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Ground-Based Icing Condition Remote Sensing System Definition

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National Aeronautics and
Space Administration

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Abstract

This report documents the NASA Glenn Research Center activities to assess and down select remote sensing technologies for the purpose of developing a system capable of measuring icing condition hazards aloft. The information generated by such a remote sensing system is intended for use by the entire aviation community, including flight crews, air traffic controllers, airline dispatchers, and aviation weather forecasters. The remote sensing system must be capable of remotely measuring temperature and liquid water content (LWC) and indicating the presence of super-cooled large droplets (SLD). Technologies examined include Profiling Microwave Radiometer, Dual-Band Radar, Multi-Band Radar, Ka-Band Radar, Polarized Ka-Band Radar, and Multiple Field of View (MFOV) Lidar. The assessment of these systems took place primarily during the Mt. Washington Icing Sensors Project (MWISP) in April 1999 and the Alliance Icing Research Study (AIRS) from November 1999 through February 2000. A discussion of the various sensing technologies is included. The result of the assessment is that no one sensing technology can satisfy all of the stated project goals. Therefore a proposed system includes radiometry and Ka-band radar. A multilevel approach is proposed to allow the future selection of the fielded system based upon required capability and available funding. The most basic level system would be the least capable and least expensive. The next level would increase capability and cost, and the highest level would be the most capable and most expensive to field. The Level 1 system would consist of a Profiling Microwave Radiometer. The Level 2 system would add a Ka-Band Radar. The Level 3 system would add polarization to the Ka-Band Radar. All levels of the system would utilize hardware that is already under development by the U.S. Government. However, to meet the needs of the aviation community, all levels of the system will require further development. In addition to the proposed system, it is also recommended that NASA continue to foster the development of Multi-Band Radar and airborne microwave radiometer technologies.

Background

The NASA Inflight Icing Remote Sensing activity started with the findings of 1997 White House Commission on Aviation Safety and Security, which directed NASA to significantly increase the level of safety for aircraft, including all-weather operations. NASA then initiated the Aviation Safety Investment Strategy Team (ASIST), which prioritized aviation safety activities required to meet the White House goals. The ASIST Weather team identified Inflight Icing as one of its top 3 priorities to improve flight safety. Simultaneous to this activity, the NASA Advanced General Aviation Transport Experiment (AGATE) was defining technologies required to enhance General Aviation (GA) aircraft safety and operation. Within AGATE, the Ice Protection Systems Workpackage was defining the Avoid and Exit strategy as the key to improving flight safety in the icing environment. Key to success of the Avoid and Exit strategy was the ability to remotely measure the icing environment.

In 1997, NASA Glenn Research Center (then Lewis Research Center), the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), and the FAA sponsored the Inflight Remote Sensing Icing Avoidance Workshop. The outcome of this workshop was the formulation of the NASA Icing Remote Sensing activity.

The NASA Icing Remote Sensing Activity was designed around the findings of the 1997 workshop. Tasks were defined that address the three major areas of concern: Meteorological Issues, Operational Issues, and Technological Issues. The Meteorological and Operational Issues are being addressed to define the requirements of future remote sensing systems that will adequately measure the environment and pass the appropriate information to the user in the most appropriate manner and format. These two areas will not be discussed further in this report. The primary thrust of the NASA Icing Remote Sensing activity is to develop the required sensing technologies and test them in the real-world aviation environment. This first requires the assessment of existing technologies followed by the selection of the most promising technology or technologies for further development. It is this selection of candidate technologies that is documented here. Many of the issues involved with the assessment and development of an icing condition remote sensing system have been examined by Ryerson[1].

The assessment of remote sensing technologies was done with several assumptions in mind. 1.) The information generated by an icing remote sensing system will be used not only by flight crews, but by the entire aviation community, including also air traffic controllers, airline dispatchers, and aviation weather forecasters. 2.) The development of ground based systems will likely be less costly and technically more achievable than for airborne systems due to relaxed size, power, and weight restrictions. Therefore, ground based system development should occur before airborne system development. 3.) It is likely that no one technology will be able to satisfy the requirements of the remote measurement of icing conditions. And finally, 4.) a multiple level development approach may be necessary to adequately address varying user requirements.

The majority of the NASA funded effort to assess the remote sensing technologies took place during the Mt. Washington Icing Sensors Project (MWISP) in April 1999 and the Alliance Icing Research Study (AIRS) in November 1999 to February 2000. To assist in the assessment of the candidate technologies, reviews of the various technologies were presented at the 2000 In-Flight Icing Remote Sensing Workshop hosted at the Ohio Aerospace Institute by NASA Glenn Research Center in November, 2000[2]. A detailed description of the candidate technologies and discussion of their strengths and weaknesses can be found in the following section.

Technology Assessment

Basic Requirements

The primary requirement for the ground based icing condition remote sensing system is that it be capable of measuring environmental conditions sufficient to identify areas of icing hazard. However, inflight icing potential is not directly measurable. It does not exist until an aircraft passes through the environment. To determine icing hazard, one would ideally measure the liquid water content (LWC) of the cloud, the ambient temperature, the droplet size distribution of the cloud, and the horizontal and vertical extents of the icing conditions.

Icing becomes a hazard to aircraft when the ice accretion rate exceeds the capacity of the aircraft's ice protection system or when excessive ice accretes on unprotected areas. The accretion rate is a function of many factors, but the most significant is the cloud LWC (assuming below freezing temperatures). With all other parameters held constant, the ice accretion rate is directly proportional to the LWC. Temperature is also a significant factor since temperatures must be below freezing on the aircraft structure for icing to occur, and typically the ice accreted just below freezing is the most hazardous (ice formed at these just-sub-freezing temperatures causes the largest degradation to the aircraft lift and drag). The cloud droplet size distribution can become a significant factor to icing hazard when the droplet sizes are larger than the sizes assumed by the aircraft designers and regulators. Super-cooled Large Droplets (SLD) are much larger than the cloud droplets normally used for the design and testing of aircraft ice protection systems.

Over the last several years, it has become apparent that these conditions happen often enough to be an aircraft safety concern. Therefore to fully assess the hazard level of the environment, at least an indication of the presence of SLD is also required.

Technology Options

Three basic technologies were selected for assessment based upon the findings of the 1997 Inflight Remote Sensing Icing Avoidance Workshop. The three technologies are radar, lidar, and radiometry. For the radar option, several variations were identified for individual evaluation. Four radar measurement techniques were identified: Ka-Band Radar, Polarized Ka-Band Radar, Dual (X/Ka) Band Radar, and Multi-(X/Ka/W) Band Radar. The radiometry technology assessed is the Profiling Microwave Radiometer. And the lidar technology examined is the Multiple Field of View (MFOV) Lidar.

In addition to these individual technologies, two hybrid technologies have been assessed. They are the combination of the Profiling Microwave Radiometer and Ka-Band Radar, and the combination of the Profiling Microwave Radiometer and the Polarized Ka-Band Radar.

Each of the technologies has been assessed in five areas: Current readiness, Strengths, Weaknesses, System Cost, and Current Operational Constraints. For each of these 5 areas, the authors have scored the technology from 0 to 5 points (0 = very unfavorable, 5 = very favorable)(see Table 1). The individual scores were added to obtain an overall total score for that technology, which obviously can range from 0 to 25. The individual technologies and their scores are listed in Table 2, Technology Assessment Table, and the two hybrid technologies and their scores are listed in Table 3, Hybrid Technology Assessment Table.

