MOBILE AIRCRAFT ICING FORECAST SYSTEM

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ABSTRACT

An integrated mobile field system for forecasting ground and in-flight aviation icing hazards would be a vital asset for winter operations. Improved icing forecasts are critical to managing aviation icing hazards. Forecast accuracy, currently limited by existing weather observational systems, do not benefit from technology that has been shown to improve icing forecasts. Advanced ground-based and airborne sensors with state-of-the-art retrieval algorithms will improve the accuracy of regional forecast models. It is feasible to package these sensors with appropriate communication and information systems into a mobile forecast system that would increase aircraft reliability and safety.

INTRODUCTION

Aircraft icing presents a serious hazard for military aviation. An integrated mobile field system for forecasting ground and in-flight aviation icing hazards would provide important tactical and strategic advantages during mid-latitude winter and year-round polar operations. Freezing precipitation and supercooled cloud liquid will cause an aircraft to accrete ice, potentially compromising its performance and safety. improved forecasting capability reduces risk by identifying and characterizing icing conditions that endanger military aviators, restrict surveillance opportunities, and impact combat effectiveness.

Effective management of icing hazards requires a systems approach. Hazard redaction needs to be information-driven starting with meteorological measurements that are sensitive to impending and existing icing hazards. Expert systems must integrate the meteorological data stream into regional forecast models to ensure timely analysis and accurate, reliable forecasts. The pilot, air traffic control, and the airfield controllers must possess appropriate tools and training to evaluate the impact of the impending forecast on specific air operations. The successful integration of these components will allow pilots and controllers to make informed decisions that will decrease the impact of weather on air operations. A conceptual system design is depicted in Figure 1.

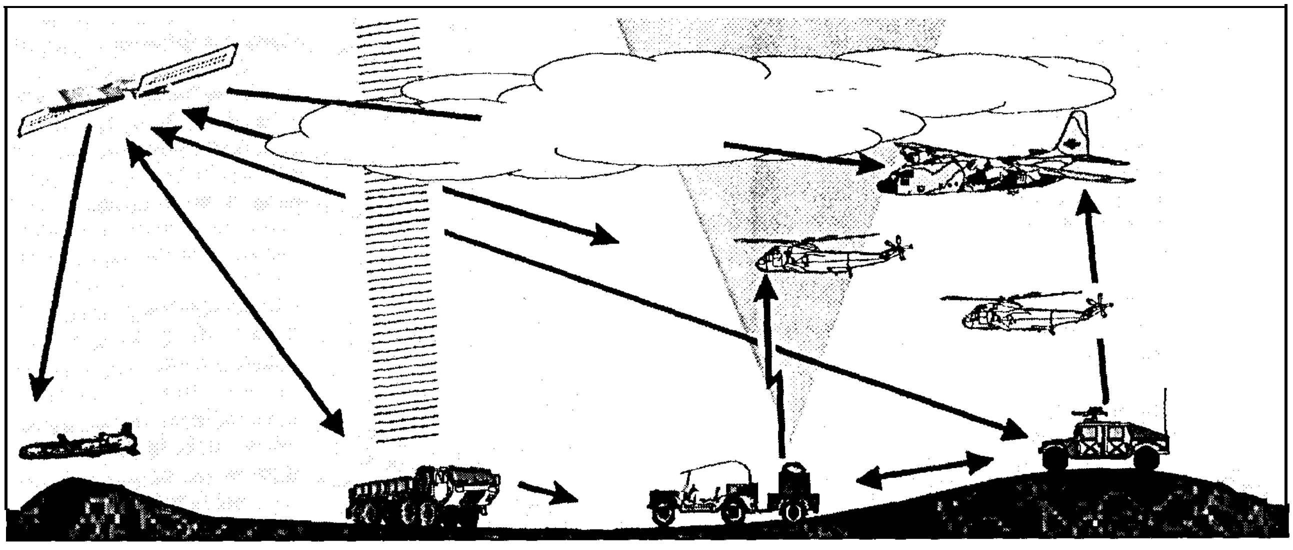

Figure 1. ***Mobile Aircraft Icing Forecast System.*** *An integrated mobile field system for forecasting ground and in-flight aviation icing hazards enhances combat effectiveness by providing timely, accurate information to aviators, air traffic controllers, and field commanders during winter operations.*

