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VERTICAL REFLECTIVITY PROFILES: AVERAGED STORM STRUCTURES AND APPLICATIONS TO FAN-BEAM RADAR WEATHER DETECTION IN THE U.S. *

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1. INTRODUCTION

The FAA is deploying over 100 next generation airport surveillance radars (ASR-9) at selected major airports across the country. Like previous ASRs, the ASR-9 utilizes dual broad elevation fan beams (Figure 1) along with a rapid scan rate (12.5 RPM) to exercise its primary function of detecting aircraft over a 60 nmi radius. In addition, the ASR-9 has a separate dedicated weather reflectivity channel which allows air traffic controllers to display quantitative precipitation intensity reports corresponding to the NWS six-level intensity scale on their PPI display. The 30 second update rate of the weather channel coupled with the large sample volume swept by the ASR-9 fan-beam combine to provide timely and useful indications of precipitation intensity within the terminal airspace.

The PPI display of precipitation intensity which is presented to the air traffic controller is essentially a 2-D (R,θ) representation of the 3-D (R,θ,ϕ) reflectivity field sampled by the fan-shaped beam of the ASR-9. Since the antenna gain varies with elevation angle (Figure 1), the parameter reported by the ASR-9 weather channel represents a beam-weighted, vertically averaged estimate of storm intensity. Previous research has shown that the vertically integrated reflectivity automatically reported by fan-beam radars such as the ASR-9 correlates well with estimates of vertically integrated liquid water content (VIL), a useful meteorological parameter which is a measure of overall storm intensity. (Dobson, et al., 1978, Alaka, et al., 1979). Dobson found a linear relationship between VIL and fan-beam reflectivity from 30 to 60 dBZ assuming the beam is filled with precipitation (see discussion in Section 4).

If the beam is non-uniformly or only partially filled with precipitation, then the inherent vertical integration introduced by the fan-beam may cause an underestimation of the storm intensity. This beam filling loss is most acute at long range, where the vertical extent of the beam intercepts more than 10 km of altitude. The magnitude of this error depends on the complex interaction between the vertical reflectivity structure of the storm and its interception by the fan-shaped beam. If the shape and altitude extent of the vertical reflectivity profile (such as could be provided by a pencil-beam radar) are known, then a suitable adjustment can be calculated and applied to the fan-beam reflectivity estimate in order to produce the desired reflectivity report.

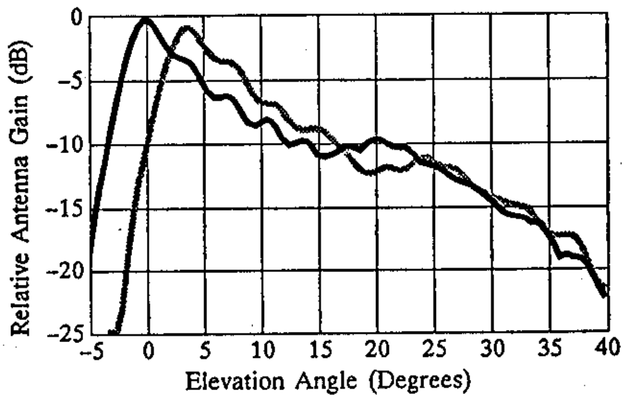

Figure 1. ASR-9 antenna pattern in the principal elevation plane. Black curve is low beam; gray curve is high beam. Plot is for a 0° elevation antenna tilt.

The six-level weather thresholds are stored in processor memory for each range gate as functions of receive beam (high or low). The thresholds can be adjusted to compensate for beam filling losses. The adjustments initially implemented in the ASR-9 were derived using a reflectivity profile model which assumes the maximum reflectivity of the storm is distributed constantly from the surface up to 4 km, and then falls off at 3 dBZ per km above 4 km. The success of the reflectivity correction depends on how well the model profile matches actual storm profiles. If regional variations in general storm morphology are significant, then different beam filling loss correction models may need to be developed for specific regions. Understanding the significance of these regional variations in storm vertical reflectivity structure and their impact on ASR-9 weather report accuracy provided the motivation for this study.