Table 1
Meaning of technology scoring

	Score = 0	Score = 5
Current Readiness	Technology only a concept	All hardware and software available for purchase and fielding
Strength	No strengths	Technology capable of accurately measuring all parameters required for the determination of icing conditions aloft
Weakness	Technology incapable of producing any information that would help detect icing conditions aloft	No weaknesses
Cost	Very expensive (well over $1 million)	Very inexpensive (complete system for under $100,000)
Current Operational Constraints	Must be constantly attended and unable to operate in many meteorological conditions	Capable of running unattended for long periods of time with 100% accurate data capture

Profiling Microwave Radiometer

System description

The Radiometrics Corp. TP/WVP-3000 Water Vapor, Temperature, and Cloud Liquid Water Profiling Radiometer (Figure 1) was assessed for use as an icing condition remote sensing system.

The profiling radiometer utilizes discrete measurements in the 22 to 60 GHz range[3]. This range of frequencies provides the observation of several spectral features in the atmosphere. Broadening around the 60 GHz oxygen band provides information on temperature profiles. Similarly water vapor profile information can be obtained by observing the broadening around the 22 GHz water vapor line. Liquid water emits over the entire range and increases approximately with the second power of the frequency, so by examining the temperature and water vapor measurements, liquid water profile information can be obtained.

The radiometer is controlled at a low level by a self-contained microprocessor which in turn is controlled by a data acquisition computer running FORTRAN software. The data acquisition computer takes the raw radiometer measurements at the discrete frequencies and along with several meteorological measurements and calculates temperature, water vapor, and liquid water profiles with a neural network. The neural network is trained using historical radiosonde data from the intended operational region over the various seasons. Work is currently underway to eliminate the reliance on the neural net and the need for location and season specific programming and to include some physics of cloud formation into the calculations.

Assessment of the radiometer is based upon the review and analysis of data produced at the Mt. Washington Icing Sensors Project (MWISP) in April, 1999, the Alliance Icing Research Study (AIRS) in December, 1999 through January, 2000, and NASA operation of the instrument during January through March, 2001.

Data examples

Figure 2 is a sample of the data produced by the radiometer system. Seen in this graphic is the temperature (top), humidity (middle), and liquid water profiles (bottom) plotted from 0 to 10 km (vertical scale) over a span of five days (time in the horizontal axis). This data is from the AIRS field test in Montreal, Canada in December of 1999. Measurements are stored at approximately every eight minutes (this time is defined by the scanning time for each frequency and also the amount of self-calibration done at each scan). The vertical resolution of the measurements varies with height. Below 1 km the resolution is 0.1 km, and above 1 km the resolution is 0.25 km.

Scoring

1) Current readiness, scored **4** out of 5:

The profiling radiometer examined in this activity is a commercially available product. Radiometrics, Inc. manufactures and markets their MP3000 radiometer, and it is available for purchase with relatively short lead times. During the assessment of this system several shortcomings have been identified, but their correction should not significantly alter the cost or availability of the system.

2) Strengths, scored **4** out of 5:

The profiling radiometer examined in this effort typically does a good job measuring temperature profiles and does nearly as well measuring water vapor (humidity) profiles[4]. Temperature and humidity profiles together typically can provide reasonable indication of cloud location. The microwave radiometer technology has been shown to provide accurate integrated (over the view path) liquid water measurements.

3) Weaknesses, scored **3** out of 5:

The profiling radiometer currently doesn't do very well with liquid water profiles[5]. Also, the technology as currently configured cannot provide any indication of large droplets in a cloud. Work is currently underway to improve the liquid water profiling measurement. While typically strong, the temperature and humidity profile accuracy can be limited in inversion situations or whenever the parameter changes very rapidly with altitude. Since the radiometer uses the temperature profile along with the cloud base temperature measurement to define the cloud base, additional work is required to improve cloud base identification in inversion conditions.

4) Cost of system, scored **4** out of 5:

Due to the fact that a profiling radiometer is currently commercially available, the cost of this technology is quite reasonable. Complete profiling radiometer system costs (including instrument and data acquisition computer) are approximately one quarter of a million dollars.

5) Current operational constraints, scored **4** out of 5:

The profiling radiometer examined has been run unattended in numerous filed tests. As with all microwave instruments, this device has problems with water contamination on the radome. This instrument has a blower and heater to minimize the length of time of contaminated measurements. However, the measurements from the instrument are invalid for a fairly significant amount of time during liquid precipitation events. This is considered to be a problem that can be solved with adequate engineering effort.

Figure 1, Radiometrics Inc. Profiling Radiometer

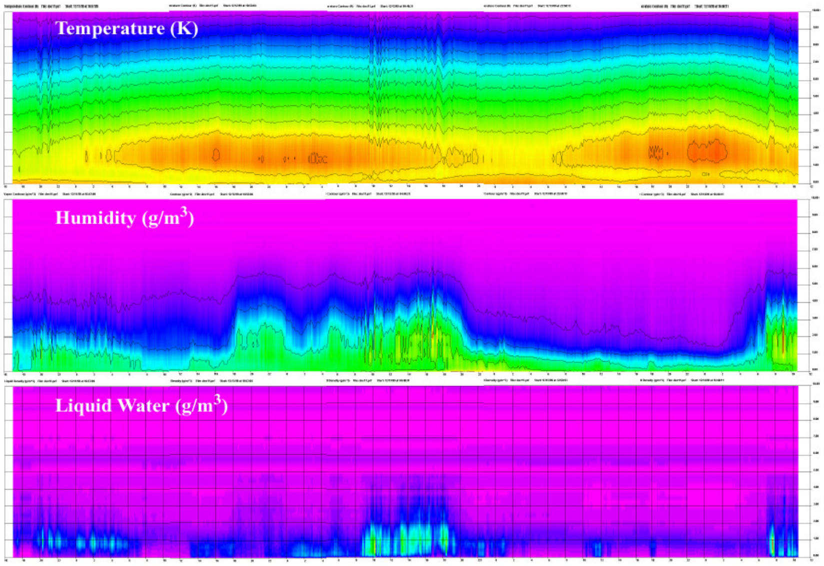

Figure 2, Example of Profiling Radiometer Data

Ka-Band Radar

System description

While not a subject of the active NASA assessment activities for icing remote sensing systems, the Ka-Band cloud radar has the potential for significant contribution to a hybrid system (see below). Therefore, its attributes have been examined and scored here.

The system described here is the NOAA/ETL Millimeter-wave Cloud Radar (MMCR)[6] (Figure 3). It functions at 34.86 GHz with a peak transmit power of 100W. It has a 1.8 m diameter antenna that produces a 0.3 deg wide beam. It is designed to stare at the zenith. Its range is approximately 20 km with a resolution of 45 m. Due to long sample time and the large antenna, the radar is very sensitive despite its low power. It is able to detect very thin clouds and layered clouds in addition to very thick clouds. Post-processed scans are available every 10 seconds. The strength of this radar for icing remote sensing is its ability to accurately define the boundaries of the cloud. The MMCR was designed for unattended measurement of cloud profiles for the Department of Energy's Atmospheric Radiation Measurement (ARM) program, and has operated in numerous sites in the US and from ships in the Arctic, Pacific, and Indian Oceans.

Data examples

Figure 4 is a sample of the data that is produced by the MMCR[7]. It shows the spatial and temporal resolution as well as the sensitivity (down to around -40dBZ at 10km) of this radar.

Scoring

1) Current readiness, scored **4** out of 5:

Ka-Band radars are currently available for purchase from radar manufacturing firms. The radars currently available may not be the optimal instrument for use with an icing remote sensing system, so some development effort is likely to be required.

2) Strengths, scored **1** out of 5:

As a stand-alone device, the cloud radar can provide a good indication of the boundary of the clouds and an indication of the density of hydrometeors in the cloud, however this information by itself is of little value.

