J9.5 Weather Radar Terrain Occultation Modeling using GIS

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1. INTRODUCTION

Geographic Information System (GIS) techniques are applied to estimate the effects of terrain and manmade obstacles on radar beam propagation, and their resulting impact on radar coverage over regions of interest. The resulting radar coverage patterns can be combined with geographic data layers to analyze societal impacts of radar occultation, including protected population numbers and demographics, and radar sample volume vertical extents over drainage basins. This technique is being investigated for operational applications such as radar "siting" and optimal radar network distribution. The GIS technique currently supports customary radar beam elevations, but also includes predictions for negative beam elevation angles. Radar beam ducting is not yet addressed. Limitations of this approach and recommendations for technique improvement are provided.

The technical approach estimates radar beam occultation on a "cell by cell" basis, following an idealized radar energy pulse along a radial at each azimuth angle α, as the centroid of radio energy rises (or falls) with respect to the Earth Geoid starting at elevation angle ε. This technique has been outlined by Saffle (2003), then with the National Weather Service (NWS) Office of Science and Technology, and is similar to the original NEXRAD occultation techniques employed by Leone et al. (1989). The current approach has been demonstrated using the Commercial Off-The-Shelf (COTS) ArcView™ GIS by ESRI. The NWS prefers to maintain the algorithm in Avenue™ for application with ArcView 3.x, since that capability can be operated across several operating systems including Windows™, UNIX and Linux. This approach has also been demonstrated in ArcGIS™ 9, where it runs considerably faster, but ArcGIS 9 is currently available only for Windows. The GIS-based technique requires the Spatial Analyst™ and 3D Analyst™ extensions.

Radar cell centroid locations and height above the Earth Geoid are calculated using a Visual Basic (VBa) utility, version 2 of which has been provided freely to public domain for Windows as NEX2SHP.exe (Shipley, 1999). This utility is described in Section 2, and produces point or polygon Shapefiles™ for input to the occultation analysis procedure. The NEX2SHP utility decodes Level 3 NEXRAD product #19 (Radar Reflectivity), and can produce GIS-compatible polygon or point features as a function of {lon, lat, z} from NEXRAD radar measurements, as shown for Tropical Cyclone Georges in Figure 1, Shipley et al. (2000).

Version 7 of the NEX2SHP utility updates the height approximation released in version 2, with an improved range-height equation introduced by Saffle (2003), as discussed in Section 2.1. The version 7 utility has also been generalized to create radar beam test patterns for additional radars including the FAA TDWR.

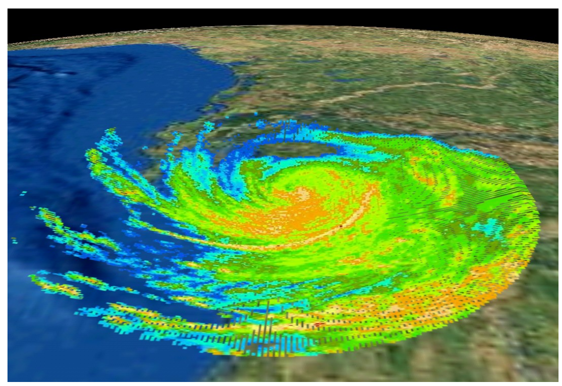

***Figure 1** – NEXRAD level 3 product #19 radar reflectivity centroids (points), for Tropical Cyclone Georges, as seen from the Mobile, Alabama NEXRAD on 27 Sep 1998 at 2041 ut with beam elevation angle of 0.5 degrees.*

1.1 Overview of the procedure

The radar Analysis is performed in five steps and in the following order:

a) Generate theoretical radar coverage pattern - Radar operating parameters are defined, the radar beam propagation pattern is generated as centroids or polygons, and these are mapped to a digital elevation model (DEM), cf. section 2.

b) Merge radar and terrain databases – the radar beam centroid height difference is calculated with respect to local terrain elevation, and/or man-made obstacles, cf. section 3.

