7.5 NOAA/ETL's POLARIZATION RADAR-MICROWAVE RADIOMETER SYSTEM FOR DETECTING IN-FLIGHT ICING CONDITIONS – PROGRESS IN THE DESIGN AND DEVELOPMENT OF GRIDS

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1. INTRODUCTION

NOAA ETL has, in partnership with the FAA, investigated the use of both passive and active remote sensors to determine the presence of icing conditions aloft. Each cycle of theoretical modeling, instrument system development, and experimental observation, refined our approach and led to the conclusion that the combination of a dual-polarized cloud radar with a microwave radiometer would provide the required measurements. Tests during the 1999 Mt. Washington Icing Sensors Project (MWISP) demonstrated the capability of ETL's dual-polarization Ka-band (8.66-mm) radar to distinguish supercooled large droplets (SLD; 50-500 microns in diameter) from clouds with non-hazardous ice particles. By measuring one parameter, a depolarization ratio (DR), the technology was shown to be capable of distinguishing among the various types of ice crystals, and to differentiate all of these from clouds of SLD. Adding a microwave radiometer (MR) to measure the column-integrated quantity of cloud liquid water (LW) helps to detect and quantify the icing hazard.

The technology has now progressed to the point where an operational system is being developed for demonstration. The final engineering design of a robust Ground-based Remote Icing Detection System (GRIDS) has been completed. Hardware and software development is now in progress.

2. THE GRIDS FINAL DESIGN

GRIDS is a combination of the world's most sensitive cloud radar, a dual channel microwave radiometer and customized algorithms, all housed in a self-contained package that only requires power and internet access. GRIDS has been designed for autonomous 24/7/365 operations.

Five existing ETL technologies provided the foundation for GRIDS: (1) the scanning K_a-band dual-polarization radar and (2) autonomous millimeter cloud radar (MMCR), (3) microwave radiometry, (4) a state-of-the-art Radar Data and Acquisition System (RADS) and lastly (5) a suite of theoretical developments to determine the optimal radar polarization state to distinguish between liquid and ice particles. To these, GRIDS adds the capability to ingest temperature profile information from either an operational model or local soundings.

***The Radar*:** The GRIDS radar provides the ability to (1) provide unambiguous profiles the detailed structure of clouds (including number of cloud layers and their boundaries); and (2) to discriminate between spherical and non-spherical particles using the DR.

Hydrometers depolarize a signal primarily according to their shape and the elevation angle χ of the antenna. The simplified concept is that ice depolarizes the signal but spherical SLD do not. Actually, SLD cause the smallest (χ-independent) DR. *The state of the transmitted polarization is key*: a circular transmitted polarization state provides superior hydrometeor differentiation. Data from MWISP and other projects, show excellent agreement between measurements and

Table 1. Typical GRIDS operating modes.

Mode	40° Slant	Vertical
Pulse rep. pd.	110 µs	71 µs
Pulse width	1.55 µs	1 µs
No. FFT points	64	256
No. spectra averaged	8522	3301
No. range gates	69	67
Unambig. range	16.49 km	10.64 km
Max. unambig. radial velocity	± 9.77 m/s	± 15.14 m/s
Radial velocity resolution	0.305 m/s	0.118 m/s
Range resolution	232.3 m	150 m
Height resolution	150 m	150 m
Dwell time	60 s	60 s
Est. sensitivity at 10 km *AGL*	-58.9 dBZ_e	-58.7 dBZ_e

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scattering theory, providing proof of concept (Matrosov et. al. 1996, 2001; Reinking et al. 1997, 2000, 2002).

A beam transmitted at a fixed χ of 40° will provide the necessary, optimal differentiating DR measurement. An optional capability to also measure both DR and hydrometeor velocity spectra (V_s) at χ = 90°, will respectively enhance specific ice type identification and may sort liquid from ice by particle fallspeed differences (Zawadski et al. 2000). GRIDS will provide a time-height profile of cloud reflectivity, DR, the icing hazard, and optionally V_s.

The time-tested K_a-band technology from the MMCR (Moran et al. 1998), provides the basic transmitter and receiver electronics, up/down converter technology for 60 Mhz - 35 Ghz, and the robust design for automated operation, calibration, diagnosis, and control.

