time). Days earlier, the flight process described in figure 9 was used, and because of bad weather, a four-day delay in the flight occurred. When the mission finally began, the upper-level winds were the calmest observed of all the flights to date. In addition, the use of the SODAR enabled meteorologists to monitor the development of a low-level gravity wave which caused winds to change direction many times. The relaying of this nowcast information to the planners, followed by recommended changes, permitted the pilots to vary normal procedures. Pilots delayed the landing for nearly an hour, and landed from the opposite direction. When the mission was completed a new altitude record for a solar-powered vehicle was achieved. This flight and many others were the final product of the atmospheric behavior research process that this paper describes.

Summary

A process which evaluates the atmospheric behavior in support of uninhabited aerial vehicle planning and operations has been developed. By examining the hour-to-hour, day-to-day, and month-to-month variations in the atmosphere, a picture of the feasibility for conducting flight test operations at any site becomes apparent. Evaluating the forecast output in relation to the real-time observed changes in the atmosphere, the meteorologist can produce a nowcast that will provide valuable new data to mission planners. The desired goal of updating the mission plan is to ensure that the aircraft remains in the desired test area and in close proximity while conducting the mission. To date, this forecast and monitoring process has assisted the Pathfinder UAV in reaching a maximum altitude of 71,500 ft. The success of Pathfinder and other UAV programs is strengthened considerably by understanding the atmospheric behavior and preparing for such changes as directly affect aircraft operations. Using climatology to determine favorable locations and seasons to fly, supported by real-time forecasting and observations, has made flight test operations safer and more repeatable.

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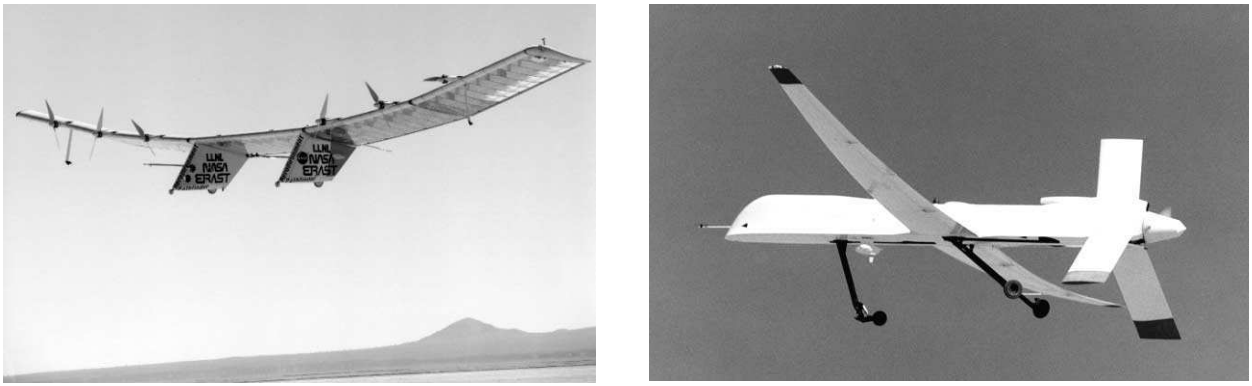

