DEVELOPMENT OF DUAL POLARIZATION AVIATION WEATHER PRODUCTS FOR THE FAA*

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1. INTRODUCTION

In the United States, the WSR-88D (NEXRAD) Doppler weather radar network will be upgraded with a dual polarization capability (Istok *et al.*, 2009) beginning in late 2010. This will allow for type characterization of bulk scatterers (hydrometeor classification) in addition to the standard radar moments. Knowing which scatterers dominate a radar return offers physical insight into underlying atmospheric processes. The dual polarization NEXRAD will be fielded with a hydrometeor classifier algorithm (Park *et al.*, 2009), known as HCA. It was developed primarily to improve radar-based quantitative precipitation estimates. Classification of both meteorological and non-meteorological (birds, insects, ground clutter) scatterers will be possible.

Many Federal Aviation Administration (FAA) weather systems use products created from NEXRAD. For the past nine years, the FAA has tasked MIT Lincoln Laboratory (LL) with providing benefit from NEXRAD to the FAA weather systems through the development and maintenance of weather radar algorithm products (Smalley *et al.*, 2002, 2003, 2005, 2008). Those products are Data Quality Assurance (DQA), High Resolution VIL (HRVIL), High Resolution Enhanced Echo Tops (HREET), and the Machine Intelligent Gust Front Algorithm (MIGFA). These products are used by the FAA's Corridor Integrated Weather System (CIWS), the Integrated Terminal Weather System (ITWS), and the Weather and Radar Processor (WARP).

The FAA now has tasked LL with the development, implementation, and integration of dual polarization weather radar products for use in their weather systems and decision support systems. Based on a analysis of dual polarization weather radar capabilities (Smalley, 2007), two areas were identified for development: (a) improvements to existing NEXRAD products (data quality and mitigation of terrain blockage) and (b) identification of aviation related icing and hail hazards. The ability to better identify the icing hazard is of particular benefit to the FAA. Many unfortunate icing-related aviation tragedies have occurred, especially with commuter and general aviation craft. This paper will outline the progress to date and the planned timeline for the development of dual polarization products for aviation.

2. DUAL POLARIZATION PRODUCT DEVELOPMENT APPROACH

The development, implementation, and integration of the dual polarization (hereafter pol) algorithm products will occur over a five year period beginning in September 2008. LL will execute the first two stages while the NEXRAD Radar Operations Center (ROC) will handle integration into the radar network. Once in the NEXRAD network, FAA weather systems will have access to the products.

Dual pol products are planned from the new algorithms Icing Hazard Level (IHL) and Hail Hazard Layer (HHL). They will be discussed further in Section 3. Existing NEXRAD algorithms will be augmented by dual pol data as well. DQA will be updated to include the clutter and biologicals classes from the HCA. DQA provides edited reflectivity data to the FAA's HRVIL and HREET. HRVIL will take advantage of dual pol data by using specific differential phase shift, (K_{DP}) to mitigate signal loss from partial beam blockage.

Our development plan addresses major areas necessary for creation of robust dual pol weather products. The scientific foundation of each algorithm must be based on understanding physical processes within the atmosphere as sensed by dual polarization radar. LL has partnered with dual pol subject matter experts from the National Center for Atmospheric

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Research (NCAR) and the National Severe Storms Laboratory (NSSL) to bolster the scientific basis of the algorithms. These experts have direct experience with hydrometeor classification and dual pol parameters regarding all the goals of the planned algorithms. A key consideration is the appropriateness of each class for aviation product needs.

Usable NEXRAD dual pol data is a necessity to test the developing algorithms. LL has identified Valparaiso University's (VU) C-band dual polarization weather radar in northern Indiana as a proxy data source. LL has partnered with VU for a three year study in support of IHL.
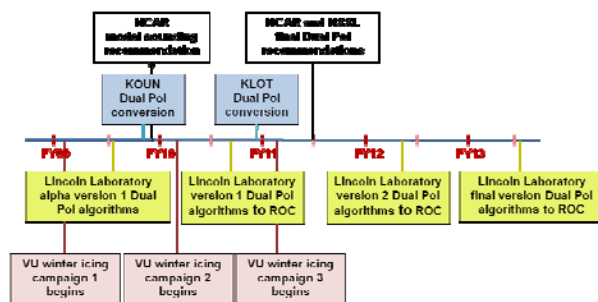

Figure 1. The Dual Pol Product Timeline is described in detail in the text.