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2. ICING METEOROLOGY

Ground and in-flight aircraft icing is usually associated with freezing precipitation. Non-precipitating clouds also present in-flight hazards when they contain appreciable amounts of supercooled liquid. An aircraft encountering sub-freezing liquid acts as a nucleation site for' liquid to freeze. Large areas of freezing precipitation are commonly associated with regional winter storms that dump snow in the North and rain in the South. The boundary between the rain and snow exhibits freezing rain and drizzle and usually contains an abundance of supercooled cloud liquid.

The severity of hazard associated with supercooled cloud liquid or freezing precipitation depends on the local meteorology. Important microphysical parameters include liquid water content, temperature, and drop-size. Statistics on liquid contents and drop-size distributions are limited, leading many studies to rely on "typical" values. The vast majority of clouds and rainfall events have liquid contents ranging from 0.01 g/m^3 to 1.0 g/m^3 with isolated occurrences of clouds and precipitation exceeding 1.0 g/m^3 [1]. High liquid water contents pose significant hazards because they induce rapid ice accretion rates. Although standard terminology has not been developed to classify drop sizes, reference to '(cloud droplets" usually includes particle sizes ranging from 10 µm to 100 pm, "drizzle drops" generally range from 50 µm to 500 µm, and "rain drops" are usually defined to be larger than 500 µm [2]. The larger drops present a greater hazard because they also induce rapid accretion rates.

3. AVIATION HAZARDS

icing compromises aircraft performance by changing the aerodynamics of the wings and propellers, decreasing lift. Icing also increases weight and drag and can disable control surfaces. Ice shed from the airframe occasionally impacts and damages adjacent aircraft structures. The rate at which ice accumulates depends on meteorological conditions and aircraft-specific characteristics such as velocity and airfoil shape. Exposure time is critical because prolonged exposure increases the amount of ice that will accumulate.

Helicopters, piston-engine, and turboprop aircraft are most susceptible to icing. Not only do they fly at lower altitudes where icing occurs most often, but they also operate close to their performance margins and are less able to tolerate a loss of lift, and are therefore less able to climb to avoid icing. Since they fly slower than jets, they require additional time to exit hazardous areas, prolonging exposure. Smaller aircraft and helicopters are often not certified to fly in icing conditions and are not equipped with deicing systems. Ryerson [1] provides a brief review of how icing affects military air operations.

4. SENSOR TECHNOLOGY FOR DETECTING ICING HAZARDS

4.1 OVERVIEW

A system-level analysis should drive the choice of sensors. In general, the combination of several types of sensors will provide a clearer picture of the local weather than a network of identical sensors [3]. Issues affecting a sensor's selection include its contribution to the existing meteorological network, technological maturity, suitability for the intended platform, and the potential to compromise security. in-situ sensors directly sample local meteorology, while remote sensors probe meteorological properties at a distance. Microwave remote sensors usually have an advantage over optical sensors in detecting icing conditions because they can "penetrate" clouds. Remote sensors can be divided into two categories: active systems which emit signals and then measure their interaction with the environment and passive systems that measure natural radiation emitted by the environment. Although active systems usually provide the best portrait of the meteorological environment, they also tend to require more power, are harder to conceal, are more expensive, and are more likely to interfere with other C^3I systems. The choice of sensors requires optimizing system needs, cost, and logistical requirements.

Sensors for improving icing forecasts have already been developed and many are commercially available. However, there are two areas where targeted research and development would yield significant benefit.

Considerable value could be derived from re-engineering research instrumentation. Scientific sensors developed with a design emphasis that maximized capability, accuracy, and operational flexibility can be redesigned with a focus on developing an application-specific design, increasing reliability, improving automation and reducing cost. R&D is also needed to develop advanced airborne sensors to detect and forecast icing. Commercial airborne sensors currently detect ice formation with acoustic, optical, and impedance probes. The next generation of sensors will likely measure meteorological parameters and estimate the icing rate prior to ice forming on the aircraft. This approach will give pilots extra time to develop effective avoidance and mitigation strategies.