3) Weaknesses, scored **1** out of 5:

By itself, the cloud radar is weak for icing condition remote detection. The cloud radar can provide no information on the liquid state of the cloud, the amount of moisture in the cloud (even if the liquid state is already known), temperature of the environment, or cloud droplet size.

4) Cost of system, scored **3** out of 5:

Currently available cloud radars are quite expensive since they are custom made instruments for each research application. However, there is a good potential that the costs of such devices required to define the boundaries of icing clouds can be significantly lower.

5) Current operational constraints, scored **4** out of 5:

Cloud radar systems have been designed to run unattended. However, as with all of the technologies examined, the problem with radome contamination has not been adequately addressed for this form of remote sensing system to ensure 100% availability for the winter operations environment.

Figure 3, NOAA Environmental Technology Laboratory (ETL) Millimeter-Wavelength Cloud Radar (MMCR)

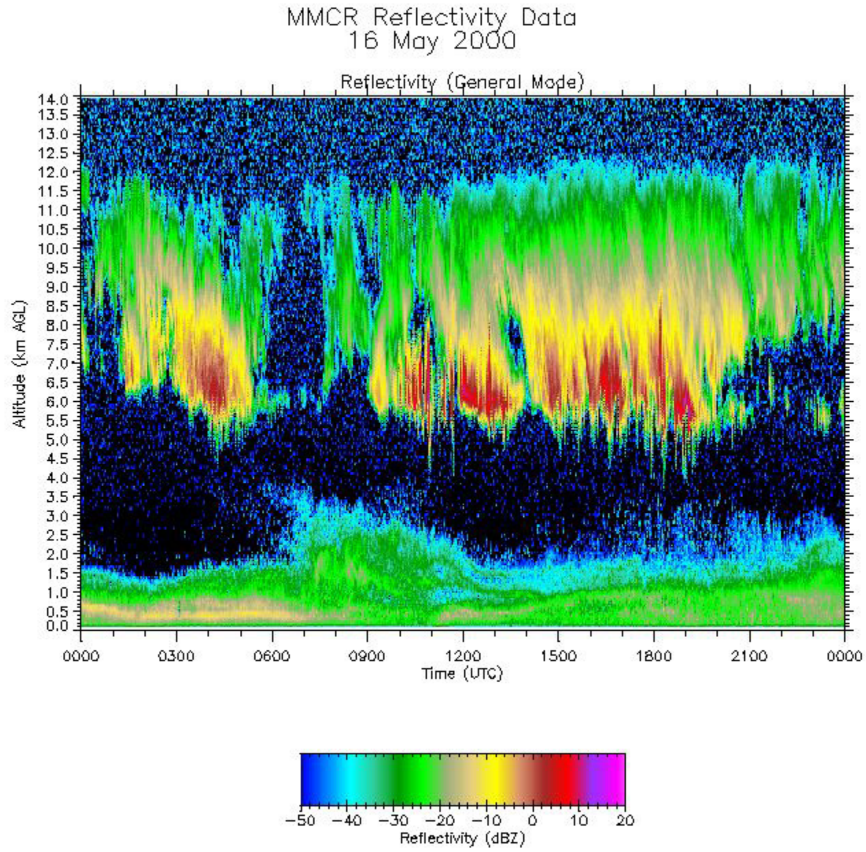

Figure 4, Example of Department of Energy Atmospheric Radiation Measurement Program MMCR Data

Polarized Ka-Band Radar

System description

While NASA has not funded examination of Polarized Ka-Band Radar for use as an icing condition remote sensing technology, NOAA ETL, with funding from the FAA, has completed an extensive examination. At the MWISP field test, NOAA ETL operated their Polarized Ka-Band Radar (NOAA/K)[8] along with their X-Band Radar and dual frequency microwave radiometer . The NOAA/K radar was originally built in the early 1980's and has been continuously upgraded since then. It has a very flexible configuration including multiple polarization methods, scanning techniques, signal processing methods, and even antenna selection. The system configuration that resulted in the best results for super-cooled large droplet (SLD) identification at MWISP is the one described here[9].

The system was configured to perform horizon-to-horizon range-height indicator (RHI) scans. A slant linear polarization was obtained by transmitting a quasi-linear polarization state at a 45 deg slant and receiving the corresponding co- and cross-polarization signals. This configuration has yielded detection methodologies that appears capable of determining cloud particle type, and if spherical, also size range. In other words, this detection technique should be capable of identifying areas of SLD.

While the radar can clearly indicate the boundaries of the cloud, indicate some of the structure of a cloud, and likely be able to measure the presence and size range of liquid droplets, this form of radar is not capable of measuring cloud liquid water content nor temperature. To measure these other parameters that are considered necessary for the quantification of icing condition hazard, some other form of measurement must also be used. A hybrid system has been defined that combines the strengths of the polarized Ka-band radar and the profiling radiometer and is described and scored later in this document.

Data examples

Figure 6 is a plot of the various depolarization signals measured by the NOAA/K radar at MWISP. This plot shows the slant-linear depolarization ratio (vertical scale) versus the horizon-to-horizon observation angle (horizontal scale, where 90 deg is zenith) for various types of cloud particles. This plot clearly shows the strong indication of when liquid water is present as compared to ice particles.

Figure 7 is an example of the data produced by the NOAA/K radar. Both displays are plots from an RHI scan. The upper graphic is the return signal strength and the lower graphic is the depolarization ratio signal. The Mt. Washington summit was just beyond the right boundary of the plotted data (the scan was limited in elevation on that side by the presence of the mountain). This figure demonstrates the fine detail of cloud structure that this kind of radar can measure.

Scoring

1) Current readiness, scored **3** out of 5:

The technology required for designing and constructing a polarized Ka-band radar are well understood. Currently no radar exists that has been designed specifically for icing detection. NOAA ETL has a project underway to build such a radar, and this radar should be available in several years.

2) Strengths, scored **3** out of 5:

This form of radar is capable of detecting spherical particles and then providing information on their size. The detection of SLD conditions is an important piece of an aviation icing hazard identification system, since for full coverage, it is necessary to identify the exceedance of Appendix C conditions in the droplet size direction.

3) Weaknesses, scored **2** out of 5:

While this technology can detect spherical cloud particles and identify if they are in the SLD size range, it has no way of providing the liquid water content nor the temperature of the icing environment. Therefore this technology can only answer a piece of the icing severity question.

4) Cost of system, scored **2** out of 5:

Development of radars that can provide the sensitivity required for the cloud particle classification is still quite expensive (over $1million). However, as advances are made in radar hardware and particle identification signal processing, the cost of such a system should come down dramatically.

5) Current operational constraints, scored **3** out of 5:

Although some unattended operation of radars like the NOAA/K is possible, they are typically operated with an engineer or scientist present. Future systems underdevelopment will hopefully eliminate this operation constraint. Also, as with the other instruments operating in the microwave waveband, this form of radar will be susceptible to radome water contamination.