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2. METHOD

2.1. Overview

Volumetric pencil-beam radar data from selected sites in the continental U.S. were used to construct vertical profiles of reflectivity from which VIL, echo tops and bases, and mean reflectivity profiles were calculated. The pencil-beam data were also used to construct the vertical profile maximum projection Z_{max} -- a useful 2-D reflectivity representation for air traffic control purposes in summertime convective storms. Z_{max} represents a conservative report of storm intensity and is indicative of the worst conditions which may be encountered by an aircraft at any altitude. There may be situations in which the Z_{max} parameterization is not appropriate. For example, Z_{max} would be overly sensitive to profile peaks caused by bright-band effects. A bright band is an enhanced reflectivity layer occurring in the region of ice-to-water phase change, usually not indicative of vigorous vertical motions.

A simulation facility was developed which calculates the equivalent ASR-9 fan-beam reflectivity estimate for a reflectivity profile positioned at any range from the radar (see Section 2.4). By using this facility, we were able to assess the amount of adjustment in the ASR-9 reflectivity estimates required to produce the desired Z_{max} reflectivity product.

2.2. Site Selection

In order to examine regional variations in precipitating cloud systems, the continental U.S. was divided into five regions : East (E), Florida and South Plains (S), Midwest (M), High Plains (HP), and West (W) (Figure 2). Digital radar data recorded during previous field experiments using radars operated by MIT Lincoln Laboratory (FL-2), MIT Center for Meteorology and Physical Oceanography, and NCAR (CP-3) were obtained for one representative site from each region. The sites selected were: Denver, Colorado; Kansas City, Missouri; Huntsville, Alabama; Boston, Massachusetts; and Seattle, Washington.

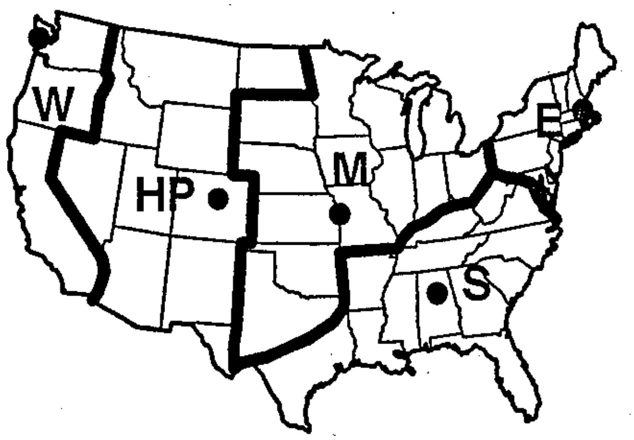

Figure 2. ASR-9 Beam Filling Loss Storm Model Regions.

2.3. Construction of Vertical Reflectivity Profiles

Each radar volume scan consisted of a series of full-circle or sector PPI scans containing between 5 and 20 elevation tilts. Selected azimuth sectors of these volume scan data were mapped onto a cylindrical coordinate grid having a range radius of 111 km and a height of 20 km. Azimuthal and range granularity were matched to those of an ASR-9 -- 1.41° and 0.926 km respectively -- while vertical granularity was 0.5 km. A profile cylinder generated from a full-circle volume scan could therefore contain as many as 30,720 individual vertical reflectivity profiles.

Each of the individual profiles in the cylinder was smoothed using a vertical reflectivity gradient check to reject single-point outliers caused by clutter residue or noise spikes in the data. Profile bins which remained empty after polar-to-cylindrical coordinate mapping were filled using a cubic interpolatory spline.

2.4. ASR-9 Fan-Beam Reflectivity Computation

For each of the reflectivity profiles in the cylinder, the equivalent ASR-9 fan-beam reflectivity Z_{asr} was computed at 4 nmi range intervals from 0 to 60 nmi and for both high and low receive beams using:

$$Z_{asr}(R) = \frac{\int_0^{\pi/2} Z(R,\phi)\, B_t(\phi)\, B_r(\phi)\, d\phi}{\int_0^{\pi/2} B_t(\phi)\, B_r(\phi)\, d\phi} \tag{1}$$

Here $Z(R,\phi)$ is the vertical reflectivity profile value found at range R and elevation angle ϕ (horizontal stratification of the reflectivity profile is assumed in converting from height to elevation angle), and $B_t(\phi)$ and $B_r(\phi)$ are respectively the transmit and receive antenna gain at elevation angle ϕ. Antenna gain measurements were previously obtained from a testbed ASR-9.