4.2 CLOUD AND PRECIPITATION TEMPERATURE MEASUREMENT

There are several methods used to measure cloud temperature. In-situ temperature probes measure cloud temperature directly. In-situ probes require an aircraft or balloon to transport the sensor. In CON US, temperature probes are currently carried on some commercial airplanes and are used to measure the temperature profile near major airports. IR radiometers are often used to retrieve cloud base temperature. They measure the infrared brightness of the cloud base and derive cloud base temperature from the measured radiance.

Atmospheric temperature profiles can be measured in the presence of clouds with microwave radiometry radio-acoustic sounding, and in-situ measurements. A microwave radiometric temperature profiler is a sensitive radio receiver tuned to the 60 GHz emissions of molecular oxygen. The radiance of oxygen emissions depends on temperature. Measurements made at several frequencies and elevation angles will yield the temperature profile. Radio acoustic sounding systems (RASS) are active sensors that transmit a powerful acoustic pulse and track its upward propagation with a VHF radar. Since the acoustic velocity is a sensitive function of temperature, the temperature profile is retrieved from the acoustic pulse propagation velocity. RASS provides higher resolution than microwave temperature profilers, although they are much more expensive and require orders of magnitude more power and area to operate. RASS are not adaptable to airborne platforms, whereas airborne radiometers are routinely used on NASA aircraft to profile temperature.

Cloud temperature is retrieved from the temperature profile with a simultaneous determination of cloud altitude using a Ka-band radar, lidar, ceilometer, or in-situ sensor. While a lidar is a laser radar, a ceilometer is a simple lidar designed to measure only cloud base altitude. High-power lidars can penetrate multiple cloud layers. However, Ka-band radars are often preferred because they can penetrate much thicker clouds with comparable signal power. in-situ balloon-borne, capacitive and resistive humidity sensors are regularly used to identify cloud height, but are limited in their temporal coverage.

4.3 MACRO- AND MICROPHYSICAL PROPERTIES OF CLOUDS AND PRECIPITATION

Dual-polarization radars, lidars, and microwave radiometers can determine cloud phase (ice or liquid). Polarization sensitive measurements discriminate between ice and liquid hydrometeors by providing sensitivity to the scattering particle height-to-width aspect ratio. As an ice crystal melts, its aspect ratio changes, altering the ratio of reflection cross-sections at each orthogonal polarization. Since radar reflectivity depends on both drop size and total water content, radars, alone, are unable to independently determine liquid content. Lidars are limited in range due to hydrometeor-induced attenuation. Liquid-sensing microwave radiometers are sensitive radio receivers tuned to continuum emissions of liquid water in the 30 GHz and 90 GHz atmospheric windows. The radiance of a cloud is proportional to the columnar liquid content. Microwave radiometers can discriminate between ice and water because the dielectric constant of ice is two orders of magnitude smaller than that of liquid and is therefore "transparent" to the radiometer. Thus, clouds or precipitation that emit significant amounts of microwave radiation must contain liquid. Although radiometers do not provide distance information, they have an advantage in some applications because they are passive and less expensive than radars and lidars. Combining radars and radiometers can be a very powerful strategy because it allows cloud liquid to be profiled [3].

In-situ sensors are very effective at determining the phase of precipitation and cloud water. For ground-based applications, rain gauges can differentiate between snow and rain. Supercooled liquid precipitation can be detected with a vibrating wire or rod. Supercooled liquid freezes to the wire or rod, thereby changing the vibrating mass. The associated shift in resonant frequency signals the presence of supercooled liquid. Vibrating wires and rods are used in ground-based stations and have been flown on radiosondes.