Figure 5, NOAA ETL Polarized Ka-Band (NOAA/K) Radar

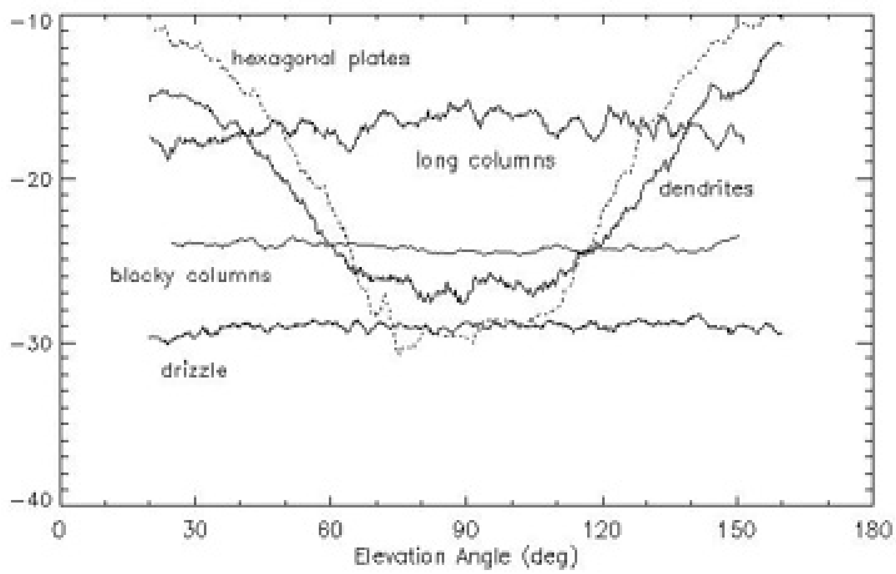

Figure 6, Example of Polarization Signal Data from NOAA/K Radar

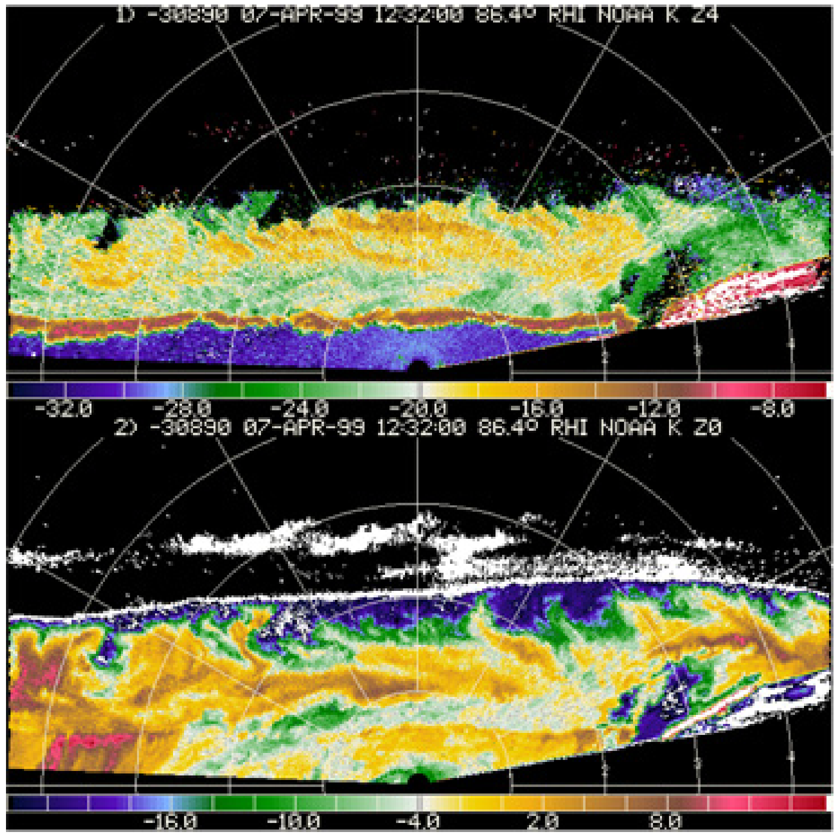

Figure 7, Example of Data from NOAA Polarized Ka-Band Radar

Dual Band Radar

System description

Weather radar users have long been aware of the frequency dependence of attenuation on atmospheric liquid water. In the early 1990s NOAA attempted to utilize this attenuation variation at X- and Ka-Bands (known as the dual band attenuation technique) as a means of remotely measuring liquid water content of a cloud[10]. They concluded that the technique looked promising, but that among other things, the sample volume of the two radars needed to be matched to obtain valid results. Since that time, several attempts have been made to test the concept in the field. NOAA ETL brought their X- and Ka-Band radars to MWISP and gathered data for the assessment of the technique[11] and Stratton Park Engineering Corporation (SPEC) operated X- and Ka-Band radars in Colorado in 1997 (under a U.S. Army Small Business Innovative Research, SBIR, contact) and at AIRS in 2000 (under a NASA Small business Technology TRansfer, STTR, contract)[12]. In these tests efforts were taken to match the radar sample volumes in the sampling space. Results proved mixed. When the cloud consisted of liquid water droplets which are much smaller than both radar's wavelengths (with linear, Rayleigh regime scattering), the technique appeared to work as expected. However, when the cloud included larger ice particles roughly the size of the Ka-band radar's wavelength (with nonlinear, Mie regime scattering), the technique failed. Since the Ka-band radar is scattering in a nonlinear manner there is no consistent trend when comparing the differential signal to the atmospheric liquid water content. Therefore, the technique is limited to clouds that do not contain rain-sized droplets or large ice crystals.

The National Center for Atmospheric Research (NCAR) has also developed a technique for estimating the rough size of the cloud droplets based upon the dual wavelength signal[11]. However, this measurement is also restricted to the Rayleigh regime, and the technique breaks down when large particles are present.

Data examples

Figure 9 shows an example of the results of the differential attenuation technique from the AIRS testing of SPEC. The differential signal (X-band reflectivity minus Ka-band reflectivity) is plotted versus range. For the region with increasing differential (the region of cloud attenuation), a straight line is fit. As long as the cloud particles are relatively small, the attenuating cloud's liquid water content is proportional to the slope of this line, and can therefore be easily calculated.

Scoring

1) Current readiness, scored **2** out of 5:

The primary concern for the readiness of this technology is the design and manufacture of the required antenna system. The antennas for the two frequencies are required to be perfectly aligned and produce beams with matching widths. While possible with current engineering practice, further development is required to ensure a low cost solution.

2) Strengths, scored **2** out of 5:

The dual band radar technique can measure the cloud liquid water content and provide an indication of the relative size of cloud particles. However, this capability is limited to the Rayleigh regime.

3) Weaknesses, scored **2** out of 5:

The measurement of liquid water content and indication of droplet size is not valid when a significant number of large particles (typically ice crystals) are present in the cloud. Recent research is indicating that most icing clouds exist in a mixed phase or combined liquid/ice crystal state[13]. Also the technique can't provide any information about the temperature of the cloud environment.

4) Cost of system, scored **2** out of 5:

Current radars that can provide a quality measurement utilizing the dual band technique are quite expensive. To date, no low cost radar manufactured to utilize this measurement technique has been of sufficient quality to ensure valid results.

5) Current operational constraints, scored **3** out of 5:

No multi-frequency radar is known that has been configured to run in extended unattended mode, but there is no particular limitation to the technology that would prevent it. As with all of the other technologies examined here, the contamination of the radar radome by water is an issue that would need to be resolved for extended, uninterrupted operations.

