Assessment of Dual-Polarized Radar Coverage in the Terminal Airspaces of Commercial Airports

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ABSTRACT

The advent of dual-polarization in the WSR-88D radar network allows for the development of new forms of artificial intelligence to detect various hazards that may affect aircraft as they travel into and out of terminal air spaces. The efficacy of these algorithms for individual airports is limited by the distance between the airport and the nearest WSR-88D radar. In this study, an assessment of the radar coverage for all commercial airports with more than 10 000 enplanements per year is performed. Three deficiencies are identified and discussed. These are: beam broadening and overshooting, cone-of-silence issues, and beam blockage. Airports that suffer from these issues are identified. Among the airports most vulnerable to beam broadening and overshooting are several core 30 airports. Some core 30 airports may also suffer from cone-of-silence issues for certain VCP modes. Beam blockage affects most airports in the western United States. The effects of these problems on interpretation of winter weather and hydrometeor habit, in particular, are also investigated. Beam broadening and overshooting are especially problematic for resolving important vertical gradients in the dual-polarized radar observations that allow the user to rightly infer the hydrometeor habit. Of lesser importance are cone-of-silence issues. This appears to be mainly a problem when there exists a gradient in hydrometeor habit over the terminal air space.

1. INTRODUCTION

Weather accounts for approximately 29% of all aircraft accidents. Causes include adverse winds, reduced visibilities, low ceilings, turbulence, engine flameout from high-density ice crystals, thunderstorms, mountain obscurations, and icing (NTSB). With the exception of high-density ice crystals, these weather patterns are most likely to occur at lower altitudes, below the typical cruising altitudes of commercial aircraft and, therefore, are most likely to impact an aircraft as it is ascending or descending into and out of a terminal air space.

Radar observations afford the most spatially and temporally resolute observations of the weather in and above terminal air spaces. An assessment of the radar coverage for the 30 most heavily-trafficked airports was performed by Cho (2010). This study considered the total possible coverage by all radars that may sample the terminal air spaces including the Airport Surveillance Radar-9 (ARSR-9), Airport Surveillance Radar-11 (ARSR-11), Terminal Doppler Weather Radars, and the Weather Surveillance Radars, 1988 Doppler (WSR-88Ds). Specific recommendations were made to enhance coverage at certain airports namely to mitigate terrain-blockage effects.

Since the Cho (2010) report was published, the WSR-88D radars were upgraded to have dual-polarized capability. In the wake of that upgrade, several radar algorithms that make use of dual-polarized observations are being or have been developed to better detect the types of threats identified by the NTSB as the primary causes of weather-related accidents (e.g., Ikeda et al. 2008; Plummer et al. 2009; Snyder et al. 2015; Williams

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et al. 2015; Mahale et al. 2016; Williams and Meymaris 2016). However, the extent to which these algorithms are beneficial in terminal airspaces is unknown. This, of course, varies by the distance between an airport and the nearest radar with dual-polarization capabilities. As the distance between the two increases, beam broadening and overshooting of the lowest radar tilt become more problematic and may limit the effectiveness of algorithm performance. This was demonstrated in Snyder et al. (2015) who showed that the vertical structure of convective signatures (namely Zdr columns) is significantly degraded by both effects as the distance between the radar and the signature is increased. Ryzhkov et al. (2006) demonstrated how beam broadening affects interpretation of the melting layer. Again, as the distance from the radar is increased, the feature becomes increasingly smeared and eventually, undetectable.

Cone-of-silence issues may also affect whether the hazard is even sampled. The formal literature primarily highlights this effect for convective storms that pass directly over a radar (e.g. Mahale et al. 2016). Less, if any, attention has been given to the potential problems encountered for winter storms. Recent work demonstrates the importance of vertical profiles of the radar moments in diagnosing the hydrometeor habit (Ryzhkov et al. 2016). Many forecast offices opt to operate radars in Volume Coverage Pattern (VCP) modes 31 or 32 for frozen/freezing precipitation. These modes have a maximum tilt of 4.5º. Offices now also have the ability to use adaptive volume scanning which terminate the VCP at lower tilts if certain criteria aren't met. In either case, the cones-of-silence are larger than what would otherwise be observed and this may affect interpretation of winter precipitation habit.