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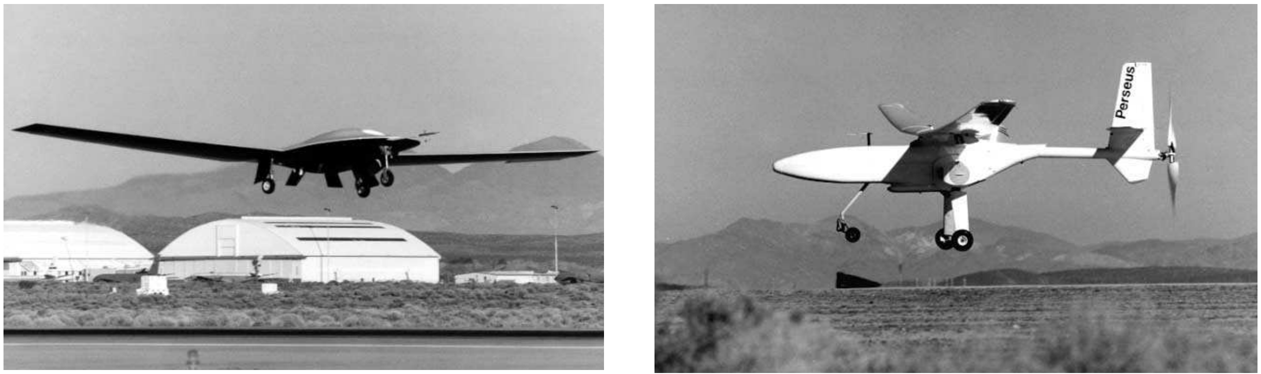
(a) The Pathfinder vehicle.

(c) The Altus I vehicle.



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(b) The Darkstar vehicle.

(d) The Perseus B vehicle.

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(e) D-2 Demonstrator.

Figure 1. Representative UAVs at NASA Dryden.

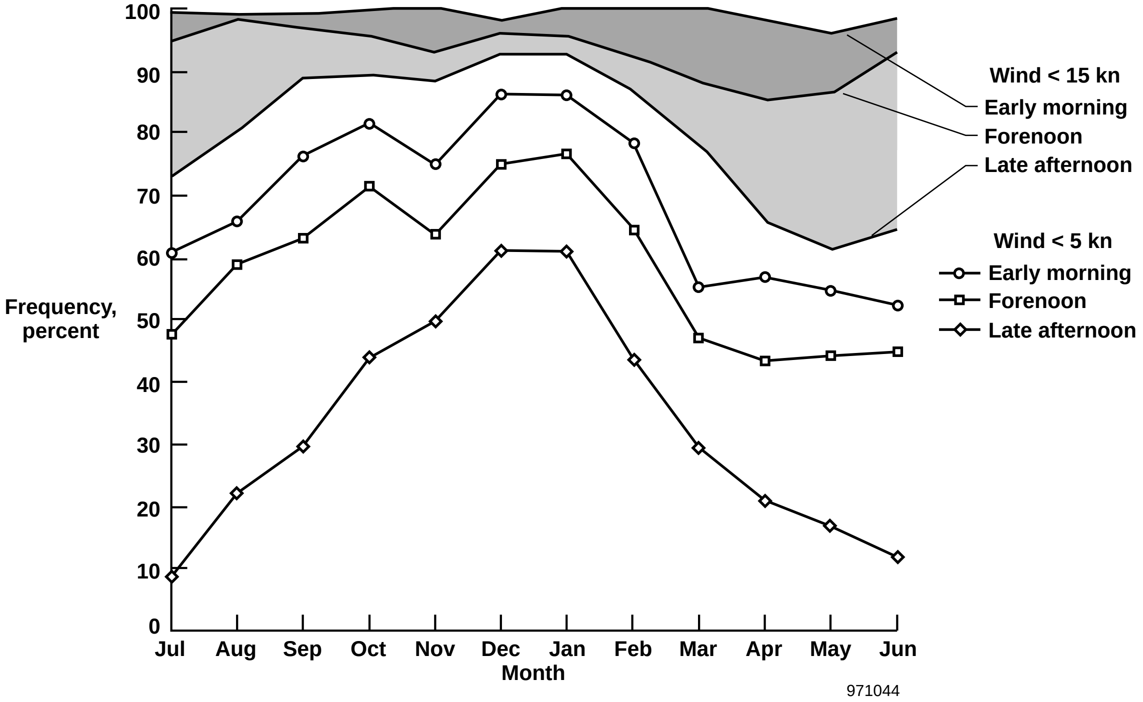


Figure 2. Frequency of winds less than 5 kn and less than 15 kn for early morning, forenoon, and late afternoon at Edwards Air Force Base, Edwards, California.