Figure 8, SPEC, Inc., Dual Band (X/Ka) Radar

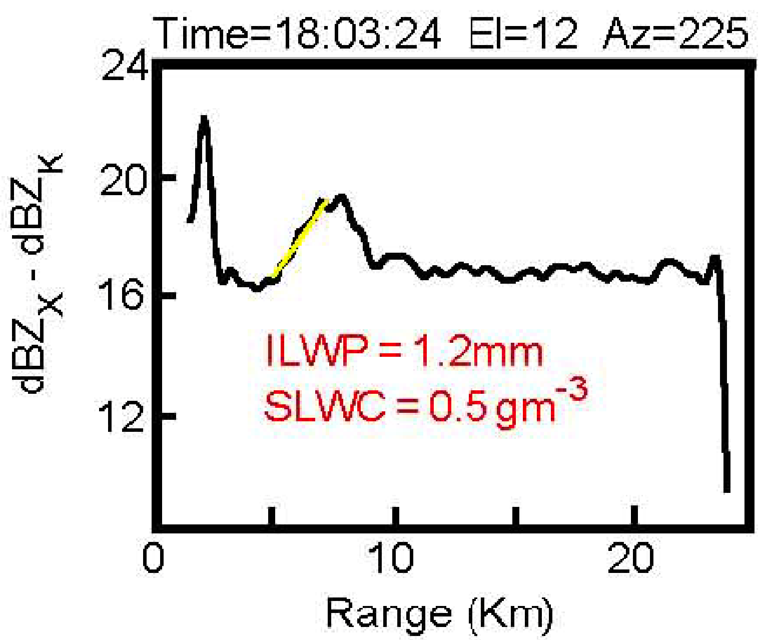

Figure 9, Example of SPEC Dual Band Radar Data

Multi-Band Radar

System description

Quadrant Engineering, Inc. under a US Army contract funded by the FAA started assessment of Multi-Band Radar technology in 1997[14]. They performed a series of computer simulations of the radar response to icing conditions and determined that an X-/Ka-/W-Band configuration was the optimal system. They determined that this configuration would be capable of measuring cloud liquid water content and also provide an indication of cloud droplet size. Quadrant utilized a neural net analysis technique for their simulations. With a neural net, they were able to examine the response of different radar configurations to thousands of various environmental states. Quadrant tested the different configuration with varying levels of signal noise. Interestingly, they found that the Multi-Band Radar configured in an X-/Ka-/W-Band system could also measure cloud temperature if no noise was introduced, however, when any noise was introduced to the simulation the measurement failed. They theorized that the noisy-signal simulation was the best comparison to how the system would function in the real world.

Based upon the analytical results, two field tests were funded by NASA to examine the capabilities of Multi-Band Radar to function as an icing remote sensing system in the real world. The radar configuration tested in both activities was an X-/Ka-/W-Band system. The first field test was at MWISP in April, 1999[15]. Analysis was performed by Quadrant using data from the NOAA X-Band radar (Figure 10) and the University of Massachusetts, Amherst (UMass) Ka-/W-Band system (Cloud Profiling Radar System, CPRS)(Figure 11). Similar testing was performed at AIRS in Montreal, Canada from December, 1999 to February, 2000. The AIRS testing used the McMaster University X-Band radar and the UMass CPRS.

By using the extra frequency and processing the data through a neural net, Quadrant and UMass have found that they are not limited to the Rayleigh regime with the Multi-Band Radar as is the Dual Band Radar.

Data examples

Figure 12 shows an example of the Quadrant results from the MWISP field test. The four plots show the liquid water content and cloud droplet size measurement for different ranges. The left vertical scale is liquid water content, the right vertical scale is for droplet size. The horizontal scale is time. The solid line on the plots is the liquid water content, the dot-dash line is the Median Volumetric Diameter of the water droplets, and the dotted line is the Mean Z Diameter. The MZD is the particle diameter that corresponds to the mean cloud reflectivity. When the MZD becomes significantly larger than the MVD, large droplets are present in the sample volume.

Scoring

1) Current readiness, scored **2** out of 5:
Research radars exist that can be used for this type of measurement. However, development would be required to produce a good Multi-Band Radar that has matching beam widths and is optimized for icing cloud measurement.

2) Strengths, scored **3** out of 5:
The Multi-Band Radar has been shown to produce measurements of liquid water content and indication of large droplets. These measurements do not appear to be limited to the Rayleigh regime of only relatively small cloud particles as is the dual-band attenuation technique.

3) Weaknesses, scored **3** out of 5:
Analysis has shown that radar systems with realistic noise values will not be capable of measuring cloud temperature.

4) Cost of system, scored **2** out of 5:
As with the Dual-Band Radar technology, current radars that can provide a quality measurement utilizing a multi-band technique are quite expensive

5) Current operational constraints, scored **3** out of 5:
Again, like the Dual-Band Radar, no multi-frequency radar is known that has been configured to run in extended unattended mode, but there is no particular limitation to the technology that would prevent it. And, as with all of the other technologies examined here, the contamination of the radar radome by water is an issue that would need to be resolved for extended, uninterrupted operations.

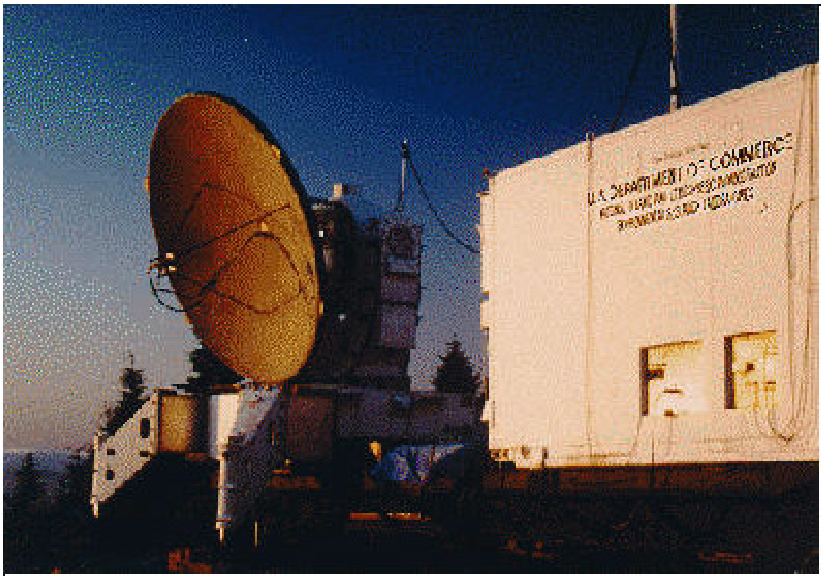

Figure 10, NOAA ETL X-Band Radar (used with UMass Ka/W-Band Radar at MWISP for Multi-Band Radar Data Acquisition)

Figure 11, University of Massachusetts (UMass) Ka/W-Band Radar (used with NOAA ETL X-Band at MWISP for Multi-Band Radar Data Acquisition)