The goal of this study is two-fold. First, an evaluation of the radar coverage in the terminal airspace for all commercial airports with more than 10 000 enplanements per year is performed. This is done for all radars with coverage over each airport and all possible VCP modes. Second, a case study analysis for select airports and select weather profiles is performed to gauge the effects of beam broadening, overshooting, and cone-of-silence issues on the interpretation of the radar profiles.

This paper is organized as follows. In Section 2, the assessment of radar coverage is discussed. In Section 3, meteorological implications of beam broadening and overshooting at select airports will be presented. Concluding thoughts are provided in Section 4.

2. DUAL-POLARIZED RADAR COVERAGE IN TERMINAL AREAS

For this project, the terminal airspace is defined according to the Terminal-Area Icing Weather Information for NextGen (TAIWIN) initiative. Namely, it is defined as extending in the horizontal 60 nmi and in the vertical, up to 10 kft. For our assessment, only radars within 300 km of each airport will be considered. The reason for this is to be consistent with the National Weather Service's operational mosaicking software Multi-Radar/Multi-Sensor (MRMS) which discards data beyond 300 km from radar. This is done to reduce error from beam broadening and overshooting. Several of the locations considered also have Terminal Weather Doppler Radars, but only dual-polarized radars are included since the intent herein is to assess the viability of new technology that makes use of dual-polarized data. The airports considered in this assessment are all commercial airports that have at least 10 000 enplanements yearly and that are in the contiguous United States (CONUS). Non-CONUS locations are not considered due to limited radar coverage. The above assessment is performed for all planned Volume-Coverage Pattern (VCP) modes for fall 2018 and forward. These are VCPs 12, 31, 32, 35, and 215. Note that VCPs 31 and 32 have the same tilts and, therefore, are treated as the same in this study. More information on these patterns and the tilts included in each can be found at (ROC 2016).

Four different potential deficiencies of radar coverage in the various terminal areas are identified. These are: Limited nearby coverage, beam blockage by terrain or other ground-based features, cone of silence issues, and limited upstream coverage.

2.1 *Limited nearby coverage*

There are only 142 NEXRAD radars across the CONUS, leading to limited coverage for numerous airports. An example of limited nearby coverage is shown for Charlotte Airport (KCLT) along a 60-nmi transect oriented southwest to northeast and centered at the airport for VCP 31/31 (Fig. 1). The radar in Greer, South Carolina (KGSP) is the closest radar to KCLT with a distance of 76 miles. Along this particular transect, the beam depth ranges from 4265 to 9547 ft. Previous work demonstrates that melting layers can be shallower than this (Boodoo et al. 2010; Ryzhkov et al. 2016). Similar degrees of beam broadening are observed for other airports (Table 1). Among these are four airports that are considered part of the Federal Aviation Administrations (FAAs) core 30 airports.

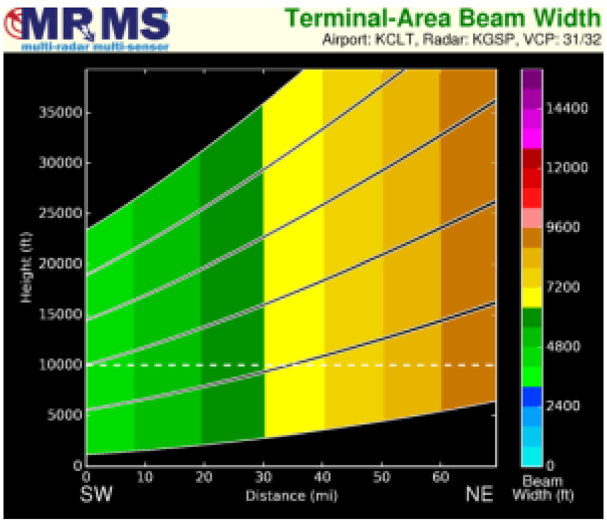

FIG. 1: Radar coverage for Charlotte Airport (KCLT). Dashed line represents top of terminal airspace. Beam width of KCLT along transect SW-NE ranges from 4,000 ft – 8,800 ft.