2.5. Calculation of VIL

The vertically integrated liquid water content (VIL) was computed for a given vertical reflectivity profile using the formulation proposed by Greene (1972):

$$VIL = 3.44 \times 10^{-6} \int_{h_{base}}^{h_{top}} Z^{4/7} dh \tag{2}$$

where h_{base} and h_{top} are the cloud base and cloud top in meters, and Z is the radar reflectivity factor in the standard units of mm^6/m^3. VIL has units of kg/m^2 and represents the in-cloud water content per unit area.

2.6. Calculation of ASR-9 Reflectivity Adjustments

The ASR-9's weather thresholds are stored as functions of range, receive beam, and weather level. The Z_{asr}(R,beam,weather level) curves and the Z_{max} values provide the information needed to derive threshold adjustments to bring the measured reflectivity in line with Z_{max}. The problem becomes one of computing the reflectivity scaling factor η which minimizes the mean square relative error ϵ between Z_{max} and Z_{asr} over the ensemble of profiles $\{p_1, p_2, \ldots, p_{N-1}, p_N\}$:

$$\epsilon^2(\text{R,beam,wx level}) = \sum_{p=1}^{N} \left[\frac{Z_{max} - \eta Z_{asr}(\text{R,beam})}{Z_{max}} \right]^2 \qquad (3)$$

The scaling factor which minimizes the error is given by:

$$\eta(\text{R,beam,wx level}) = \frac{\sum_{p=1}^{N} (Z_{asr} / Z_{max})}{\sum_{p=1}^{N} (Z_{asr}^2 / Z_{max}^2)} \qquad (4)$$

Equation (4) was used to calculate η (the reciprocal of the required threshold adjustment) as a function of range for both receive beams and for each of the six NWS weather levels. The weather level of a profile was defined to be the NWS level corresponding to Z_{max}.

3. VERTICAL REFLECTIVITY PROFILES

Vertical reflectivity profiles from each site were grouped into three intensity classifications, and the mean profile for each intensity category was computed. Profiles were assigned the greatest intensity category defined by peak reflectivity or altitude (18 dBZ top) criteria shown in Table 1. Mean profiles for the moderate and strong storm intensity categories for each of the five sites are shown in Figures 3 and 4 with solid curves. The number of profiles used to calculate each site-specific mean profile is given in parentheses. An overall mean profile was constructed by computing the unweighted mean of the five site-specific mean profiles for each intensity category and is depicted as a dashed curve in each of the graphs of Figures 3 and 4. Results from Konrad (1978) for observations taken at Wallops Island, Virginia are also shown for comparison. Konrad computed mean profiles from individual profiles grouped into 5 dBZ bins. For comparison with our results, we re-grouped Konrad's mean profiles into our corresponding moderate or strong intensity categories, normalized each mean profile by it's peak reflectivity value, and computed mean relative reflectivity profiles.

Moderate profiles from Boston, Denver, Huntsville, and Kansas City tend to fall off significantly between 8 and 12 km. This is probably associated with the rapid decrease of moisture near the tops of the storms and the limiting effect of the tropopause. The Wallops Island profile is not inconsistent with this idea. The Huntsville, Kansas City, and Wallops Island profiles indicate a sharp reduction in drop sizes and/or number density above a surface-based high relative reflectivity layer. The surface-based constant reflectivity layer seen in the Denver profile exhibits lower relative reflectivity presumably due to the presence of a dry subcloud environment in some of the profiles. Profiles constructed from wintertime stratiform precipitation in Seattle are quite different from those from other sites. The mean profile exhibits a pronounced peak at 3 km, which is attributed to bright band effects.

Table 1. Storm profile intensity classification criteria.

Category	Reflectivity (dBZ) [NWS Levels]	Altitude (ft)
Weak	< 41 [1 – 2]	< 25,000
Moderate	41 – 50 [3 – 4]	25,000 – 35,000
Strong	> 50 [5 – 6]	> 35,000

Strong mean profiles extended 2–6 km higher than their moderate counterparts (Figure 4). This is especially true of the Kansas City profiles, probably because of the increased frequency of supercell storms in the Midwest. The Wallops Island profiles showed the least amount of change between the two intensity categories. There were almost no strong profiles from the Seattle data set, so no mean profile was constructed for this category.