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c) Calculate beam obstruction cross section – radar beam pattern model is used to estimate percentage of beam occulted by terrain and/or man-made obstacles along the propagation path of the radar beam for each radial. Beam occultation is integrated starting with no obstruction at the beam origin (radar site location), cf. section 4.

d) Interpret obstruction pattern – extract "range ring" feature depicting theoretical performance limit, given a user-defined occultation threshold level, cf. section 5.

e) Visualize in three dimensions - Convert 2-D products developed in previous steps to 3-D for visual inspection, quality control, and effective communication.

2. Radar Beam Propagation Model

When the input data file is a text file with extension *.txt, the NEX2SHP utility attempts to interpret the contents as named parameters. If valid, these parameters are then used to create a theoretical radar feature dataset, currently in the Shapefile format. The contents of the text file are interpreted as follows:

***Table 1** – Input parameters for NEX2SHP version 7*

lat	39.00	* radar latitude [decimal degrees]
lon	-100.05	* radar longitude [decimal degrees]
zmsl	1500	* local ground level at radar base [m MSL]
elevangle	0.5	* elevation angle [decimal degrees]
towerheight	30	* height of antenna above ground [m AGL]
numradials	360	number of azimuthal samples per scan
numrangebins	230	number of range bins per azimuth
rangebinlength	1.0	length of each range bin [km]
verticalbeamwidth	1.0	vertical beam angular width [decimal degrees]

** indicates required parameter*

If omitted, the default values for optional parameters are assumed to describe a NEXRAD system as shown in Table 1. The utility also supports a command line execution mode, namely:

nex2shp infile, outfile, Point/Poly, IncLonLat (1)

where:

infile	input file as "path/filename.ext"
outfile	output file as "path/filename"
Point/Poly	string = "point" or "poly"
IncLonLat	string = "yes" if desired in table

A Shapefile consists of, at a minimum, three files with identical filenames: *.shp providing the shape description, *.dbf providing the tabular (relational) data records for each shape, and *.shx providing an index between the spatial and relational contents. If only two parameters are supplied, then the utility will create a point shapefile and will not include lon/lat fields in the table. NEX2SHP does not directly create a geodatabase.

2.1 Vertical Beam Height vs. Range

The height of the radar beam centroid for WSR-88D (NEXRAD) volume coverage patterns is calculated following Saffle et al (2003), namely:

$$h(r, \varepsilon) = (r^2 \cos^2 \varepsilon \,/\, 8256 + r \sin \varepsilon)\ 6076 \qquad (2)$$

where:

h	height of beam center in feet
r	horizontal range in nautical miles
ε	radar elevation angle in degrees.

This formula has also been tested for negative beam elevation angles ($\varepsilon < 0$), and has been shown to be appropriate in the domain $\{-1^o < \varepsilon < +20^o\}$. A sample coverage for negative beam elevation angle is shown in Figure 2 as a "what if" study for the WSR-88D located at Salt Lake City, UT.

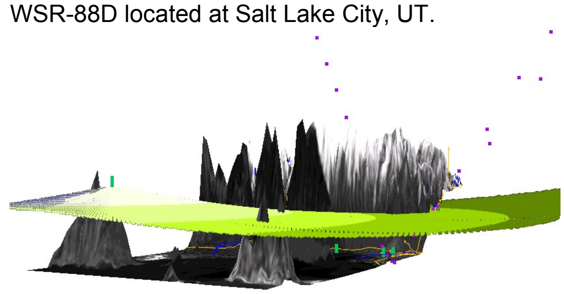

***Figure 2** – Theoretical WSR-88D beam propagation path for initial beam elevation angle of -0.5 degrees for NEXRAD located at Salt Lake City, UT. The vertical scale is greatly exaggerated.*

2.2 Range Calculation

Horizontal range is estimated assuming line-of-sight propagation at radar beam elevation angle ε over a spherical Earth Geoid with a radius of 6370 km. This approximation does not account for beam refraction nor the ellipticity of the Earth Geoid, but is sufficiently accurate to place the centroids within ± 1 km of their "true" position. The ground path of the radar beam is therefore a Great Circle emanating from the radar site and extending to the centroid position {lon, lat} of the radar measurement volume. A somber test of geolocation accuracy was provided by the Shuttle Columbia accident, where the highly defined debris plume was observed simultaneously by five WSR-88D systems in the

Texas-Louisiana region. Out of respect for the men and women of Columbia, we have elected to present only the result of this test.