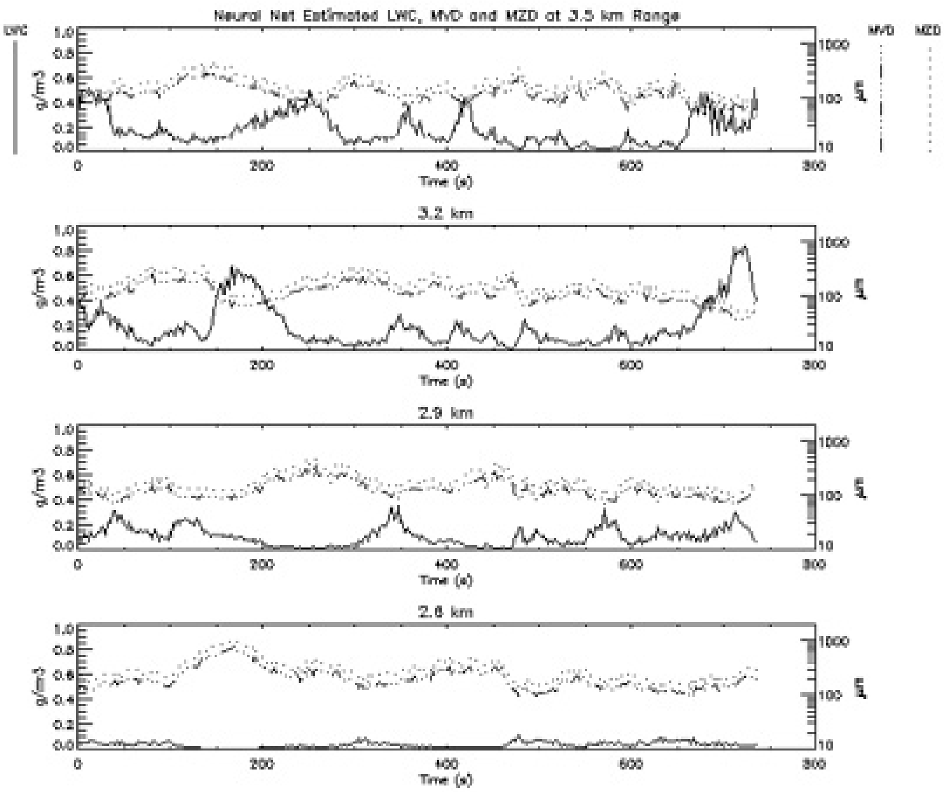

Figure 12, Example of Multi-Band Radar Data

Multiple Field of View (MFOV) Lidar

System description

The system described here is the Defense Research Establishment Val artier (DREG) Multiple-Field-Of-View (MFOV) Nd:Yag lidar[16] (Figure 13). The lidar output is 70 mJ with a pulse repetition rate of 100 Hz, a pulse width of 12 ns, a beam diameter of 12 mm and a beam divergence ranging from 0.1 to 12 mrad. The system can be operated in the RHI mode at a single FOV or in the staring mode using all FOVs. The lidar transmits a linear polarized beam and receives both the parallel and perpendicular backscatter. The MFOV provides a capability to obtain both single and multiple backscatter information. High spatial resolution sampling of aerosols and clouds can be achieved with the short pulse length, narrow beam divergence, and high sampling rate (100 Hz) MFOV lidar. The nominal along beam resolution of the MFOV lidar is on the order of several meters, while the cross-beam resolution depends on the beam diameter, beam divergence, distance from the lidar, and the scan rate. Within limits, changing the number of pulses integrated can control the sensitivity of the lidar. The MFOV configuration permits the spatial and temporal retrieval of phase (liquid vs. ice), liquid water content (ice equivalent liquid water content), and effective drop size, including information about the presence of large drops.

Data example

An example of a system RHI output for a fog and liquid cloud environment is shown in Figure 14[2]. Evident in this example is the high spatial resolution of the measurements.

Scoring

1.) Current readiness, scored **3** out of 5:

The MFOV Lidar is a research tool. Some of the components of the system are available from commercial manufactures, but a development effort would be required for this to function as a dedicated aviation icing remote sensing system.

2.) Strengths, scored **2** out of 5:

MFOV Lidar can provided most of the parameters required to remotely infer cloud icing potential including phase, liquid water content, effective drop size, and information about the presence of large drops. Of all the systems reviewed, lidar can provide the greatest spatial resolution.

3.) Weaknesses, scored **1** out of 5:

The optical depth associated with the cloud limits the lidar cloud penetration depth. For both the MWISP and AIRS experiments, the effective penetration depth of the MFOV Lidar was on the order of 150 to 200 meters. In addition, the MFOV Lidar is not eye safe and cannot be run in an unattended mode. Lidar does not directly provide information on the air temperature. By using the polarization information it is possible to infer when temperatures are below freezing if the cloud consists of ice crystals or is in a mixed phase state. But, lidar cannot be used to determine if a liquid cloud consists of super-cooled drops.

4.) Cost of system, scored **3** out of 5:

Lasers are commercially available and should be fairly inexpensive. But, the MFOV Lidar contains unique components that would drive up the cost. Additional expense would be required to optimize the system output for icing severity indication.

5.) Current operational constraints, scored **2** out of 5:

In the present configuration the lidar cannot run unattended. By using a lidar operating at an eye safe wavelength it may be possible to develop an unattended system.

Figure 13, Canadian Defense Research Establishment, Valcartier (DREV) MFOV Lidar

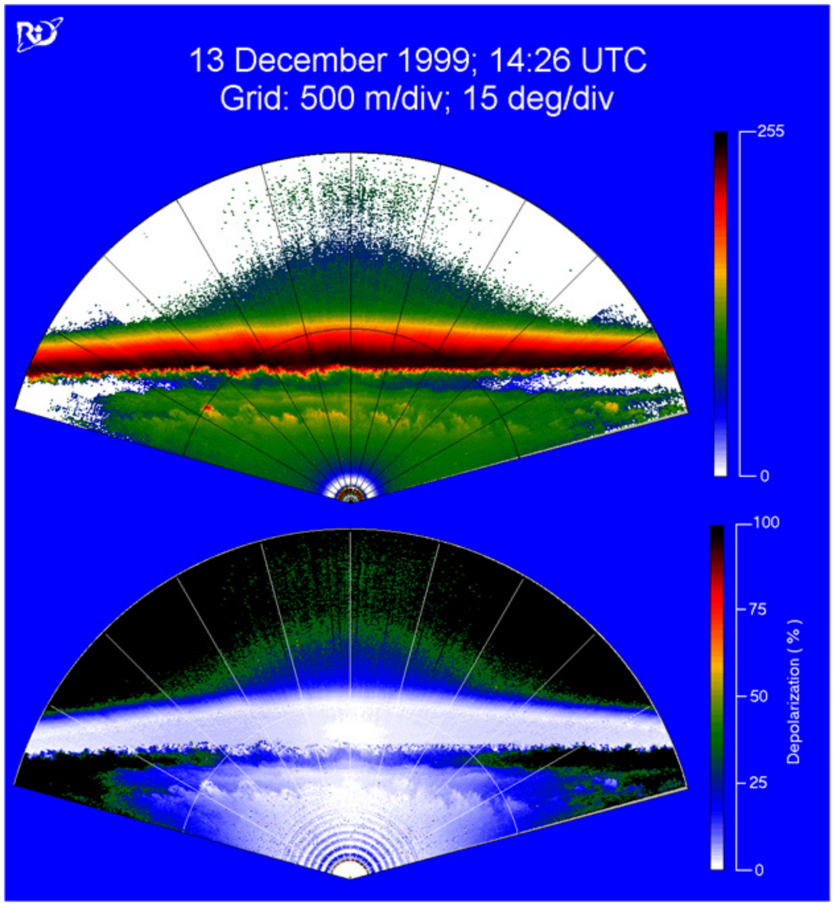

Figure 14, Example of Data from DREV MFOV Lidar

Hybrid Profiling Microwave Radiometer and Ka-Band Radar

System description

The concept behind this hybrid system is to address the shortcomings of the Profiling Microwave Radiometer by adding more accurate ranged data. By combining a Ka-Band Radar and a Profiling Microwave Radiometer into one integrated system, one becomes able to accurately identify where the clouds are, accurately determine the temperature in that cloud, and to accurately determine the amount of liquid water in that cloud. With these three pieces of information, this combined system will satisfy the most of the information needs for aircraft icing hazard identification.

The combined system will require the Profiling Microwave Radiometer to define the temperature profile and the path line integrated liquid water content. The Ka-Band Radar will contribute information on the cloud boundary locations. Based upon the temperature profile, the location of the cloud, and the integrated liquid water content, an icing hazard profile can be calculated. This icing hazard profile will then be available for use by the aviation community.

As with the separate radiometer and radar, this combined system will not scan, but will initially provide a profile directly above the instrument location. The use of this combined instrument to perform upwind scans (to provide an indication of the conditions moving into the area) will be examined also.