In order to characterize the representativeness of the mean profiles, the standard deviation of relative reflectivity was computed as a function of altitude over the ensemble of profiles from each site (Figure 5). The standard deviation was computed based on normalized linear reflectivity units which range from 0 to 1. Hence, a standard deviation of 0.30 represents a variability of 30 percent. The standard deviations are between 0.35 and 0.40 at the surface, with a slight decrease in variability with height up to approximately 8 and 12 km for moderate and strong profiles, respectively. This region of relatively high variability implies the presence of small-scale reflectivity cores occurring over a range of altitudes. The large magnitude of this variability suggests that mean profiles should not be used in computations sensitive to small-scale features.

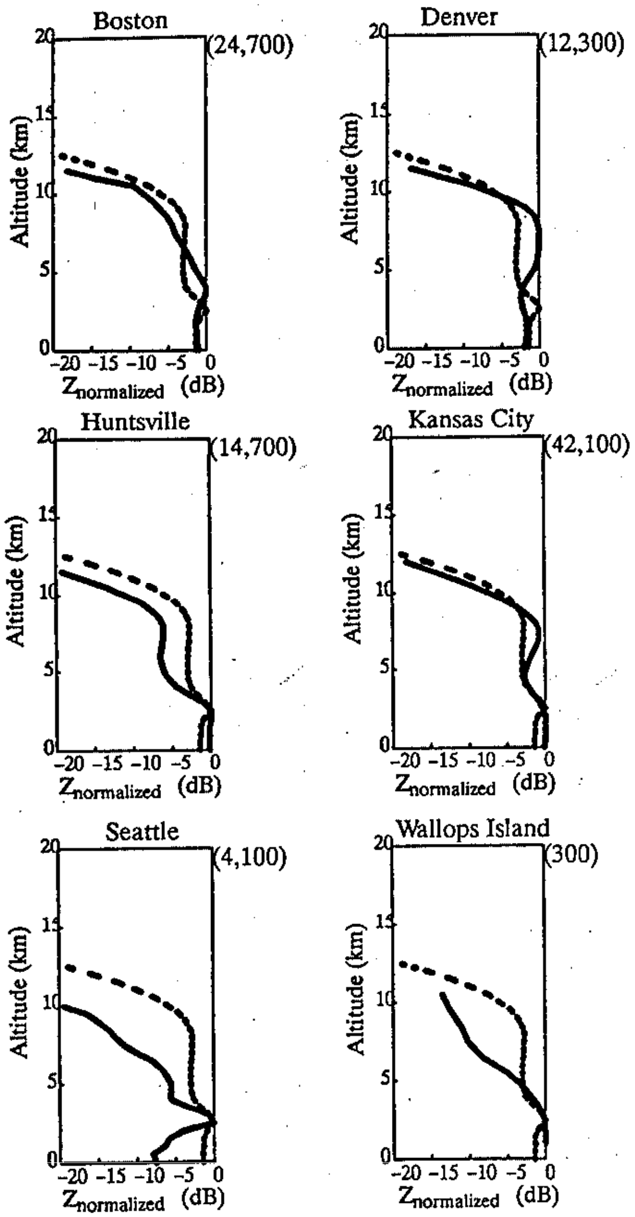

Figure 3. Mean vertical relative reflectivity profiles (solid line) of moderate intensity for each of the five sites and for Wallops Island (from Konrad, 1978). Dashed line is 5-site mean profile. Numbers in parentheses indicate the number of profiles used to determine the mean.