2.2 *Beam blockage*

Beam blockage occurs when the radar beam intersects with terrain, trees, water towers, or other features that partially or completely block the beam. An example of beam blockage is shown for Asheville Airport (KAVL) along a northwest-to-southeast transect centered over the airport for VCP 31/32 (Fig. 2a). Between 40 and 55 miles along the transect, the lowest tilt is blocked up to 68% of the full beam depth. An even more pronounced example is Aspen Airport (KASE; Fig. 2b). This airport has complete or nearly complete beam blockage along most of the transect shown.

Table 1: Airports containing limited radar coverage, ordered from highest average daily operations to lowest daily operations.

Airport	Average Daily Operations	Closest Radar (miles)	Beam Width Range (ft)
KJFK	1,256	50 (KOKX)	1,600 – 7,200
KSEA	1,128	52 (KATX)	Not shown
KPHL	1,079	44 (KDIX)	800 – 6,400
KLGA	1,011	53 (KOKX)	1,600 – 7,200
KSFB	793	57 (KMLB)	Not shown
KPBI	395	76 (KAMX)	3,200 – 9,600
KCMH	344	64 (KILN)	2,400 – 8,000
KCHS	314	60 (KCLX)	2,400 – 8,600
KBDL	256	74 (KOKX)	3,200 – 9,600
KRSW	216	90 (KTBW)	4,800 – 10,400

2.3 *Cone of silence issues*

One might expect that having the radar very close to or on airport property would be highly beneficial. However, the WSR-88D radars can only scan up to 19.5º, which implies that some of the terminal airspace will be in the radar's cone of silence. An example of this is provided at Greer Airport (KGSP) for VCP31/32 along a west-to-east transect centered over the airport (Fig. 3a). In this example, the beam depth ranges from approximately 75 ft to 3000 ft, which are comparatively small depths leading the user to expect good resolution of the vertical profiles of the radar moments. However, about 25% of the terminal airspace is not seen by the radar. This improves somewhat for VCP 12 (Fig. 3b), whose highest tilt is 19.5º. This dramatically reduces the cone of silence but, it should be noted that in most instances of winter weather, VCPs 31 and 32 are the favored modes. So, while the cone of silence may not be as problematic for warm-season precipitation, it could be problematic for winter, especially those events where a gradient in precipitation type is positioned over the airport and surrounding property.

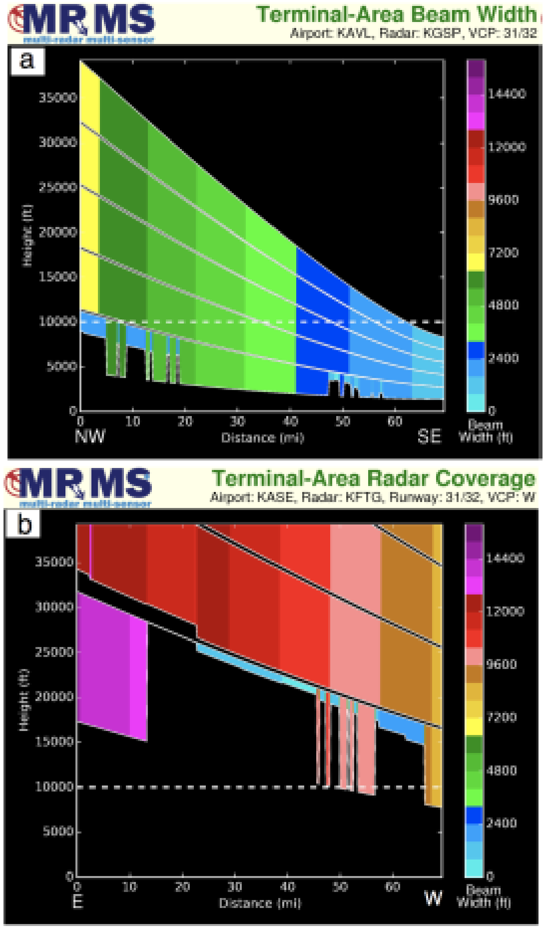

FIG. 2: Radar coverage for Asheville and Aspen airports (KAVL and KASE). Dashed line is as in Fig. 1.