Figure 1 shows the FAA/LL five year timeline for dual polarization weather radar products beginning in fiscal year 2009 (September 2008). The timeline depicts major milestones of the development plan including partner institutions. LL plans to deliver a first version of algorithms to the ROC in the summer of 2010. This is preceded by alpha versions that will be discussed in the coming sections. Second and third (final) versions are also planned. Their content will be discussed further in Section 3.

Three winter icing campaigns are planned with VU. All of these campaigns are supported at VU by meteorology department professors, staff, and student interns. The dual pol data are bolstered by on-demand radiosonde launches. The first campaign (2008-09) featured a couple of notable events. Using lessons learned, VU and LL plan that the second icing campaign in autumn/winter 2009-10 will involve some surface field verification. The third campaign in 2010-11 should occur with the nearby Chicago NEXRAD (KLOT) operating in dual pol mode allowing for comparison. KLOT will be one of the first NEXRAD's to be upgraded. Currently, the KOUN research NEXRAD in Norman, OK has been upgraded. It is anticipated

that this radar will provide some data to algorithm developers later in 2009.

Figure 2 lists contributions from the partner institutions driving dual pol algorithm development. NCAR's expertise in winter weather hydrometeor classification and in-flight icing is being leveraged with the primary focus on the IHL algorithm. NCAR has deployed operationally the Current Icing Potential (CIP) aviation icing product (Bernstein *et al.*, 2005). This provides hourly icing potential and supercooled liquid drop (SLD) potential on flight levels up to about 30 kft. It uses multiple sensors (radar included) and meteorological model data to determine the icing potential. NCAR will develop an IHL from their perspective that may function wholly or partially in a NEXRAD environment where radar volume updates range from about every four minutes to ten minutes. They will also contribute expertise on the prospective components of that IHL.
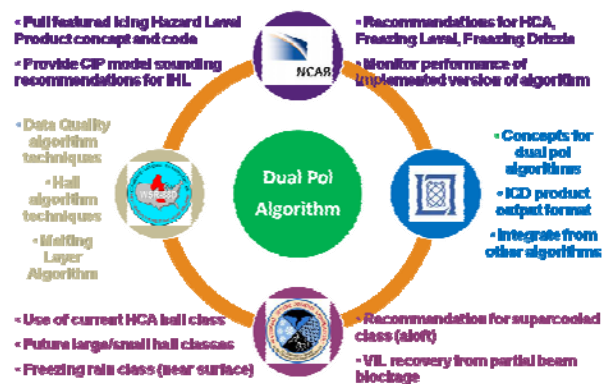

Figure 2. The dual pol product development utilizes contributions from partner institutions the highlights of which are shown here.

NSSL expertise in radar measurements, hydrometeor classification, and severe storms will be incorporated. Contributions will include recommendations on the use of K_{DP} for mitigation of partial terrain blockage, development of a small/large hail class distinction to replace the current rain/hail class in HCA, and development of a freezing rain class for surface operations.

LL's role began with the overall vision and plan of deriving benefit from dual pol weather radar for FAA weather system needs. LL will use its meteorological algorithm expertise to blend its own dual pol algorithm techniques with existing approaches used in NEXRAD algorithms and with content from the dual pol partners. Working with the ROC, LL will define the format of the IHL and

HHL products and support their use in the FAA weather systems.

3. NEW DUAL POL PRODUCTS IN DEVELOPMENT

This section introduces the Icing Hazard Level (IHL) and Hail Hazard Layer (HHL) algorithms. They both rely on the current NEXRAD HCA classes initially. The concept is that 3D regions of a given hazard will be identified within each radar volume. The 3D extent (altitude top and bottom) of the hazard will be provided on the same azimuth-range (azran) grid as used with HRVIL and HREET. That is, a 1 km x 1° grid ranging out to 300 km.