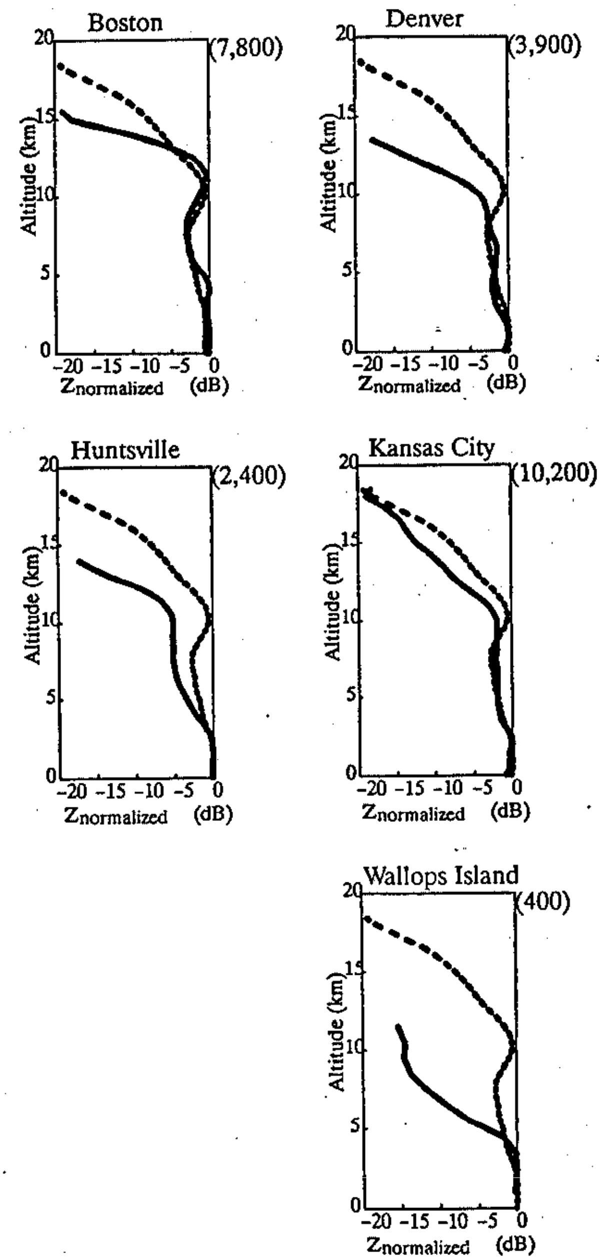

Figure 4. As in Figure 3 but for strong profiles.

4. COMPARISON OF CORRECTED ASR-9 REFLECTIVITY ESTIMATES AND VIL.

Mean vertical reflectivity profiles are useful for characterizing climatological similarities and differences between sites and different storm intensities. However, we found that the use of mean profiles for deriving threshold adjustments does not account for small-scale features often observed in the individual profiles. These features may be peaks associated with regions of hail growth or heavy precipitation aloft and may present significant hazards to aircraft. Mean vertical reflectivity profiles are therefore inappropriate for determining fan-beam reflectivity adjustments.

An illustration of this can be seen in Figure 6a which shows a set of three synthetic reflectivity profiles normalized by their own maximum reflectivity and whose shapes are comparable to profiles commonly observed at different stages during the evolution of a storm cell. The corresponding mean profile is given in Figure 6b. The deep layer of near-maximum reflectivity apparent in the mean profile is an artifact resulting from the averaging of profiles with peaks at varying altitudes. Clearly, if a vertically averaged quantity such as Z_{asr} is computed for the mean profile and compared against the corresponding Z_{max}, the resulting dis-

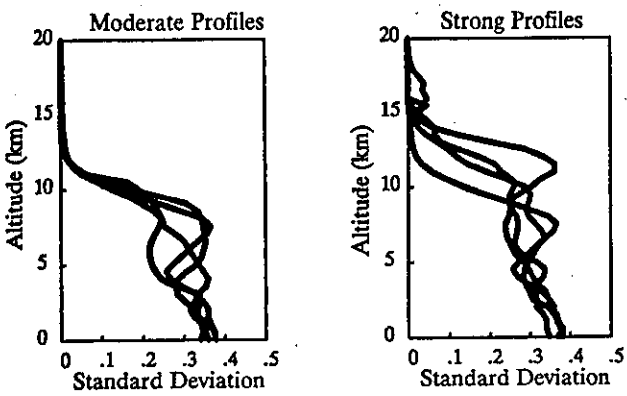

Figure 5. Standard deviations of moderate and strong mean profiles.

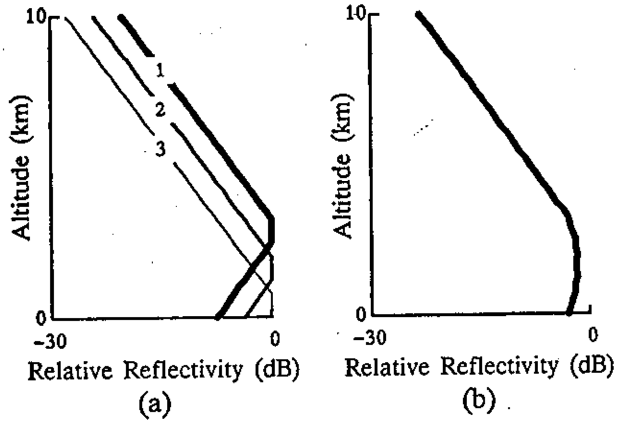

Figure 6. Example of (a) three individual profiles (normalized by their maximum value) and (b) the corresponding mean profile (not normalized a second time).

agreement will be small, suggesting that very little adjustment of the Z_{asr} estimate is required. Figure 7 plots the differential reflectivity between Z_{asr} (uncorrected) and Z_{max} using individual and averaged profiles. Relative to the mean profile, a significantly greater differential reflectivity is seen between Z_{asr} and Z_{max} computed from the individual profiles in Figure 6a, especially at those ranges where the nose of the radar beam intercepts the storm profile above or below the profile peak.