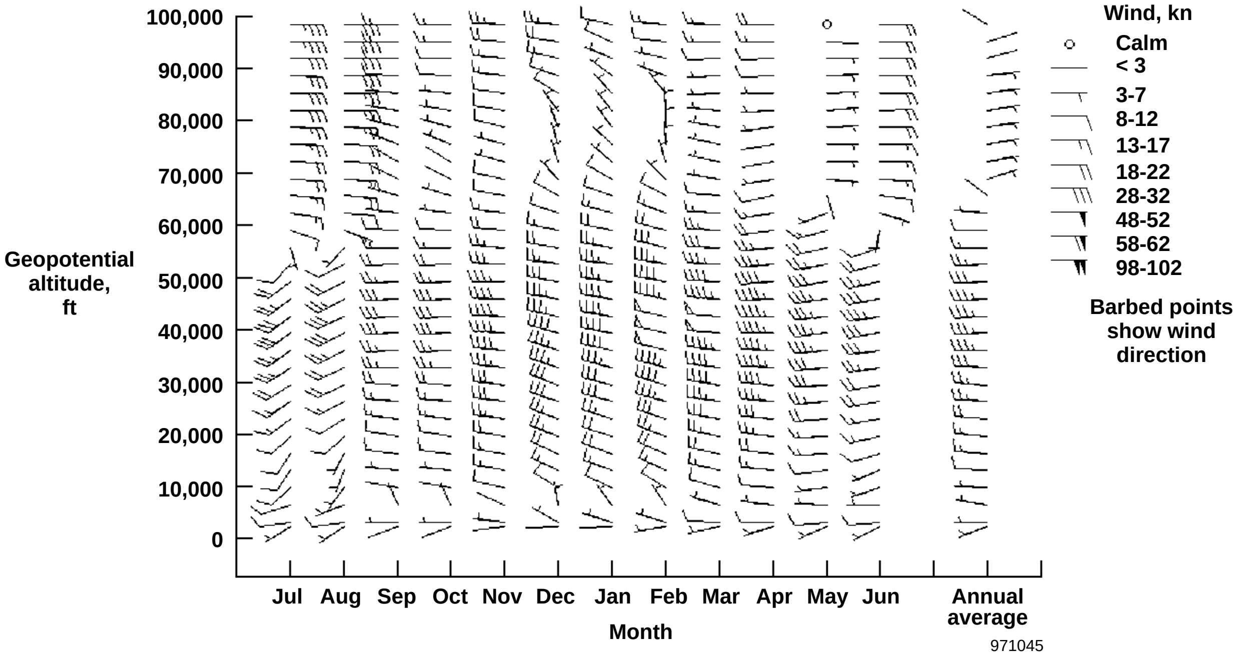


Figure 3. Monthly mean, upper atmospheric wind speed and direction for Edwards Air Force Base, Edwards, California.