Figure 3 provides a high level schematic of the approach taken for initial versions of IHL and HHL. Each algorithm identifies 3D regions for the class of interest. The class density threshold required for a region to be considered a hazard is still to be determined. Additional information such as from actual or model thermodynamic vertical soundings may also be used.
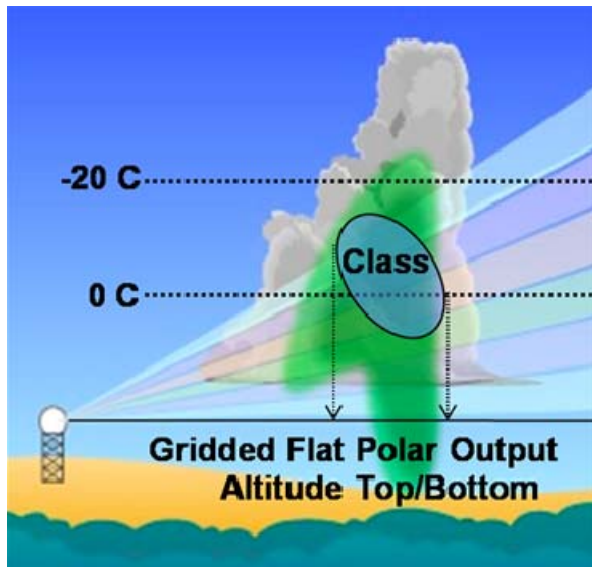

Figure 3. A general schematic is shown of the version 1 product from an Icing Hazard Level or Hail Hazard Layer algorithm.

Future versions will include more robust techniques developed by the dual pol partners. For HHL, this may mean new hail classifications (large vs. small). For IHL, perhaps a specific classifier will be used in conjunction with HCA. Spatial continuity of classes may be used to refine hazard regions. Enhancements that provide confidence and severity fields will also be evaluated.

a. Hydrometeor Classification

Hydrometeor classification is central to the success of all the algorithm initiatives. Graupel and ice crystal classes are being considered for IHL. The rain/hail class obviously applies to HHL. The clutter and biologicals classes apply to concepts of data quality. Dual-pol algorithm development has primarily been done using data from Oklahoma. When the dual pol NEXRAD is fielded, seasonal and/or regional stressing of some classes is possible. Any stressing behavior will be important to account for while developing quality version 2 and final dual pol algorithm products.

Figure 4 shows the LL analysis of HCA classes as they pertain to potential use in IHL. HCA functions in conjunction with the Melting Layer Detection Algorithm (MLDA). MLDA is used to segregate HCA classes by altitude depending on the amount of intersection with the melting layer (left column). Green indicates the HCA-MLDA class possibilities. For instance, dry snow (DS) is possible from above to within the melting layer.

Categories / Thresholds		No Echo / NE	Dry Snow / DS	Wet Snow / WS	Ice Crystals / IC	Graupel / GR	Big Drops / BD	Light/Mod Rain / RA	Heavy Rain / HR	Rain and Hail / RH	Ground Clutter/AP / GC	Biological / BI	Unknown / UK
Melting Layer	Above				Icing	Icing	Icing	Icing	Icing	Icing			
	Mostly Above				Icing	Icing	Icing	Icing	Icing	Icing			
	Within				Icing		Conditional Icing	Conditional Icing	Conditional Icing	Icing			
	Mostly Below												
	Below												

	NEXRAD HCA ALGORITHM	ICING HAZARD
Icing / Conditional Icing	Current HCA combination	None
		Icing Hazard
		Potential Hazard w/ Sounding Info
Icing / Conditional Icing	Not an allowed HCA combination	None
		Icing Hazard
		Potential Hazard w/ Sounding Info

Figure 4. The table shows the available classifications from the NEXRAD Hydrometeor Classification Algorithm sorted by vertical relation to the melting layer. Discussion is provided in the text.