The method adopted for computing a correction to the ASR reflectivity observations in order to more accurately report the storm intensity minimized the error between the reported reflectivity (Z_{asr}) and the desired reflectivity(Z_{max}). This computation was done for each of the five sites separately with one correction for each of the six NWS weather levels. These "site/level dependent" corrections were then combined and an exponential fit to the data was calculated to define the new correction. The metric used to evaluate the success of the correction was the percentage of profiles assigned to the correct weather level. The results of this

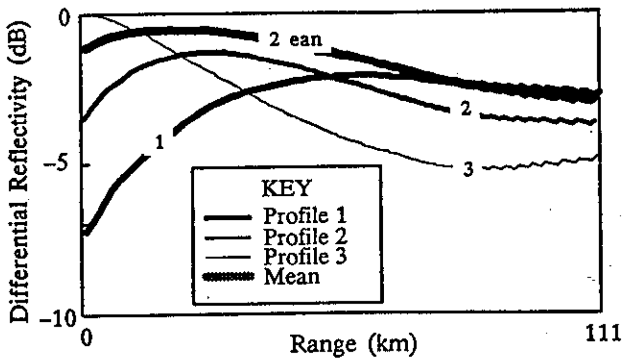

Figure 7. Differential reflectivity between the vertical profile maximum and uncorrected ASR-9 reflectivity for the three profiles and their mean shown in Figure 6. Curves are for the low receive beam.

evaluation are shown in Figure 8 as a function of range. Shown are the results for the observed or uncorrected ASR reflectivities, the current operational correction, and the exponential fit or new correction. A significant improvement over the current correction is achieved by using the new corrections computed according to the method of minimizing the error.

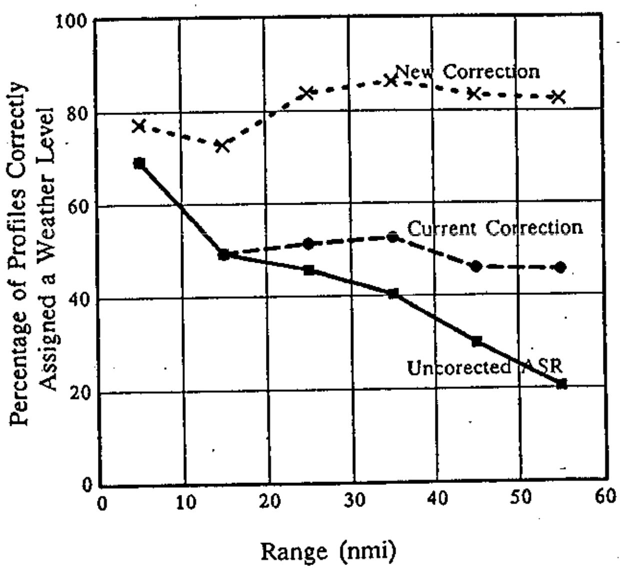

Figure 8. Evaluation of the effectiveness of the new correction compared to the current correction and the uncorrected reports of precipitation intensity. See text for further explanation.

Dobson (1978) found that fan-beam reflectivity was well correlated to VIL for a set of 37 profiles between the values of 30 and 70 dBZ. 115,000 profiles were available in the same reflectivity range from the data set used in this study and are also found to be well correlated to VIL. The correlation was computed for both uncorrected ASR reflectivity and ASR reflectivities adjusted with the new correction. This is shown in Figure 9 with boxes and triangles for the uncorrected and corrected ASR reflectivities, respectively. A linear fit to the data in dB units was computed for each reflectivity product, and yield correlation coefficients of 0.85 and 0.88, respectively, for profiles with reflectivities greater than 30 dBZ. Inspection of the data suggests a linear relationship between VIL and fan-beam reflectivity for reflectivities above 20 dBZ, but that this relationship breaks down for reflectivities less than 20 dBZ. Note that for values less than the NWS level 1 threshold (18 dBZ), no correction is applied. The results shown here differ slightly from the results of Dobson (1978) (Figure 9 dashed line).