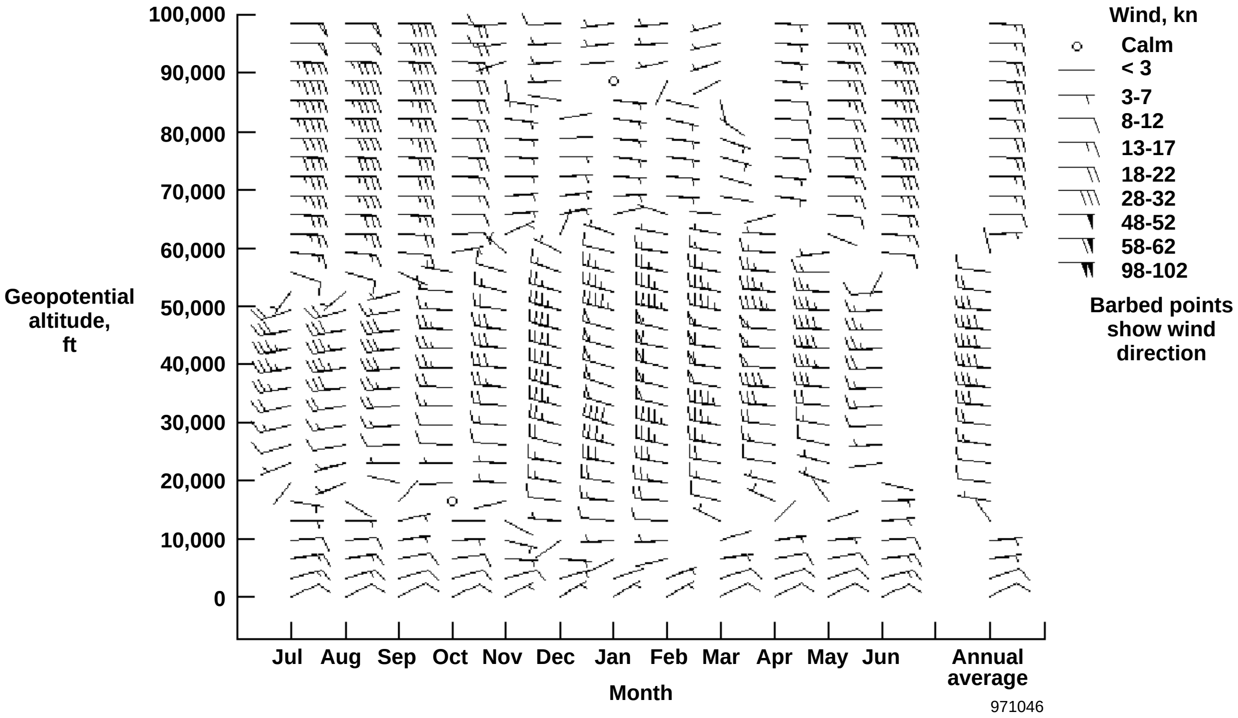


Figure 4. Monthly mean, upper atmospheric wind speed and direction for Pacific Missile Range Facility, Barking Sands, Kauai, Hawaii.

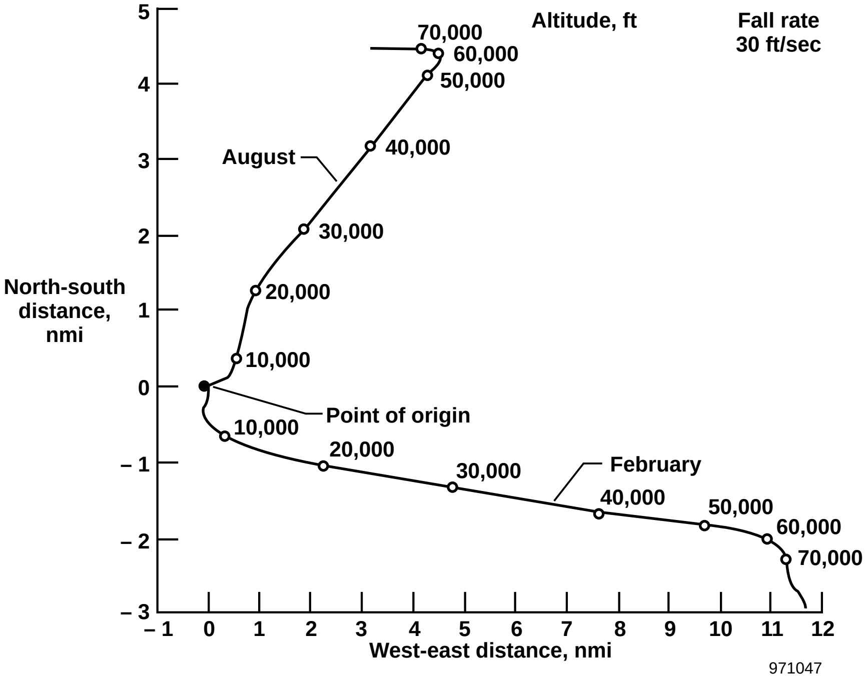


Figure 5. Impact location based on wind drift calculation using February and August climatology.