As one would logically expect, as the distance between the airport and the radar is increased, cone-of-silence issues are reduced. An example of an airport that is 8 miles from the nearest radar [Denver, CO (KDEN)] is provided in Figs. 3c,d. While the cone-of-silence is reduced, some of the terminal airspace is still not covered for VCPs 31/32. But, the cone-of-silence is completely removed from the terminal air space when VCP 12 is used.

Table 2: Airports containing the cone of silence issue, with ordered from highest average daily operations to lowest daily operations.

Airport	Average Daily Operations	Closest Radar (miles)	Beam Width Range (ft)
KDEN	1,567	9 (KFTG)	0 – 3200
KMIA	1,134	15 (KAMX)	0 – 4000
KIAD	802	3 (KLWX)	0 – 3200
KBNA	533	11 (KOKX)	0 – 3200
KSJC	449	14 (KMUX)	0 – 4000
KIND	419	1 (KIND)	0 – 2400
KPIT	386	3 (KPBZ)	0 – 3200
KCLE	327	0 (KCLE)	0 - 3200

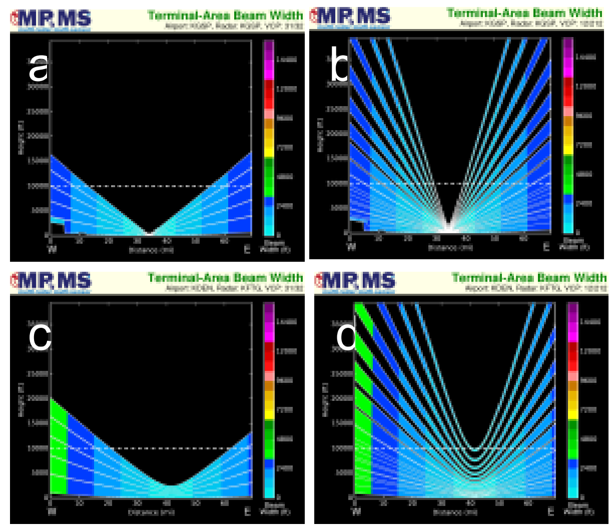

FIG. 3: As in Fig. 1 except for Greenville (KGSP; panels a,b) and Denver airports (KDEN; panels c,d).

Table 2 presents, from busiest to least busy, airports that have a radar very close in distance. This problem clearly does not affect the same number of high-volume airports as beam-broadening does, but KDEN and KIAD are included in this list. Both of these airports have winter weather patterns that may result in varying hydrometeor habit over the airport.

2.4 *Limited upstream coverage*

Although it's not central to the theme of this work, inspection of the surrounding radars to the various airports shows that there are several airports that lack radar coverage to their west. Example airports with this issue are provided in Fig. 4. When there is no radar due west of an airport, this limits the users' ability to anticipate changes in hydrometeor class, storm intensity at low level and other similar phenomena since, in most cases in the United States, weather moves from west to east.

2.5 *Creation of an online interrogation tool*

Since there are too many airports that meet our criteria (337) to discuss herein, an online tool has been developed to allow the reader to assess the beam depth over all airports considered and all VCP modes along several transects over airport properties. Figure 5 is a prototype of what this tool will look like. The user will be prompted to choose an airport at the top of the page. At that point, a regional radar map for that airport will appear (lower left). The user will be prompted to choose a radar from this map, exclusively NEXRAD (WSR-88D) radars. The user then will be prompted to choose a specific VCP mode and a figure showing the radar coverage and beam width will appear (lower right).