An important consideration for IHL is the occurrence of liquid water at altitudes above the melting layer (i.e., supercooled liquid water). With HCA, virtually all liquid water classes (rain) are not allowed in or above the melting layer. Supercooled liquid water spanning the size transition from cloud droplet to drizzle drop certainly poses an aviation hazard. The existence of that size transition zone together with some of

the HCA denied rain classes is possible. So there is merit in exploring the potential in allowing these denied classes by altitude in conjunction with vertical soundings. This merit is indicated by the Icing or Conditional Icing labels in Figure 4.

As noted earlier, the partners are focusing on this aspect. Potential new classes may arise from that. It may be necessary that classes like these are not derived from radar data solely. Within the NEXRAD algorithm processing environment (ORPG), currently only limited access to additional data is possible (RUC model temperature and RH soundings) through AWIPS. The case may need to be made for access to additional sounding or high resolution model fields or surface data.

b. Icing Hazard Level (IHL)

The alpha version of IHL has been developed using the graupel and ice crystal classes as definers of the 3D hazard spaces. Graupel is rimed aggregates. The riming occurs via the presence of supercooled water. Thus, graupel serves as an indirect link to the true hazard. It is probable that there is an ephemeral area of supercooled water outside the bounds of the identified graupel class locations where riming has begun but not to the point where the region is declared graupel.

Ice crystals may also be a secondary ice hazard. They have been linked to engine flameouts and stalls and a working group exists to study the phenomenon. For this IHL, both classes are used but it has not been determined how this will be handled in the official version 1 IHL.

Figure 5 shows the HCA depiction of the 0.5^o tilt angle elevation from the KOUN research dual pol radar in Norman, OK from 11 February 2009 at 00:30 UTC. The green rain class extends from the radar (center of image) to about 100 km range which is where the beam's altitude reaches the estimated freezing level. This graphically shows the affect of the MLDA. The blue classes are snow at higher altitude (farther range). For this IHL, the pink graupel and orange ice crystal classes are of interest. There are similar depictions of the HCA for each tilt angle elevation of the radar volume.
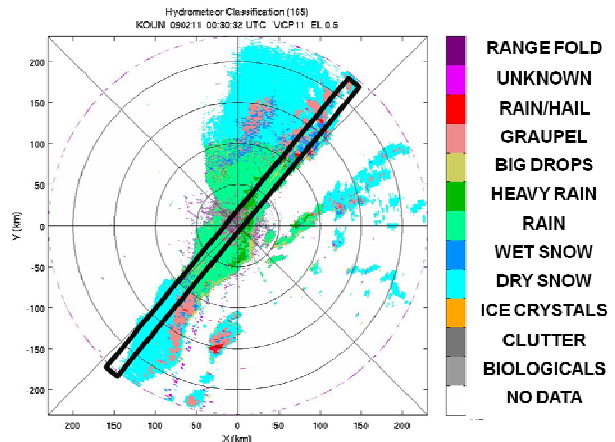

Figure 5. A base (0.5^o) tilt of radar data classified by the HCA is depicted. The elongated rectangle refers to Figure 6.
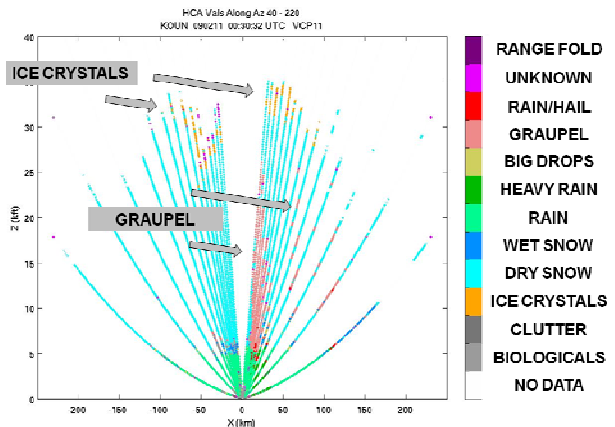

Figure 6. A vertical profile of HCA was created along the azimuth pair noted by the elongated rectangle in Figure 5.