3. Terrain Database Interaction

The NEX2SHP version 7 utility provides detailed estimates for radar beam centroid location in x (longitude), y (latitude) and z (height above MSL). The GIS technique uses this information to sample a Digital Elevation Model (DEM) at the location {lon, lat} of each centroid, and adds fields for terrain height [rtopo] and the relative height of the beam centroid [height] above local terrain. The figures provided in this paper use the 30 arcsec DEM provided with AWIPS, see Graffman (2004), although finer resolution DEMs can be inserted. The current technique approximates beam occultation by sampling at the beam centroid, so higher resolution DEMs are not currently justified except at close ranges.

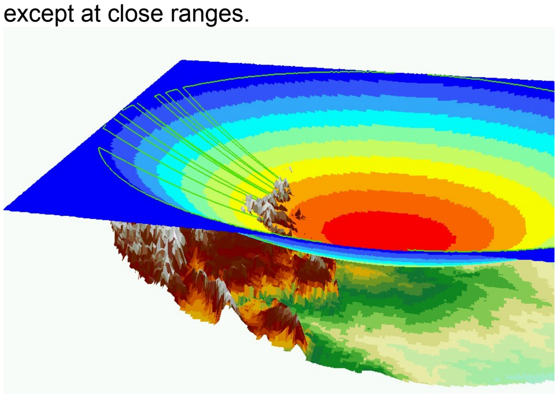

Figure 3 *– Superposition of the theoretical beam pattern generated by the NEX2SHP utility and local terrain for KBOU, the WSR-88D located at Boulder, CO. No beam centroid height values are provided beyond 230 km range, to explain why the "corners" of the elevation grid are "flat".*

4. Estimating Obstruction along Radials

The NEXRAD beam centroid table is manipulated as a point Shapefile, and is organized by range and radial running in range from 1 to 230 km, then by radial from 0 to 359 degrees azimuth. Additional fields [Power] and [BeamWidth] are added to record theoretical obstruction in percent and vertical beam extent, and occultation is then estimated along each radial through the integration of occultation in the table field [Power]. The current technique uses a simplifying assumption of a rectangular or "square" vertical distribution for beam energy. Additional occultation is known to occur from manmade objects such as towers at close ranges, and such obstacles can be included as points at their recorded locations. A method for estimating occultation by manmade objects is currently not implemented. Rectangular beam occultation is currently calculated by the formula

$$B\ [\%] = \text{Integral } \{(h+b/2)/b\}\ dr \qquad (3)$$

for $-b/2 < h < +b/2$, and where

B	integrated occultation [fraction or percent]
h	beam centroid height, field [height]
b	vertical beam width, field [BeamWidth]
dr	range cell length along radial.

5. Feature Extraction

"Range rings" for occultation greater than 25% using this technique are shown for the NEXRAD at Boulder, CO (KBOU) in Figure 4.