3. METEOROLOGICAL IMPLICATIONS

The reason beam width is important is because most microphysical processes can be identified through inspection of the vertical profiles of the radar moments (Ryzhkov, 2006). Ryzhkov et al (2016) shows that by taking an azimuthal average of the radar moments for a select tilt reveals local maxima and minima that can be used to infer the presence of dendrite production, riming, melting, and refreezing. They call these profiles Quasi-Vertical Profiles (QVPs). By studying QVPs, we are able to determine what radar resolution is adequate enough to resolve an approaching weather event.

Two example QVPs are provided in Fig. 6. The first is from KDDC at 1412 UTC 15 January 2017 and second, KMKX at 1140 UTC 13 March 2017. These correspond to surface observations of freezing rain (FZRA) and heavy snow (SN) and are made using the 10º tilt. The reader may note that these profiles appear to start at 0 m above ground level. This is not strictly true as the first 8 gates from the WSR-88D radars are censored. However, for the purposes of this research, we are treating the lowest-reported tilt as being at the surface.

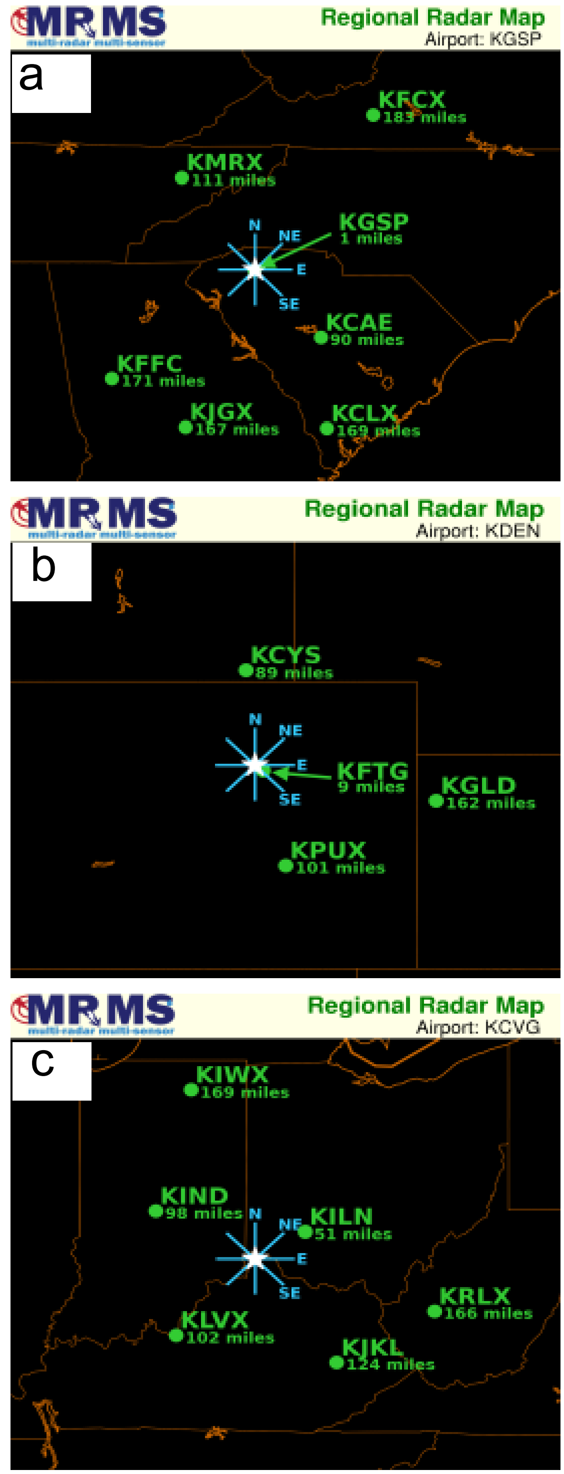

FIG. 4: Regional maps showing radars within 300 km (186 miles) of the (a) KGSP, (b) KDEN, and (c) KCVG airports.