The GRIDS 8.6-mm radar will transmit 1000 w peak power and 14.1 w average power. PIREP statistics (Schultz and Politovich 1992) indicate that ~ 90% of icing events occur at temperatures between 0 and −20°C, below 6.0 km MSL, or within 9.3 km range at χ = 40°, the fixed-beam elevation selected for GRIDS. SLD generally cause reflectivities between about +5 and −15 dBZ and are undetectable with longer wavelength radars. Essentially all clouds that create an icing hazard will have $Z_e \geq -20$ dBZ. The corresponding *cross-polar* reflectivity, Z_{cr}, is ~ −50 dBZ, so we require the GRIDS radar to gain a main-channel sensitivity of ~ −60 dBZ at 10 km AGL to determine DR of these low reflectivity clouds. The GRIDS sensitivity will be achieved with a large antenna (3 m), long dwell time (60 s) and long pulse width (1.0-1.5 μs). The design calls for 150 m vertical range resolution and 0.12 ms^{-1} vertical velocity resolution; these can be enhanced in adjusted modes. Some parameters for the 40°-slant and vertical operating modes, which optionally will be mechanically alternated in ~5 min periods, are listed in Table 1.

***The Radiometer*:** GRIDS will employ a commercially available dual-channel microwave radiometer. The MR is to be tilted to match the χ of the radar to provide continuous, independent verification of icing potential from the presence or absence of LW and the measured quantity, which can be allocated to the radar-observed cloud layer(s).

The technique is based on deriving the optical thickness of the atmosphere at two frequencies (near 24 and 31 Ghz) by measuring the corresponding radiometric brightness temperatures. It is then relatively straight forward to derive the path-integrated amounts of both water vapor and LW. Although not of direct interest for GRIDS the measurement of the total water vapor has other important applications as is discussed below.

***Temperature Ingest*:** To determine whether the droplets identified by the radar and radiometer are supercooled, an accurate estimate of the temperature must be obtained. At present, no single system can economically determine the temperature profile remotely. Thus GRIDS will rely on temperature profiles of 40- or 20-km resolution obtained from the NOAA NCEP RUC assimilation and forecast package. Data from the model will be obtained once per hour for the grid point nearest the radar. GRIDS will use the one hour forecast because practical experience dictates the 0 hr analysis cannot be obtained in a timely manner. ETL is currently running the ingest software for reliability testing and to test our fault handling capabilities.

***GRADS*:** GRIDS-RADS (GRADS) was developed to modernize the software-hardware interface of ETLs scanning K_a-band radar (NOAA-K) and the Coast Guard's iceberg detection radars (Campbell and Gibson 1997). This adaptable system will integrate the control of the instruments, external data ingest, data processing, computation, and transmission of the determined potential icing hazard indicators to users.

2.1 Development Plan

We plan to build an upgradable GRIDS this year then work towards the target GRIDS. Target GRIDS is the fully capable system. Upgradable GRIDS is the less than fully-capable interim system that will be built first with borrowed (less capable) components, to shorten the time to demonstration. As funds become available, the borrowed components will be replaced with permanent (more capable) components to achieve the target system. Table 2 summarizes the differences between the two versions of GRIDS.

Table 2 Comparison of Upgradable & Target GRIDS

Feature	**Upgradable GRIDS**	**Target GRIDS**
Transmit Power (Peak, w)	100	1000
Antenna Diameter (m)	1.8	3.0
Beam Pointing (elevation, º)	40.2	40.2, 90 (Option)
Radome	No	Yes
Icing Algorithm	Core	Refined
Autonomous Operation	No	Yes
Auto Calibration Check	No	Yes
Two Receiver Channels	No	Option
Spectral Processing	No	Option

Initial Demonstration: ETL intends to field a version of Upgradable-GRIDS during the Alliance Icing Research Study (AIRS) II project, planned for Nov'03-

Jan'04 at Mirabel Airport in Montreal Quebec. ETL will run Upgradable GRIDS at it's Erie, CO field site during a planned "pre-deployment", or instrument shakedown, associated with AIRS II during Fall'02-Winter'03.

3. ALGORITHM ENHANCEMENTS

The simplest, or core GRIDS algorithm uses four decision points based on the slant-path, fixed beam measurements of LW, Z_e, and DR plus the ingested temperature profile to determine icing potential as a function of altitude. A hazardous cloud is identified as one that exhibits measurable LW, T < 0°C, a Z_e large enough to warrant consideration (−20 dBZ, e.g.), and a DR that matches the minimum hydrometeor signature (± 2 dB), thus indicating droplets, not ice. This is a foundation for a more sophisticated algorithm.

The vertical boundaries of all cloud layers will be identified. The MR liquid *quantity* can be assigned to liquid (minimum-DR) layers to quantitatively assess icing severity. A scaled, color-coded icing hazard warning will be added. Detection and use of the uniquely high DR of any bright band will confirm altitudes where the clouds are supercooled, and that precipitation is occurring. The vertical mode will detect droplet-generating embedded convection. Appropriate combinations of measured parameters will provide data quality control.