The black, elongated rectangle in Figure 5 represents an azimuth pair (40˚-220˚) that is shown in Figure 6. All tilt angle elevations of the HCA for the radar volume for the pair are shown with the same color classifications. The vertical extent of the beams is exaggerated compared to the horizontal extent so each beam width shown is not realistic.

Graupel and ice crystal classes are highlighted. Note the differing coverage density for each class in their regions of concentration. There are another 179 azimuth pairings that taken as a whole are used to assemble 3D hazard spaces within the radar volume. Each point of the aforementioned output grid would include a top and bottom altitude to the hazard space to define its extent.

FAA weather systems do not typically use the NEXRAD products in their native high resolutions. For instance, in CIWS both the HRVIL and HREET are remapped to the CIWS 1 km grid. The products are also tailored for appropriate use by aviation personnel. Thus, HRVIL is equated to the traditional VIP levels.

Figure 7 suggests a notional use for the two class IHL. An 18 kft threshold is used corresponding to differing tactics when dealing with icing above or below that altitude (NASA on-line Aircraft Icing Training course, 2008). Thus, the high resolution IHL graupel and ice crystal hazard spaces are regrouped to upper (18 kft or above) or lower (below 18 kft) types. Importantly, the graupel class (implied supercooled water) is given priority over the ice crystal class in situations where both exist in the column over an output grid point. The white elongated rectangle corresponds to the azimuth pair noted in Figures 5 and 6. There is not an exact match between the figures. That is expected as Figures 5 and 6 are the high resolution data while Figure 7 represents a notional approach to an IHL product that includes noise dampening and smoothing.
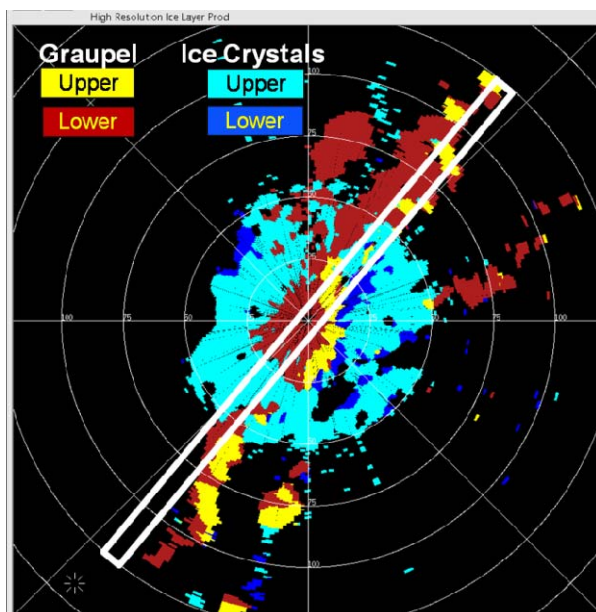

Figure 7. One notion of IHL use for an FAA weather system is shown. Upper and lower refer to an 18 kft altitude threshold.

c. Hail Hazard Layer (HHL)

The Hail Hazard Layer (HHL) algorithm product is assembled in much the same manner as described for IHL but using the HCA rain/hail class. Figure 8 shows the current NEXRAD hail algorithm logic and how it might compare to a version 1 HHL. The current hail algorithm examines already-identified storm cells for the probability of hail or severe hail. An important aspect of that is finding high reflectivity cores above the 0° C isotherm height. HHL simply relies on the noted HCA class. Heinselman and Ryzhkov (2006) showed using a method like HHL reduces false alarm rates when compared to the current hail product thus significantly improving the overall Critical Success Index.
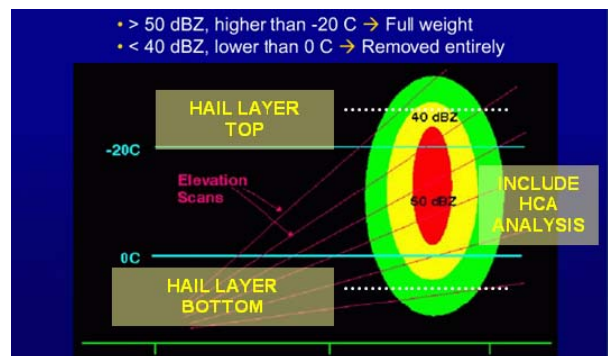

Figure 8. HHL concept as it relates to the current NEXRAD hail algorithm.