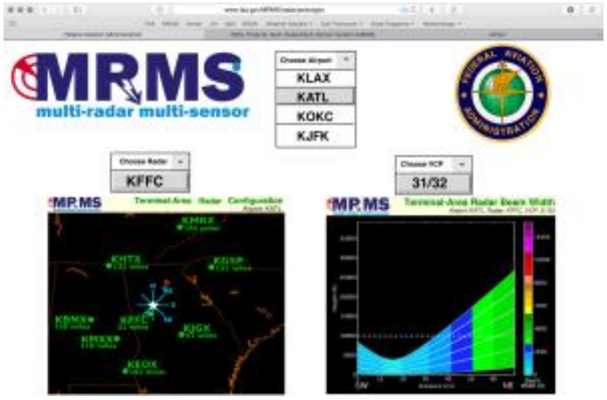

FIG. 5: Prototype of the online interrogation tool showing a regional radar map and vertical cross section of radar beam depth.

The two example QVPs differ notably. Firstly, in FZRA (Figs. 6a,c,e) the local maxima and minima denote the dendrite growth zone (between 10 and 15 kft; Fig. 6c) and melting layer (between 2 and 7 kft; Figs. 6a,c,e). The SN QVP differs greatly in that it does not have distinct microphysical layers. A liner decrease with height increases is present in Z (Fig. 6b). Both differential reflectivity (Zdr) and correlation coefficient (CC) are nearly uniform throughout the QVP (Fig. 6d,f).

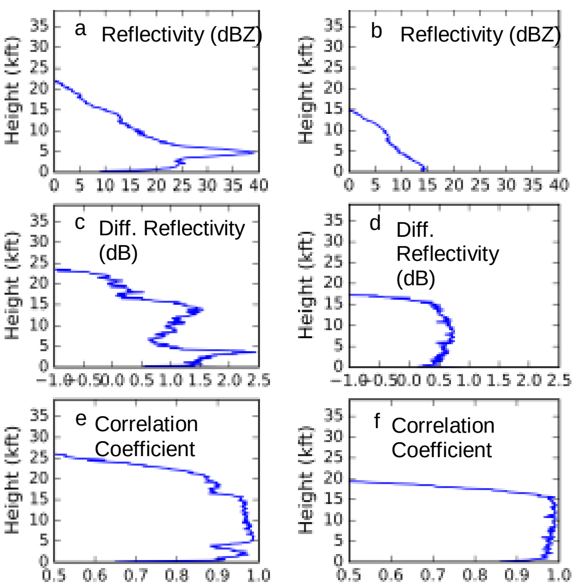

FIG. 6: Quasi-Vertical profiles of the dual-polarized radar moments for KDDC at 1412 UTC 15 January 2017 (left panels and KMKX at 1140 UTC 13 March 2017 (right panels).

3.1 *Cone of silence effects*

To assess how beam broadening and overshooting affect the interpretation of dual-polarized radar observations, the above QVPs are interpolated to the coordinate system of the radars and plotted along the transects shown in Figs. 1, 2b, 3a. Figures 7a,c,e show how the FZRA QVP should appear along the transect KGSP (i.e. Fig. 3a) if there were no overshooting or beam-broadening impacts and assuming the profiles are uniform across the transect. These can be contrasted with their counterparts in Figs. 7b,d,f which show the QVP after it has been interpolated to the radar coordinates.

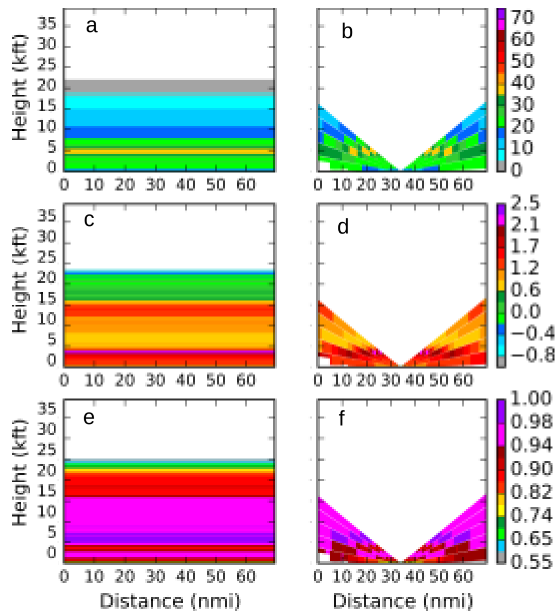

FIG. 7: Along-transect interpolation of the FZRA QVP for KGSP assuming no beam-broadening, overshooting, or cone of silence (left panels) and accounting for these effects (right panels).