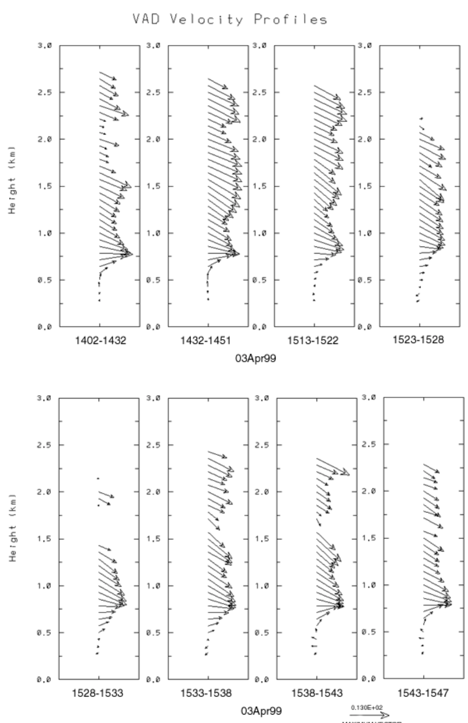

Figure 1 Sequence of wind profiles that induced gravity shear waves at the level of maximum shears near 0.8 km AGL. 3 April 1999.

3.1 Processes Affecting SLD Formation

Identification of the types of ice implies much about cloud processes that determine the formation, concentration and size of supercooled droplets. For example, the presence of ice can govern whether supercooled droplets can form. Furthermore the size, type and concentration of ice determines whether existing droplets will be maintained at small, non-hazardous sizes by the ice particles competing for the water or how fast the existing droplets will grow or be consumed.

There is increasing evidence that cloud droplet growth by collision-coalescence (SLD production) is enhanced by wind shear and turbulence (Pobanz et al 1994, Shaw et al. 1998, Vallencourt and Yau 2000, Shaw and Oncley 2001, Reinking et al. 2002), and new theoretical calculations by R. Hill, ETL). GRIDS will measure the variance of the Doppler velocity (σ_v^2, m^2s^{-2}) along the fixed beam, providing a measure of wind shear and turbulence.

For example, in an MWISP case, strong wind shears (Fig. 1) induced gravity waves. The radar-measured maximum σ_v^2 occurred in the altitude band of maximum, most hazardous shears (Fig. 2), and droplet sizes developed their maxima in specifically the same altitude band (Reinking et al, 2002). The velocity variance in embedded convection in another MWISP case was of approximately of the same magnitude at that in the gravity-wave shear zone, and droplets that had grown to SLD sizes were indicated in the tops of the cells by polarization measurements. The GRIDS measurement of σ_v^2 will indicate altitudes of turbulence, which when calibrated will in itself a benefit to aviation, and the σ_v^2, as an indicator of enhanced droplet growth, will strengthen the GRIDS icing algorithms.

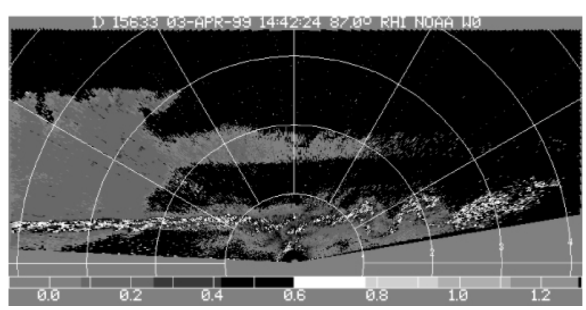

Figure 2 Velocity variance with maxima in gravity-shear waves near 0.8 km AGL corresponding to Fig. 1. measured in RHI scan with NOAA's K_a-band radar.

4. SUMMARY AND CONCLUSIONS

GRIDS/FIRST will integrate a wealth of existing hardware and software technologies into the most sensitive cloud radar ever built. The vertical profile of the in-flight icing threat will be derived from the depolarization ratio and the quantity of supercooled liquid, supported by other radar parameters. Plans are that the pilot demonstration unit will be deployed to the holding pattern of a major icing-prone airport and operate in a unattended mode. Products of the continuous stream of microphysical and additional cloud and atmospheric information from GRIDS-FIRST will warn of icing hazards.

A comprehensive document describing the GRIDS final design is available upon request from the authors.