HHL will provide the vertical extent profile of a hail hazard not presently possible with the current hail product. HHL is not limited to a set of storm cells identified by the NEXRAD storm cell tracking algorithm. It may also find hail in atypical situations such as in a displaced region from the updraft core of low precipitation type supercells. It is possible incipient hail aloft will be found where reflectivity cores have not met traditional criteria. This could be useful as a harbinger of a stronger cell in the development stage and have some tactical value.

Figure 9 shows results of HHL and the current hail algorithm for a KOUN (Norman, OK) research dual pol case from 10 February 2009 at 22:02 UTC. The left panel shows a mid-level HCA tilt elevation angle depiction with the red rain/hail class of interest. The right panel shows the top altitude (in kft) that HHL found hail for each output grid point. Superimposed on both is the legacy hail product shown as green triangles. Large triangles represent greater hail likelihood. Filled triangles represent greater severe hail likelihood. The triangles are placed slightly lower and to the right of the actual hail location.
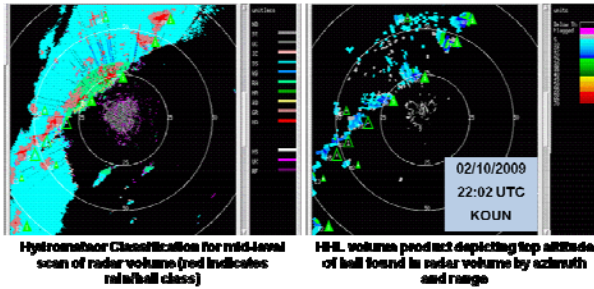
Figure 9. Current NEXRAD hail algorithm product compared with HCA classes (left) and HHL hail top altitude (right).

In many instances, the two algorithm approaches both find hail. This often agrees with the mid-tilt HCA rain/hail class depiction. At spots where the HHL hail top altitudes are not in agreement with the HCA classification shown, the hail top altitude is from a tilt elevation angle above or below the one shown for HCA. The HHL seemingly shows more areas of hail than the current hail algorithm. The products suggest there may be a complimentary aspect to their use. NSSL will be working towards a large/small hail classification for HCA. Thus, this first version approach should evolve over the development cycle.

4. UPGRADES TO EXISTING PRODUCTS

Two existing algorithms currently are to be upgraded with dual pol based techniques. The DQA provides edited reflectivity data for processing by HRVIL and HREET. DQA utilizes the three radar moments in modules that edit out contaminants such as AP clutter, constant power artifacts, solar strobes, and spikes/speckle. Without these the quality of the HRVIL and HREET products used by FAA weather systems would be significantly diminished.

The goal of a DQA dual pol upgrade is to further improve the level of data quality editing. The ultimate goal would be that HCA non-meteorological classes would suffice alone in a DQA that is improved over current standards. In particular, removal of summertime overnight bug bloom clutter (biologicals class?) would be an added improvement. LL has a functional version of DQA based on only HCA processing. In testing with research level dual pol data, the results are not satisfying and quality is diminished. Speckle is not handled well. There also is not enough data to determine the robustness of the classes used for data quality in the wide variety of challenges

NEXRAD can provide. The likelihood is there will be a hybrid approach to DQA using current techniques augmented by HCA classes.

The HRVIL product would benefit from improved DQA. Another problem, partial beam blockage by terrain, may be mitigated by using specific differential phase shift (K_{DP}) to fill in for weakened or lost VIL. In the western continental US, the radar density is reduced thereby limiting the power of mosaic techniques in CIWS for instance. Partial beam blockage by terrain further challenges the coherent national treatment of NEXRAD products in mosaics.