Characteristics such as drop size and liquid water content can be inferred by combining microwave radiometers with radars. Drop size and liquid water content can also be retrieved using lidars. in-situ instruments are able to resolve the drop-size spectrum and liquid content by measuring the intensity and angular distribution of light scattered by an atmospheric sample [4]. Ground-based systems that record light scattering along a short atmospheric path can be used to constrain drop size and phase by determining the precipitation rate of descent.

5. FORECASTING AND THE NEED FOR A SYSTEMS APPROACH

Generating a detailed picture of icing-hazards on a regional scale requires a systems approach. Advanced warning of icing hazards requires enhanced surveillance using a variety of measurement techniques from multiple locations. These data need to be rapidly integrated into a regional forecast model which includes advanced algorithms for predicting icing conditions [5]. The forecasts, in turn, need to be promptly disseminated to users in a format that highlights possible impacts to air systems, operations, and maneuvers. It is the combination of enhanced surveillance, improved modeling, integrated information systems, and reliable communications that can extend the time available to effectively mitigate the hazard, or avoid it altogether.

CONCLUSIONS

An integrated mobile field system for forecasting ground and in-flight aviation icing hazards is feasible and would provide a significant tactical advantage during winter. Advanced warning of freezing precipitation and supercooled cloud liquid is needed to improve the safety, reliability, and effectiveness of air operations. While standard meteorological sensors are relatively insensitive to critical parameters needed to accurately forecast icing, technology exists that can provide these data such as short-wavelength radars, microwave radiometers, and in-situ meteorological probes. These measurement systems can be quite compact, reducing logistical requirements and chancing mobility. Ground-based and airborne sensors with state-of-the-art retrieval algorithms will improve the capability of regional forecast models to provide accurate, timely forecasts of hazards. Packaging these components into a mobile forecast system with appropriate communication and information system interfaces is feasible. Advanced sensors that determine the ambient and approaching meteorological conditions could predict the impending rate of ice deposition, thereby increasing warning time. Autonomous and networked sensors would be an essential component in an integrated field system for forecasting aviation icing hazards. A systems-level analysis extending from meteorological sensors to the cockpit will identify effective strategies for increasing aircraft reliability and safety, given the improved forecasts. For example, tailoring hazard forecasts to specific aircraft can maximize the value of enhanced prediction capability.

ACKNOWLEDGMENTS

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REFERENCES

J. Ryerson, C., *Proc. FAA Int. Conf. on Aircraft In-Flight Icing, Vol. II* (Tech Rep. **DOT/FAA/AR-96/81,II**), p. 179, (1996)
2. Jeck, R., *Proc. FAA Int. Conf. on Aircraft In-Flight Icing, Vol. II,* (Tech Rep. **DOT/FAA/AR-96/81,II**), p. *57, (1996)*
3. Stankov, B., B. Martner, M. Politovich, *Jour. Of Atmos. and Oceanic Tech.*, **12**, p. 488, (1994)
4. Lawson, R. P., R. J 1. Cormack, *Atmos. Res., 35,* p. 315, (t 995)
5. Thompson G., R. Bruintjes B. Brown, F. Hage, *Wea. and Fore.*, (In Press - to appear in vet. *36,* 1997)

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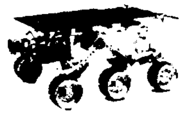
MOBILE AIRCRAFT ICING FORECAST SYSTEM



ABSTRACT

Aviation icing can compromise aircraft performance endangering military aviators, restricting surveillance opportunities, and reducing combs? effectiveness. An integrated mobile field system for forecasting in-flight and ground aviation icing hazards would be an asset for mid-latitude winter and year-round polar operations.

Meteorological forecast are currently limited by weather observation systems that are insensitive to cloud phase (liquid or ice), have limited capability to determine cloud temperature, and are unable to constrain the size distribution of cloud droplets and rain drops. Technology exists that can provide these data including short-wavelength radars, lidars, microwave radiometers, and in-situ meteorological probes. These measurement systems can be quite compact minimizing logistical requirements and enhancing mobility. Advanced ground-based and airborne sensors with state-of-the-art retrieval algorithms will provide accurate, timely forecasts of icing hazards as a standard product of the regional forecast model. It is feasible to package these components with appropriate communication and information system into a mobile forecast system.