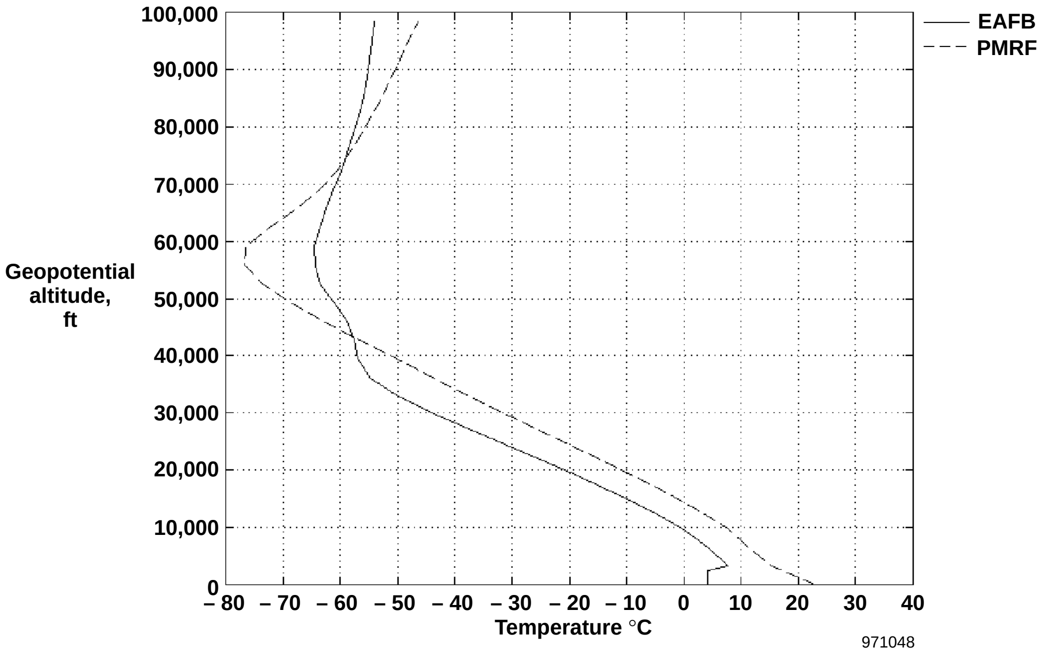
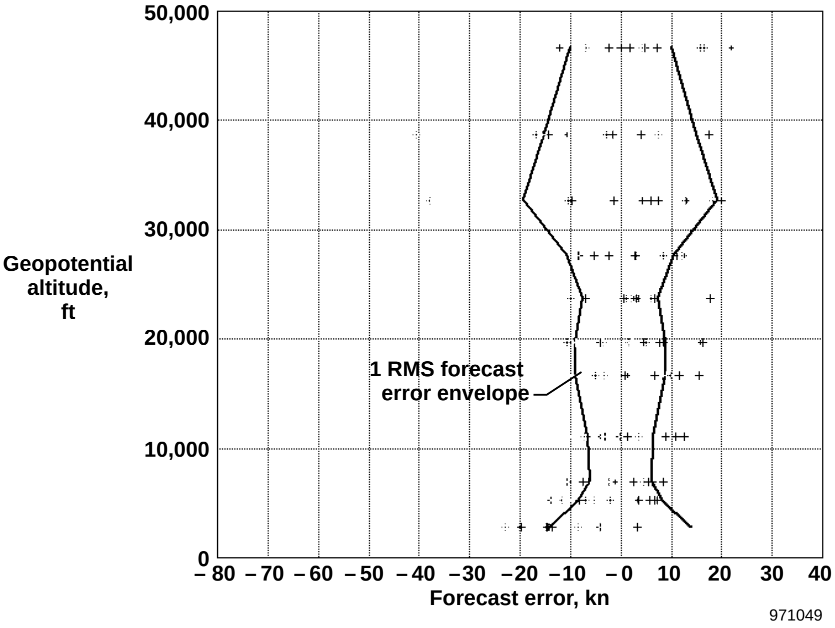