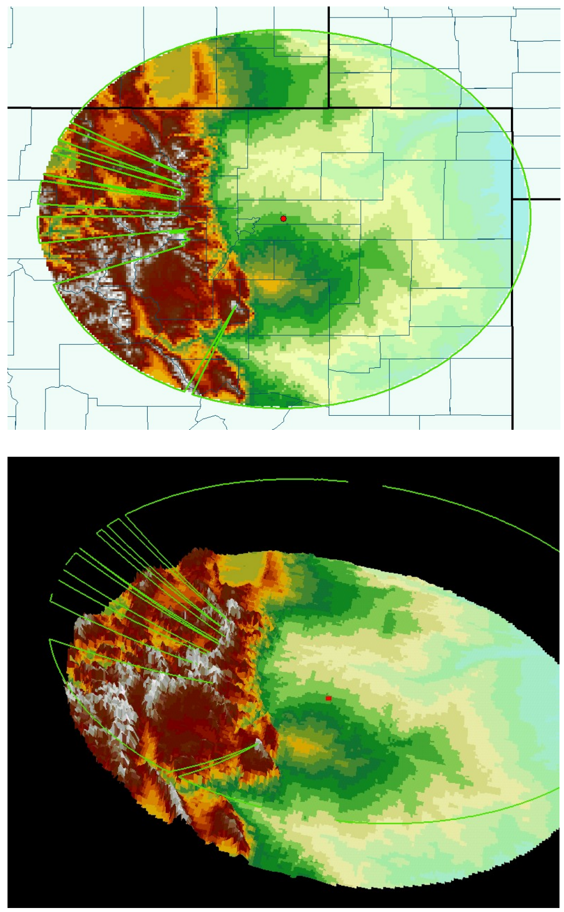

Figure 4 *– Theoretical range detection limits (aka "range rings") for the WSR-88D located at Boulder, CO (KBOU). The results are first calculated in 2-D using Spatial Analyst extension (top), then cast into 3-D using the 3D Analyst extension (bottom).*

These range rings are produced in the so-called "step 4" chain, as follows:

Step 4a (*WxA_Select.ave*) – select the first point in each radial where integrated occultation, field [Power], exceeds a threshold (default is 25%). This script can be modified to also select the first point where beam height exceeds a threshold (e.g. beam height exceeds 10 kft above local terrain, viz. [height] > 10 kft).

Step 4b (*Blank-Poly_theme.ave*) – attach a null polygon feature.

Step 4c (*Point2Poly.ave*) – convert the selected points from step 4a into a single polygon.

Step 4d (*WxA_P2Pl.ave*) – convert the polygon from step 4c into a polyline feature, or "range ring".

Subsequent conversions of the 2-D features into 3-D features are accomplished using standard GIS functions. The range ring generated in step 4d is cast into 3-D by draping it on a surface generated from the field [zmsl] in the original NEX2SHP point Shapefile (an example of this surface shown in Figure 3).

6. Comparison with Standards

Factors leading to variation among the studies, in order of significance:

1) Range-Height behavior significant differences at longer ranges, and ducting issues associated with non-standard atmospheres,

2) Sample volume definition,

3) Tower location for close-range obstacles,

4) Vertical beam distribution – note if symmetrical, then 50% blockage calculation is independent of distribution shape,

5) Tower height – typically assumed ~ 30 m,

6) Horizontal beam spread – current application assumes that all beam energy is confined horizontally to a narrow beam at the sample centroids,

7) Digital Elevation Model resolution – related to #6, various spatial resolutions from 30 arcsec (~1 km) to 1 arcsec (~ 30 m) can provide different results, especially in high relief terrain.

A comparison to current standard results from the NEXRAD Radar Operations Center (ROC) are shown in Figures 5 and 6 for site EMX (Tucson, AZ). This site is instructive since it includes significant terrain features near the NEXRAD site (within 10 km). Standard ROC screen images were provided for EMX (Istok, 2004) and registered to an ArcGIS map document using standard georegistration techniques. Figure 5 illustrates the incorporation and registration of ROC digital elevation into ArcGIS, and lends confidence that the two independent techniques use the same digital terrain. Figure 6 provides a larger scale view of occultation for both ROC and GIS. There are some differences, which may be associated with factor #1 (range-height equation), and which is subject to further study.

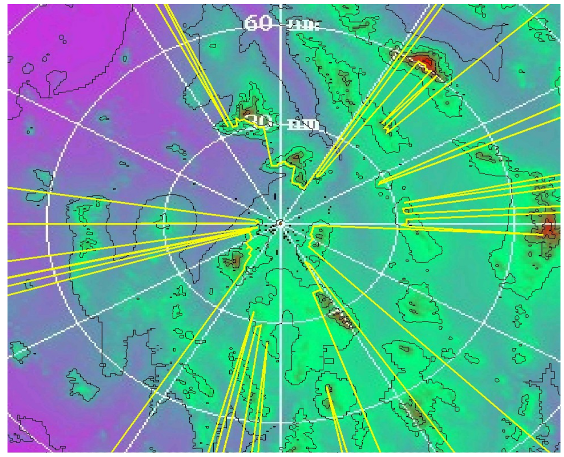

Figure 5 – *Georegistration of a ROC DEM image for KEMX (Tucson, AZ), overlaid with GIS terrain elevation every 500 m (black contours) and radar beam occultation (yellow "range rings") for 0.0 degree beam elevation. A larger scale perspective is shown in Figure 6. Visual comparison lends confidence to similarity in the factors #7 (digital elevation) and #3 (radar location) between the two independent methods.*