As is expectable, beam broadening and overshooting are negligible for this airport/radar combination and both the bright band melting layer and dendritic growth zone are discernable. A clear cone of silence is seen as discussed in Section 2.3. Were there a gradient in hydrometeor process across this airport, the cone of silence may have impeded detection of important processes that may affect airport operations. Deeper investigation of this is left to future work.

3.2 *Beam blockage effects*

A similar exercise is performed for the KASE (Fig. 8) using the FZRA QVP. There are significant areas with no radar returns simply because the QVP is for a shallow-enough precipitation system for overshooting to occur, particularly between 10 and 40 miles along the transect. But, between 50 and 65 miles, there is coverage. Though a considerable portion of this suffers from marked beam blockage, this actually works to the advantage of the users. Note that where the beams are unblocked, the returns for Zdr are lower and in the region of increased blocking (between 55-63 miles; Fig. 8d), the returns are higher, suggestive of the Zdr bright band. So, in this regard, beam blockage isn't an entirely negative thing. However, bright band in reflectivity and the corresponding minimum in CC are not at all evident (Figs. 8b,f).

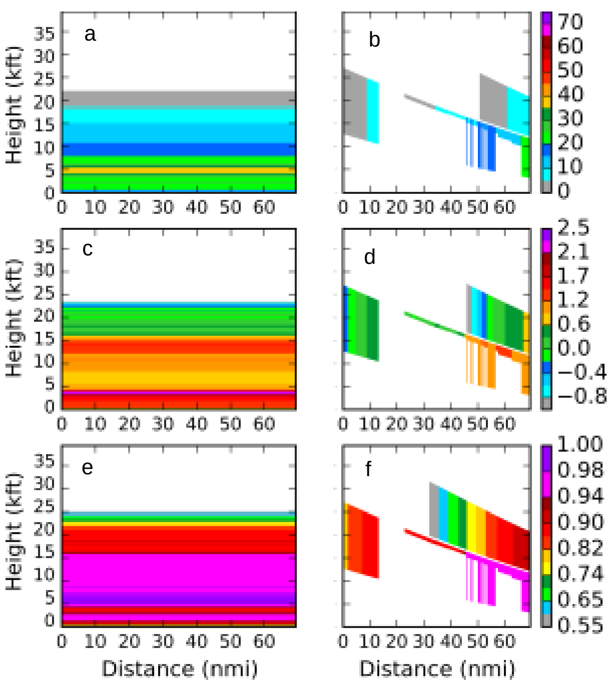

FIG. 8: As in Fig. 7 except for KASE

3.3 ***Limited nearby radar coverage effects***

A common issue seen at various airports in the CONUS is not having sufficient radar coverage, such as at KCLT (Section 2.1). Fig. 9 shows what the radar resolution should look like for both FZRA (Figs. 9a,e,i) and SN (Figs. 9c,g,k). Recall that these QVPs are markedly different. However, when interpolated to the coordinate system of the radar, the patterns are quite similar, although the colors differ. Notice the pattern of Zdr in FZRA (Fig. 9f) and SN (Fig. 9h). The two patterns are almost identical, changing just in color. This suggests that artificial intelligence used to infer the hydrometeor habit at this and other airports that have sufficient distance from the nearest radar, will fail.

4. CONCLUSIONS

Various weather events cause a multitude of aircraft accidents. The winter weather events of FZDZ and SN give us an inside look on how beam broadening and overshooting affect the interpretation of dual-polarized radar observations. These two problems impact the radar resolution in the terminal airspace substantially as seen in four deficiencies: Limited nearby coverage, beam blockage by terrain or other ground-based features, cone of silence issues, and limited upstream coverage. Alongside more case study analysis' on varying weather events, FAA's web tool will lead to better detection of these terminal airspace threats.