Additional accuracy may be possible due to the combination of the two technologies. If radar can very accurately define the regions of scattering, then the radiometer could adjust the weighting of its calculations of integrated water content. Liljegren has shown that this is a promising technique[17], and it would likely be adopted for use with this system.

Scoring

1.) Current readiness, scored **4** out of 5:

Since both the radiometer and the radar individually were ranked at 4 out of 5 for readiness, this combined system is also ranked at that level. There will be some developmental issues in combining the two technologies, however, they are not seen as being too severe.

2.) Strengths, scored **4** out of 5:

The combined use of the two technologies will result in a more accurate measurement of the liquid water content profile. The integrated liquid water content from the radiometer will initially be evenly distributed between the cloud boundaries. This will result in somewhat inaccurate liquid water content magnitudes, but the location of the liquid water should be very accurate.

3.) Weaknesses, scored **4** out of 5:

As with its component technologies, this hybrid system will not be capable of providing any cloud droplet size information.

4.) Cost of system, scored **3** out of 5:

While this hybrid system is made up of two relatively lower costing systems, its combined cost is considered to be moderate. If higher volume production is achieved, the cost of this system could become competitive with the current lower cost remote sensing technologies.

5.) Current operational constraints, scored **3** out of 5:

While this system is expected to operate in an unattended mode, it will still be susceptible to radome contamination, which is still an issue with all of the microwave frequency instruments.

Hybrid Profiling Microwave Radiometer and Polarized Ka-Band Radar

System description

The combination of a Polarized Ka-Band Radar and a Profiling Microwave Radiometer is even more powerful than the combination of a cloud profiling Ka-Band Radar and a Profiling Microwave Radiometer. As discussed above, by adding the polarization to the Ka-Band Radar, one gains the ability to detect super-cooled large droplet (SLD) conditions within an icing cloud. With the SLD detection, the icing condition remote sensing system then becomes an even more powerful tool to aid the aviation community keep aircraft out of severe icing conditions. In their presentation at the 2000 In-Flight Icing Remote Sensing Workshop[18], NOAA ETL described such a system that they call the Ground-based Remote Icing Detection System (GRIDS). Figure 15 shows a concept drawing of such a system.

Scoring

1.) Current readiness, scored **3** out of 5:

The radiometer portion of this system is currently available for commercial purchase, but the Polarized Ka-Band Radar is not. However, the radar is currently being developed by NOAA ETL and if funding continues, should be available in several years.

2.) Strengths, scored **5** out of 5:

The combination of a Polarized Ka-Band Radar and a Profiling Microwave Radiometer provides all the information required for a vertically profiling icing severity remote sensing system. This system would be able to provide an accurate measurement of the temperature profile, location of super-cooled liquid water, liquid water content within the cloud boundaries, and an indication of SLD conditions.

3.) Weaknesses, scored **5** out of 5:

The only weakness of this system is the constraint of not scanning (volume scans). It will be limited to vertical profiles. However, the restriction to vertical profiles is an assumed constraint of the overall activity at this time. Sometime in the future the technologies may progress to the point where a volume scan type operation will be possible.

4.) Cost of system, scored **2** out of 5:

The addition of polarization to the Ka-Band Radar will make this system significantly more expensive than the one that does not include polarization.

5.) Current operational constraints, scored **3** out of 5:

Radome contamination is the primary constraint to operation of such a system. No Polarized Ka-Band Radar has yet operated in an extended unattended mode, however NOAA ETL is planning to operate GRIDS in this manner.

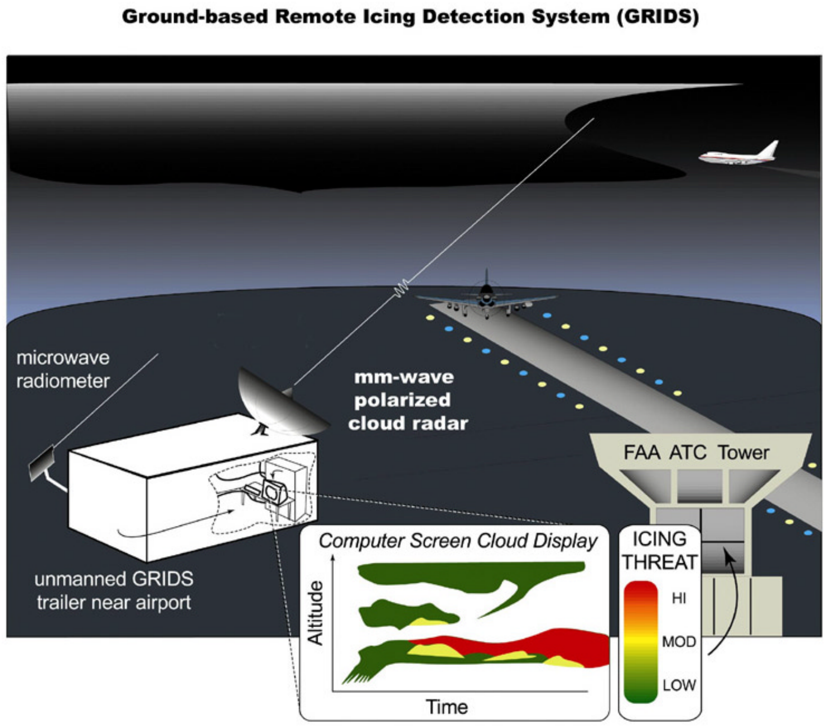

Figure 15, Concept Drawing of NOAA ETL GRIDS
(Combination Polarized Ka-Band Radar and Radiometer System)

Table 2
Technology Assessment Table

Technology	Current Readiness	Strength	Weakness	Cost	Current Operational Constraints *	Total **
Profiling Microwave Radiometer	4 (off the shelf)	4 (temp and int. LWC)	3 (LWC profile inaccuracy, no dropsize)	4	4 (radome contam.)	19
Ka Band Radar	4	1 (indication of cloud)	1 (no LWC, no dropsize, no temp)	3	4 (radome contam.)	13
Polarized Ka Band Radar	3 (build planned)	2 (indication of liquid water, indication of large drops)	2 (no LWC, no temp)	2	3 (attended)	12
Dual Band Radar	2	2 (LWC and indication of large drops in Rayleigh regime)	2 (no LWC and no dropsize in Mie regime, no temp)	2	3 (attended)	11
Multi-Band Radar	2	3 (LWC, indication of large drops)	3 (no temp)	2	3 (attended)	13
MFOV Lidar	3	2 (cloud edge LWC, dropsize)	1 (poor cloud penetration, no temp)	3	2 (attended, window contam., eye safety)	11

Scoring is on a scale of 1 (poor) to 5 (excellent)
* "Attended" indicates the need for attended operation and/or analysis
** Total out of a possible of 25

Table 3
Hybrid Technology Assessment Table

Technology	Current Readiness	Strength	Weakness	Cost	Current Operational Constraints *	Total **
Profiling Microwave Radiometer with Ka Band Radar	4	4 (temp and improved LWC profile)	4 (no dropsize)	3	4 (radome contam.)	19
Profiling Microwave Radiometer with Polarized Ka Band Radar	3 (build planned)	5 (temp, improved LWC profile, indication of large drops)	5	2	3 (radome contam., attended)	18

Scoring is on a scale of 1 (poor) to 5 (excellent)
* "Attended" indicates the need for attended operation and/or analysis
** Total out of a possible of 25

Proposed Ground Based Icing Condition Remote Sensing System

Proposed system description

Since the future funding potential for implementing icing condition remote sensing is unknown, three versions of ground based icing potential remote sensing system are defined. The difference between these stand-alone systems is capability, accuracy, and cost. As would be expected, the lowest cost system is the least capable, with the next more expensive system adding an additional level of capability, and the most expensive system being the most capable and accurate. These three systems will be described as Level 1, Level 2, and Level 3, with Level 1 the least costly, least capable and Level 3 the most costly and most capable.