A systems-level analysis extending from the meteorological sensor to the cockpit will identify effective strategies for increasing aircraft reliability and safety. For example, tailoring hazard forecasts to specific aircraft can maximize the value of enhanced prediction capability. The dangers of in-flight icing can also be mitigated with the development of autonomous systems for now-casting icing hazards. Advanced sensors can be developed which increase warning time by estimating ice deposition rates from the determination of ambient and approaching meteorological conditions. Deployment of autonomous detection systems would bean important component in developing an integrated field system for forecasting icing hazards.

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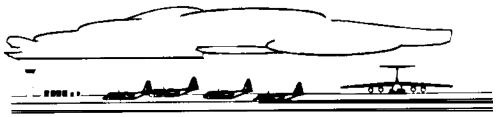
ICING HAZARDS

Aircraft **Act As Nucleation Sites For** Subfreezing Cloud **Liquid**

Hazard: Ice accumulation reduces lift compromising aircraft performance.

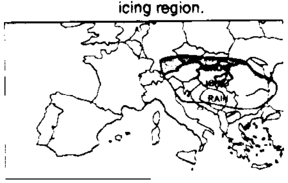
Specific Action Areas:

- Perform an independent, system-level analysis of operational forecast needs
- Establish mobile aircraft icing forecast capability
- Develop advanced airborne sensors and systems for icing forecasting and detection



Severe Icing Is *Usually* Associated with Precipitation
(Freezing Drizzle or Freezing Rain)

Typical winter storm icing region.



Icing potential depends on:

- Ambient temperature
- Liquid density
- Drop size distribution
- Airframe Temperature
- Exposure time
- Aircraft specific characteristics
  (wing shape, aircraft velocity, surface finish)

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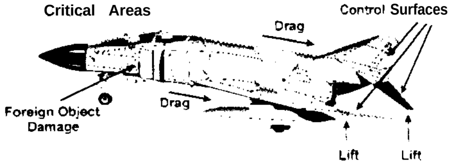


Ice accretion on aircraft and rotorcraft:

- Decreases lift by changing aerodynamics of the wings and propellers
- Increases drag
- Adds weight
- Can disable control surfaces
- Can cause foreign object damage

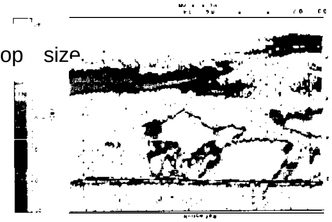
MILITARY AVIATION ICING HAZARDS **CAN** BE MANAGED **WITH** A
MOBILE, INFORMATION-BASED, SYSTEMS APPROACH **TO**
ICING FORECASTING, DETECTION, PROTECTION, **AND** AVOIDANCE.

FORECAST SENSORS

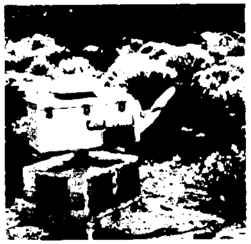
Existing meteorological networks are either insensitive to or have limited capability to determine

- Cloud phase (ice or liquid)
- Cloud temperature
- Cloud droplet or rain drop size

Airborne meteorological sensors can be used to quantify PIREPS.



This 90 GHz JPL/UMass cloud radar image shows the utility of airborne snd ground-based radars for retrieving the liquid/ice transition altitude.



JPL water radiometers determine the **integrated** *liquid water column from natural microwave emissions.*

A system-level analysis should drive the choice of sensors. Issues affecting the choice include

- Contribution to forecast accuracy
- Suitability for intended platform
- Potential to compromise security
- Technological maturity
- Logistics
- cost

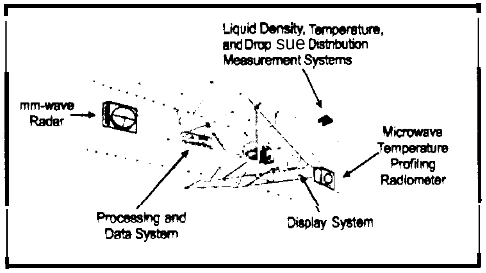
AUTONOMOUS SENSORS

Remote sensors

- Capability to look-shed and detect impending icing conditions
- Sense the temperature profile and ice/liquid transition altitude