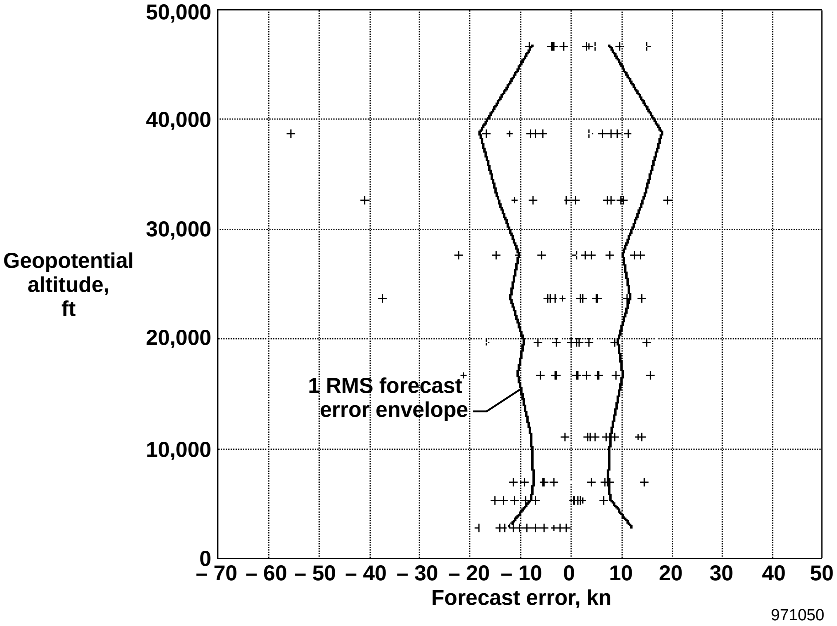