The Level 1 system consists of a Profiling Microwave Radiometer. This system utilizes technology that has been shown to produce accurate temperature profiles and liquid water integrated values. The system also shows the potential for producing liquid water profiles that while somewhat inaccurate may be of significant value to flight crews, controllers, dispatchers, and forecasters.

The Level 2 system addresses the Level 1 system weakness by adding a Ka-band radar to define the cloud base and tops. This information combined with the radiometer's liquid water profile and integrated liquid water content will provide much more accurate icing hazard identification.

The Level 3 system adds polarization to the radar to add the identification of supercooled large droplets (SLD).

All forms of this system will produce vertical profiles of icing hazard potential. A volume scan that fully covers the area surrounding an airport (similar to the output of a Terminal Doppler Radar) is not seen to be feasible at this time. However, it may be possible to supplement the vertical profiles with profiles at 30-45 degrees elevation in the up-wind direction to provide a near-term prediction or trend analysis. This up-wind concept has been demonstrated in the FAA Weather Support to Deicing Decision Making (WSDDM) system[19].

Since Level 2 builds upon Level 1, and Level 3 builds upon Level 2, it is recommended that the NASA ground based icing condition remote sensing demonstration system be developed to Level 3. With the Level 3 system operational, all three operation Levels may be assessed and verified.

Status of hardware for proposed system

One benefit of the selection of this set of technologies is that all are already separately in some level of development, and within 2 to 3 years, hardware should exist within the government for even the Level 3 system. NASA Glenn Research Center has been examining the Radiometrics Corp. Profiling Microwave Radiometer that can be the basis of the Level 1 system. NASA Glenn Research Center has also managed an SBIR contract with Technology Service Corp., which will deliver an X- and Ka-band radar system. This radar should be sufficient for at least the initial development of the Level 2 system. And NOAA ETL, with funding from the NWS and FAA, are developing their Ground-based Remote Icing Detection System (GRIDS) which should satisfy the longer term radar requirements for Level 2 and the polarized radar requirements for Level 3.

Recommended Development Path

While much of the basic hardware required for the proposed system either already exists or is in the process of being procured, there are still developmental activities that must take place to successfully field the three levels of system proposed.

<u>Level 1</u> requires additional work to improve the all-weather capability of existing radiometers. Current radiometers have difficulty operating in precipitation that wets the instrument radome. This issue impacts the accuracy of temperature profiles, liquid water profiles, and integrated liquid water, and thus is seen as a critical issue. Also, the accuracy of the liquid water profiles can very likely be improved with further software and/or hardware development.

To maximize the value of the information generated by an icing condition remote sensing system, the proper form of information must be delivered to the users (flight crews, controllers, dispatchers, and weather forecasters) in an accurate and timely manner. The current icing severity index is not appropriate for passing remotely sensed data to users. Hazard identification algorithms must be refined to produce information of value to the different users. Also, the adoption of an appropriate data distribution technique is required to ensure the user receives icing products in a timely and understandable manner. Existing ground data networks will likely be acceptable for controllers, dispatchers, and weather forecasters, but additional work is required to define and pursue the best method for distributing the information to flight crews.

Level 2 requires the integration of the Ka-band radar with the Level 1 radiometer. The adequacy of the radars that are to be delivered to NASA Glenn Research Center is yet to be determined. Also the optimal technique for combining the two systems has yet to be defined. At a minimum, additional work will be required to integrate the radar and radiometer systems to produce a single icing potential product. If the existing radar proves to be inadequate, additional development and procurement will be required.

Level 3 will likewise require the integration of the GRIDS system with the radiometer. The GRIDS is being designed to stare at non-vertical angles to maximize the polarization signal from large droplets. A technique of combining a vertical staring radiometer and a non-vertical staring radar must be developed.

Additional Development Opportunities

In addition to the development of the proposed ground based icing condition remote sensing system it is important that NASA continue to foster the development of Multi-Band Radar and Airborne Radiometry.

Multi-Band Radar holds the greatest promise of accurate measurement of LWC and indication of large drops in a scanned volume out to a reasonable range. This form of scanning system is the long term vision of ground based icing condition remote sensing. However, this form of system will require advancements in radar technology that may be 10 years in the future. Therefore the Multi-Band Radar does not warrant the primary effort of this activity, but should continue to be developed for future application.

Airborne radiometry holds the greatest promise for practical airborne remote detection capability. It holds the potential for reasonable cost, size, and weight that would allow a significant amount of the current aircraft fleet to adopt the technology. Airborne radar technology needs to overcome the requirement of large antennas and powerful transmitters before it can be seriously considered for remote detection of icing conditions. The current technology airborne radars do not have the required system accuracy that is required to detect icing at operationally realistic ranges (~20 km). A significant advancement in basic radar technology will be required before its use is practical for icing detection from airborne platforms. On the other hand, radiometry is particularly attractive for airborne use. Radiometers are by their nature field integrators (i.e. they have been shown to do well at measuring the total amount of liquid water along its beam). And aircraft icing is an integrating phenomenon (i.e. the amount of ice accreted on an airframe is proportional to the total amount of the liquid water the aircraft encounters on its flight path). If a horizontally viewing radiometer can be successfully fielded it will tell the flight crew what the exposure risk to airframe ice accretion will be along potential flight paths. And it is the knowledge of the risk of various flight path options that a flight crew requires to make good inflight icing avoidance decisions. Therefore, airborne radiometry should also continue to be developed for future application.

Recommendation Summary

A combined radiometer/radar system shows the greatest promise to provide the most valuable data to flight crews within the next 10 years. Therefore, development of this form of system should be pursued.

However, at a lower level of effort and funding, the continued development of Multi-Band radar technology and airborne radiometry is justified due to its long term potential.

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13. ABSTRACT *(Maximum 200 words)*

This report documents the NASA Glenn Research Center activities to assess and down select remote sensing technologies for the purpose of developing a system capable of measuring icing condition hazards aloft. The information generated by such a remote sensing system is intended for use by the entire aviation community, including flight crews, air traffic controllers, airline dispatchers, and aviation weather forecasters. The remote sensing system must be capable of remotely measuring temperature and liquid water content (LWC), and indicating the presence of super-cooled large droplets (SLD). Technologies examined include Profiling Microwave Radiometer, Dual-Band Radar, Multi-Band Radar, Ka-Band Radar, Polarized Ka-Band Radar, and Multiple Field of View (MFOV) Lidar. The assessment of these systems took place primarily during the Mt. Washington Icing Sensors Project (MWISP) in April 1999 and the Alliance Icing Research Study (AIRS) from November 1999 to February 2000. A discussion of the various sensing technologies is included. The result of the assessment is that no one sensing technology can satisfy all of the stated project goals. Therefore a proposed system includes radiometry and Ka-band radar. A multilevel approach is proposed to allow the future selection of the fielded system based upon required capability and available funding. The most basic level system would be the least capable and least expensive. The next level would increase capability and cost, and the highest level would be the most capable and most expensive to field. The Level 1 system would consist of a Profiling Microwave Radiometer. The Level 2 system would add a Ka-Band Radar. The Level 3 system would add polarization to the Ka-Band Radar. All levels of the system would utilize hardware that is already under development by the U.S. Government. However, to meet the needs of the aviation community, all levels of the system will require further development. In addition to the proposed system, it is also recommended that NASA continue to foster the development of Multi-Band Radar and airborne microwave radiometer technologies.

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