Additional Applications: In addition to it's core duty for in-flight icing, GRIDS has numerous other applications . In the broader realm of `aviation weather', GRIDS will provide detailed information on multiple ceilings and visibility, in-cloud turbulence and help to validate icing models. In other weather applications GRIDS can detect freezing drizzle (highway safety) and monitor rain in shallow, near-surface clouds (often missed by NEXRAD). Data from GRIDS can provide verification for numerical forecast models as well as cloud fields for assimilation in numerical weather models. Continuous (i.e. 24/7/365) profiling with GRIDS will provide valuable data for climate and cloud process studies including climatologies of the vertical structure of cloud properties and the role of clouds in the vertical partitioning of water substance and radiant energy. Lastly, GRIDS will provide valuable data to validate, calibrate and extrapolate satellite cloud observations and to clarify the impact of the vertical dimension on passive satellite cloud retrievals.

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5. REFERENCES

Campbell, W.C., and J.S. Gibson, 1997: A programmable real-time data processing and display system for the NOAA/ETL Doppler radars. *Preprints, 28th Conf. Radar Met.,* Austin, TX. Amer. Met. Soc.,178-179.

Hogg, D.C., F.O. Guiraud, J.B. Snider, M.T. Decker, and E. R. Westwater, 1983: A steerable dual-channel microwave radiometer for measurement of water vapor and liquid in the troposphere. *J. Cli. Appl. Meteorol., 22,* 789-806.

Matrosov, S.Y., R.F. Reinking, R.A. Kropfli, B.E. Martner, and B.W. Bartram, 1996: Estimation of ice hydrometeor types and shapes from radar polarization measurements. *J. Atmos. & Ocean. Tech.,* **13,** 85-96.

Matrosov, S.Y., R. F. Reinking, R. A. Kropfli, B. E. Martner, and B. W. Bartram, 2001: The use of radar depolarization ratios for estimating shapes of ice hydrometeors. *J. Appl. Met.,* **40**, 479-490.

Moran, K.P., B.E. Martner, M.J.Post, R.A. Kropfli, D.C. Welsh, and K.B. Widener, 1998: An unattended cloud-profiling radar for use in climate research. *Bull. Amer. Met. Soc.,* **79,** 443-455.

Pobanz, B.M., J.D. Marwitz, and M.K. Politovich, 1994: Conditions associated with large-drop regions, *J. Appl. Met.* **33,** 1366-1372.

Reinking, R.F., D.L. Korn, A.S. Frisch, B.W. Orr, L.R. Bissonnette, and G. Roy, 2002: Radar observations of effects of mountain blocking on traveling gravity shear waves and associated clouds. *Boundary-Layer Met.* (submitted).

Reinking, R. F., S.Y. Matrosov, B.E. Martner, and R.A. Kropfli, 1997: Dual-polarization radar to identify drizzle, with applications to aircraft icing avoidance. *J. Aircraft*. **34,** 778-784.

Reinking, R.F., S.Y. Matrosov, R.T Bruintjes, and B.E. Martner, 2000: Verified detection of supercooled large droplets with dual-polarized millimeter-wave radar. *9th Conf. Aviation, Range and Aerospace Met.,* Orlando, Fl. Amer. Met. Soc., Boston. 537-542.

Reinking, R.F., S.Y. Matrosov, R.A. Kropfli, and B.W. Bartram, 2001: Evaluation of a 45°-slant quasi-linear radar polarization state for distinguishing drizzle droplets, pristine ice crystals, and less regular ice particles. *J. Atmos. & Ocean.. Tech...,* **19,** 296-321.

Riley, J., and B. Horn, 1996: Plenary sessions. Proc. FAA Intn'l. Conf. Aircraft Inflight icing. DOT/FAA/AR-96/81, I, 263 pp. (Available from NTIS, Springfield VA 22161.)

Schultz, P., and M.K. Politovich, 1992:Toward the improvement of aircraft-icing forecasts for the continental United States. *Wea. and Forecasting,* **7,** 491-500.

Shaw, R.A., W. C. Reade, L.R. Collins, and J. Verlinde, 1998: Preferential concentration of cloud droplets by turbulence: Effects on early evolution of cumulus cloud droplet spectra. *J. Atmos. Sci.,* **55,** 1965-1976.

Vaillancourt, P.A., and M.K. Yau, 2000: Review of particle-turbulence interactions and consequences for cloud physics. *Bul. Amer. Met. Soc.,* **81,** 285-298.

Zawadski, I., W. Szyrmer, and S. Laroche, 2000: Diagnostic of supercooled clouds from single-Doppler observations in regions of radar-detectable snow. *J. Appl. Met.,* **39,** 1041-1058.