Figure 6. Mean temperature comparisons for January at Edwards Air Force Base (EAFB), Edwards, California and Pacific Missile Range Facility (PMRF), Barking Sands, Kauai, Hawaii.

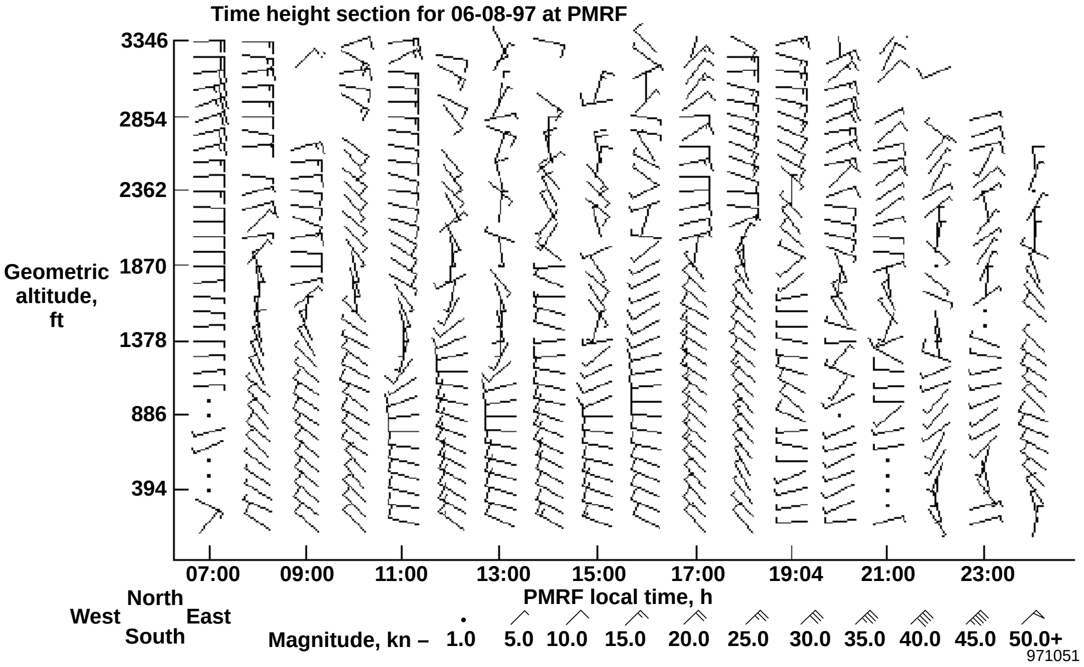


(a) West-east.

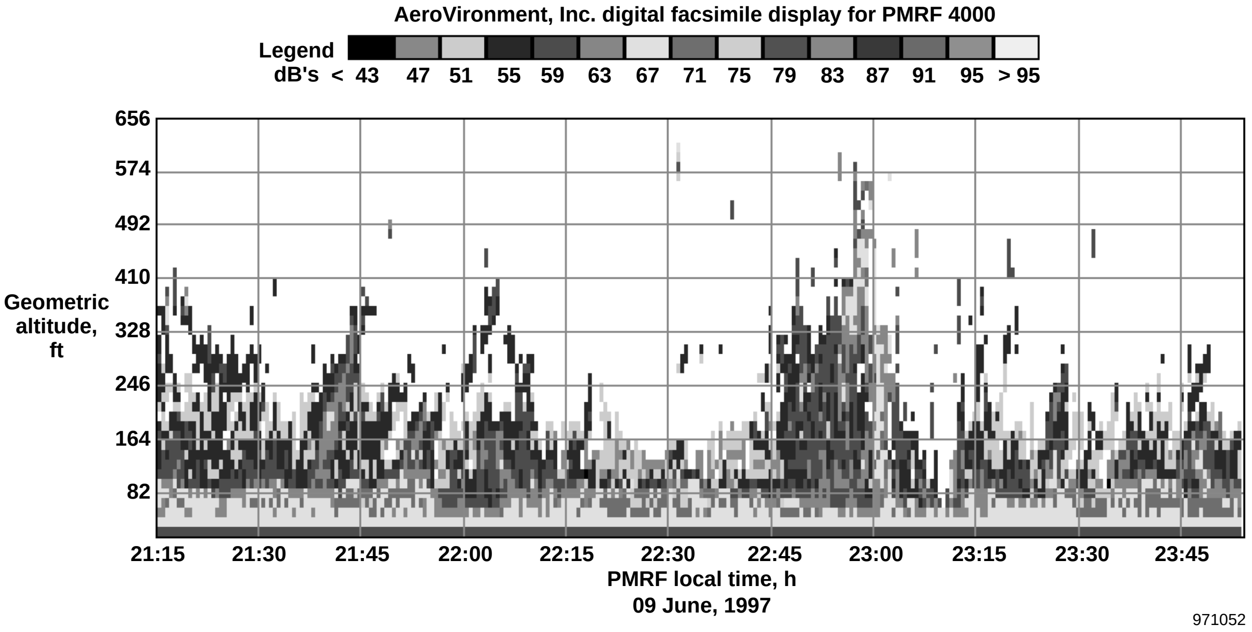


(b) South-north.

Figure 7. Twenty-four-hour wind forecast errors for randomly selected days.



(a) Example of SODAR time-height wind cross section.



(b) Example of SODAR facsimile display time-height cross section for turbulence.

Figure 8. SODAR wind and turbulence displays.