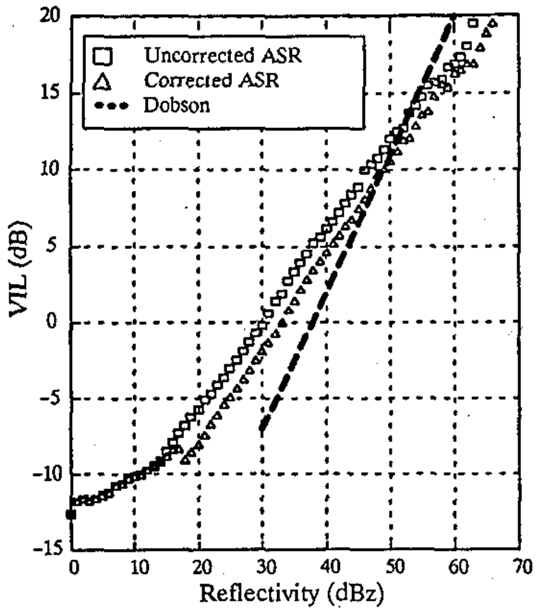

Figure 9. Comparison of VIL and ASR reflectivity for uncorrected ASR reflectivity (boxes) and corrected ASR reflectivity (triangles), where the correction is only applied to reflectivities greater than 18 dBZ. The dashed line indicates results of a similar comparison done by Dobson (1978).

5. SUMMARY

The ASR-9 radar provides air traffic controllers with estimates of precipitation intensity quantized into the NWS six weather levels. The fan-beam reflectivity estimates may not be representative of the storm intensity in those instances where the vertical reflectivity profile is non-uniform. To counteract this effect, the weather reflectivity thresholds may be adjusted on a regional and range basis. Five regions across the continental United States were identified, and one site from each region studied. The analysis began with a characterization of the vertical reflectivities at each site through derivation of the mean profiles for moderate and strong storms. Examination of these profiles and their associated standard deviations lead to the conclusion that there is a large degree of variability in the shapes of these profiles and the altitude extent of the highest reflectivity features. Because of this variability, mean profiles were found to be inappropriate for use in calculation of the adjustments of the weather levels.

Weather level adjustments were computed by minimizing the relative error between the fan-beam reflectivity Z_{asr} and the storm intensity represented by Z_{max}. A single correction was found to be suitable for all regions and weather levels. This correction yields substantial improvement over the initial adjustment based on a model reflectivity profile. Both adjusted and uncorrected fan-beam reflectivity estimates were found to be linearly correlated with VIL for reflectivities above 20 dBZ. This result may be useful in future interpretation of fan-beam reflectivity estimates.

6. REFERENCES

Alaka, M.A., R.C. Elvander, and R.E. Saffle, 1979: Nowcasts and Short-Range (0-2 Hour) Forecasts of Thunderstorms and Severe Convective Weather for Use in Air Traffic Control. Technical Report, U.S. Dept. of Commerce, NOAA, FAA-RD-79-98.

Dobson, E.B., A. Arnold, and F.L. Robison, 1978: Weather Detection Using Fan-Beam Radars. Preprints, 18th Conference on Radar Meteorology, 413-416.

Donaldson, R.J., 1961: Radar Reflectivity Profiles in Thunderstorms. J. Meteor., 18, 292-305.

Greene, D. R., 1972: A Comparison of Echo Predictability: Constant Elevation vs. VIL Radar Data Patterns. Preprints, 15th Radar Meteorology Conference, 111-116.

Joss, J. and A. Waldvogel, 1989: Precipitation Estimates and Vertical Reflectivity Profile Corrections. Preprints, 24th Conference on Radar Meteorology, 682-688.

Konrad, T.G., 1978: Statistical Models of Summer Rainshowers Derived from Fine-Scale Radar Observations. J. Appl. Meteor., 17, 171-188.

Weber, M.E., 1986: Assessment of ASR-9 Weather Channel Performance: Analysis and Simulation. Project Report ATC-138, Lincoln Laboratory, MIT, FAA-PM-86-16.