With future upgrades to dual polarized radars, several issues may be diminished. Some may think these problems can be fixed by simply locating a radar closer to a select airport. As we observed in KGSP, putting a radar on airport property is not only expensive but may also lead to other deficiencies. Airport surveillance radars can also add to our goal of diminishing terminal airspace threats if their future updates consist of dual-pole capabilities. Beam broadening and overshooting are two sources of error that cannot be ignored and affect how radar algorithms in turn may not be as beneficial in the terminal airspace as we think.

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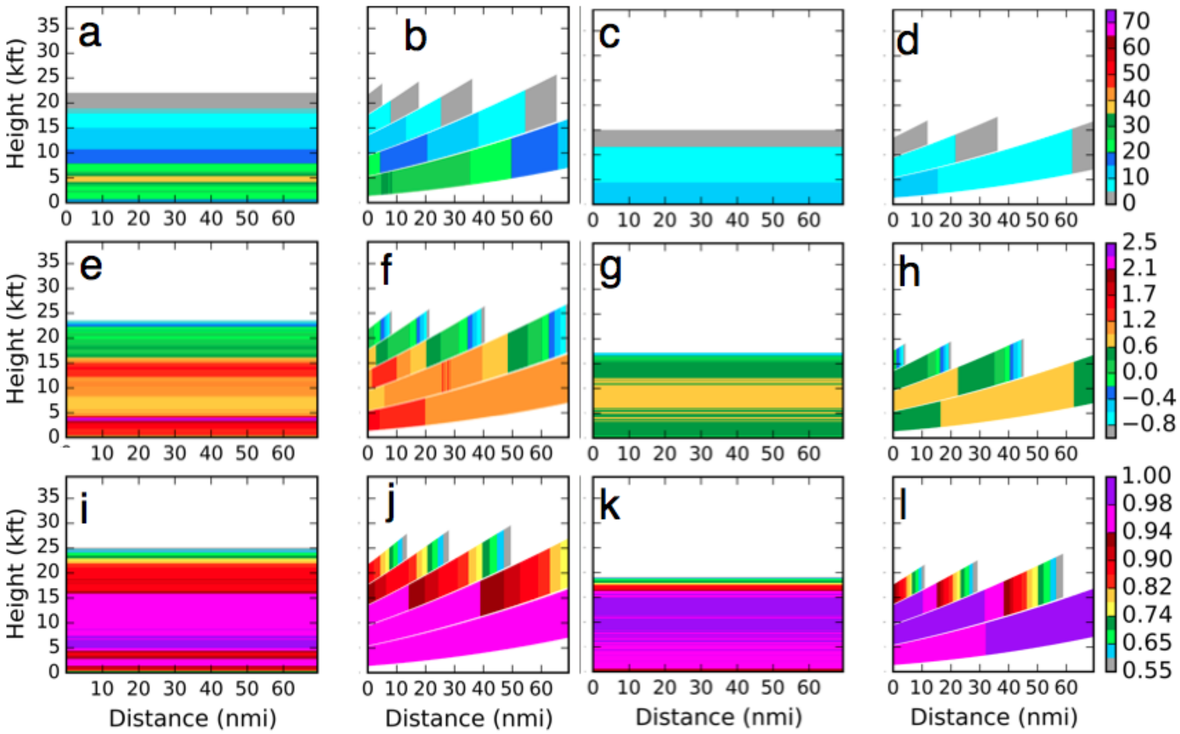

FIG. 9: As in Fig. 7 except for KCLT (left 6 panels) and using the SN QVP (right 6 panels).

conclusions, and recommendations are those of the authors and do not necessarily reflect the views of the National Science Foundation, NOAA, or the U.S. Department of Commerce. The authors would also like to thank the Federal Aviation Administration for providing partial funding for this research.

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