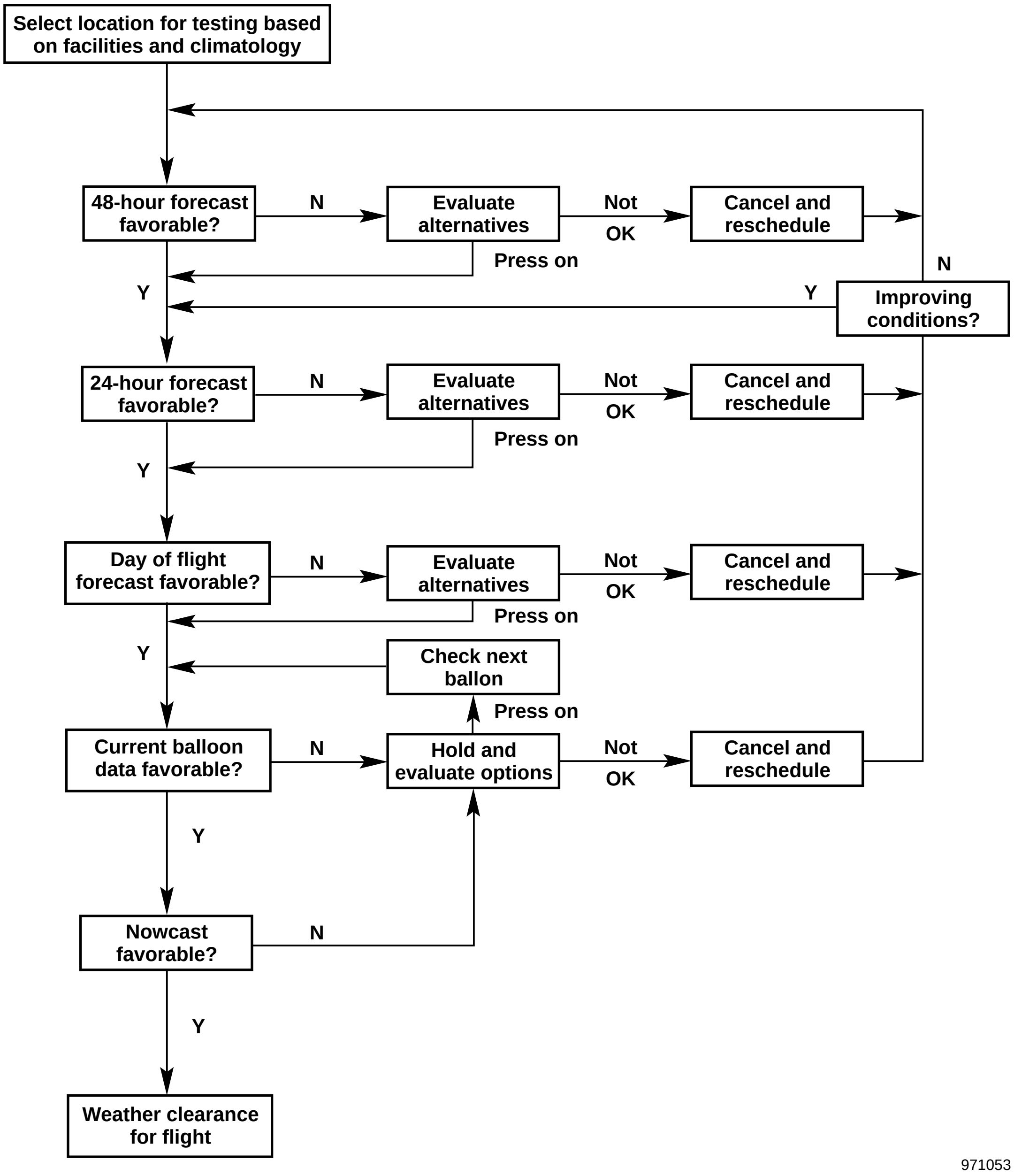


Figure 9. Flow chart for weather decision process.

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