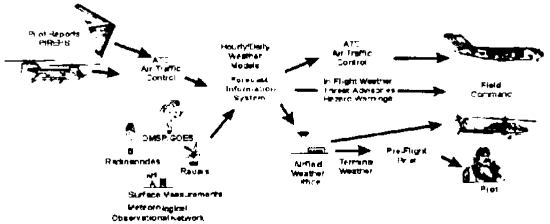
Advanced h-situ Sensors

- Use meteorological measurements to determine icing potential
- Develop algorithm to estimate the ice accumulation rate
- Determine the liquid density and drop size
- Discriminate between ice and liquid deposition with spectral imaging

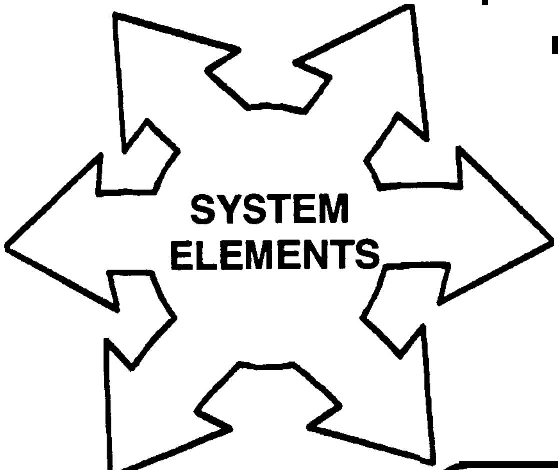


Aircraft equipped with icing potential assessment system can nowcast icing deposition rate, increasing hazard warning time.

INFORMATION MANAGEMENT



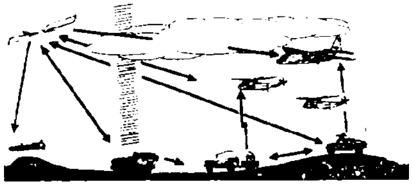
- Enables high-resolution regional forecast models
- Hazard forecasts tailored to each class of aircraft (i.e., jets, turboprops, rotorcraft, UAVs)
- Forecasts available in audio, text, and graphical formats
- Commercial-off-the-shelf (COTS) computing hardware
- Data gaps handled seamlessly



SYSTEM ELEMENTS

COMMUNICATIONS

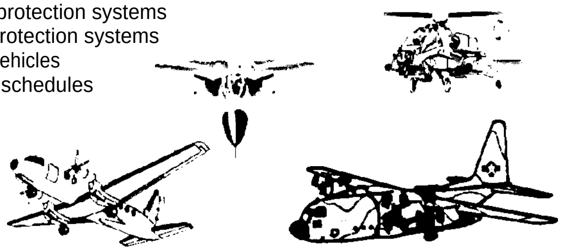
Reliable rapid communications ensure timely hazard warnings: Reliability ensured by seamless integration of space, ground and airborne sensors and information systems



AIRCRAFT HAZARD MITIGATION

Forecasts and nowcasts provide field commanders, pilots, and air traffic control ime to develop effective mitigation and avoidance strategies including:

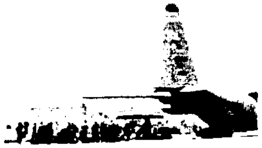
- Activate ice protection systems
- Deploy ice protection systems
- Reroute air vehicles
- Modify flight schedules



MOBILITY

Field-deployable systems require

- Compact sensors
- Vehicle mwnted subsystems (Sensors, computers, etc.)
- Integrated communication
- On-site information systems



Security and reliability can be enhanced using:

- Distributed mobile systems
- Appropriate use of passive sensors
- Integration of forecasts into existing weather forecast system

Military photos courtesy: DefenseLINK and DOD Web sites