K_{DP} will be used to aid in a similar mitigation for NEXRAD quantitative precipitation estimates. LL has a functional version of HRVIL based solely on the conversion of K_{DP} to VIL. As compared to traditional HRVIL, the relative magnitude of VIL is maintained with the dual pol version but is reduced. LL is studying that reduction as well as a variety of approaches for use (stand-alone, hybrid) within a NEXRAD processing environment. In conjunction with NSSL, LL will determine limitations on the applicability of the approach (level of blockage) and sensitivity to factors such as precipitation intensity (one or multiple conversions).

5. SUMMARY

For the FAA, LL has developed a five year development plan to create new or augment existing NEXRAD products for beneficial use in FAA weather systems. The first year of effort has seen development of alpha version 1 algorithms for Icing Hazard Level (IHL), Hail Hazard Layer (HHL), dual pol Data Quality Assurance (DQA), and partial beam blockage mitigated high resolution VIL (HRVIL). This paper discusses some early results.

The development plan was described. A timeline is established and partnerships are formed. Those partners, NCAR, NSSL, and Valparaiso University, are providing critical scientific developments and proxy data towards the development of the dual pol algorithms. Many challenges remain regarding the algorithms and their initial fielding. Ambitious content from all institutions is anticipated and necessary for success.

In late 2010, the NEXRAD network will begin transition to dual pol capability. About two years

later, the version 1 dual pol algorithms developed for FAA weather systems should begin to flow within the network. At that point, the FAA should begin to receive its investment return in the NEXRAD dual pol upgrade and importantly improve its depiction of weather and its hazards for aviation purposes.

6. REFERENCES

"Aircraft icing training", online course, NASA Glen Research Center Icing Branch, October 23, 2008. http://aircrafticing.grc.nasa.gov/courses_inflight.html

Bernstein, Ben C., McDonough, F., Politovich, M. A., Brown, B. G., Ratvasky, T. P., Miller, D. R., Wolff, Cory A., and Cunning, G., 2005: Current Icing Potential: Algorithm Description and Comparison with Aircraft Observations. Journal of Applied Meteorology.

Heinselman, Pamela L., and Ryzhkov, A.V., 2006: Validation of Polarimetric Hail Detection. Weather and Forecasting.

Istok, Michael J., Fresch, M., Jing, Z., Smith, S., Murnan, R., Ryzhkov, A., Krause, J., Jain, M., Schlatter, P., Ferree, J., Klein, B. R., Stein III, D., Cate, G., and Saffle, R. E., 2009: WSR-88D Dual Polarization Initial Operational Capabilities. 25th Conference on Interactive Info Processing Systems in Meteorology, Oceanography and Hydrology (IIPS), Phoenix, AZ, Amer. Meteor. Soc.

Park, HyangSuk, Ryzhkov, A. V., Zrnic, D. S., and Kyung-Eak Kim, The Hydrometeor Classification Algorithm for the Polarimetric WSR-88D: Description and Application to an MCS, 2009. Weather and Forecasting.

Smalley, David. J., Mann, E. B., Ivaldi, C. F., and Bennett, B. J., Improving Weather Radar Data Quality for Aviation Weather Needs, 2008: 13th Conference on Aviation, Range, and Aerospace Meteorology (ARAM), New Orleans, LA, Amer. Meteor. Soc.

Smalley, David J., 2007: Evaluation of potential NEXRAD dual polarization products. Project Report ATC-336. MIT Lincoln Laboratory, 23 pp.

Smalley, David. J., Bennett, B. J., and Frankel, R. S., MIGFA: The Machine Intelligent Gust Front Algorithm for NEXRAD, 2005: 32nd Conference on Radar Meteorology, Albuquerque, NM, Amer. Meteor. Soc.

Smalley, David. J., Bennett, B. J., and Pawlak, M. L., New Products for the NEXRAD ORPG to Support FAA Critical Systems, 2003: 19th Conference on Interactive Info Processing Systems in Meteorology, Oceanography and Hydrology (IIPS), Long Beach, CA, Amer. Meteor. Soc.

Smalley, David. J., and Bennett, B. J., Using ORPG to Enhance NEXRAD Products to Support FAA Critical Systems, 2002: 10th Conference on Aviation, Range, and Aerospace Meteorology (ARAM), Portland, OR, Amer. Meteor. Soc.