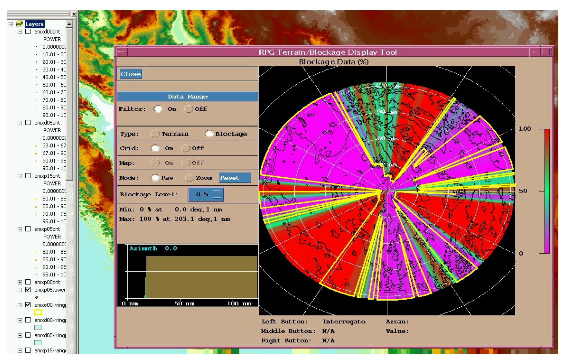

Figure 6 – *A larger scale view of Figure 5, showing an entire ROC image for KEMX "registered" to the ArcGIS 9 map document. GIS occultation for the 0.0 degree beam elevation (yellow "range rings") are overlaid onto ROC occultation for 0.5 degree beam elevation. A notable difference appears at 210 degrees azimuth, where the GIS technique shows beam passage through reduced elevation at close range (compare with Figure 5).*

The goal of this exercise is to validate and/or reproduce the original NEXRAD site surveys commissioned by the NWS and executed by Stanford Research Institute (Leone et al., 1989). These SRI results are available from the NWS as

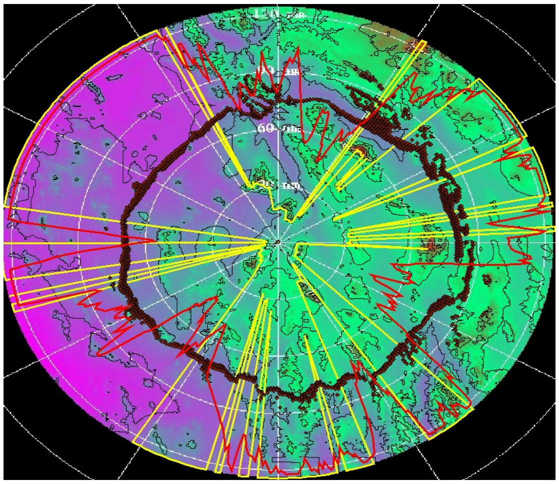

***Figure 7** – Comparison to the original SRI NEXRAD site survey coverage pattern for KEMX (red "range ring"). The original site survey estimated useable volume defined by the combination of non-occulted rays and sample volumes below 10 kft. GIS results for 0.0 degree beam elevation occultation (the yellow "range ring") and 0.5 degree beam centroid heights at 10 kft Above Ground Level (AGL) are overlaid, showing general agreement with the SRI result. The GIS pattern for 1.5 degree beam elevation is not occulted by terrain.*

polyline Shapefiles, and one example for KEMX is shown in Figure 7. The original site survey not only accounts for occultation by terrain and manmade obstructions, but also estimates the radar coverage volume for detectable regions located below 10 kft (Leone et al., 1989, state that the limiting altitude is 6 kft). The exact definition of the sample volume is being precisely defined, but it is generally thought that radar coverage is available when beam energy is above 25% (occultation) and the sample volume is located within 10 kft of the surface (local terrain elevation).

7. Recommendations for Improvement

The following improvements are recommended:

Azimuthal sampling and DTED resolution – the current application samples the terrain at the centroid of each radar sample volume. This is appropriate when the radar sample volume is small or similar as compared to the terrain resolution. However, when the terrain resolution is smaller than the radar sample volume, then it is more appropriate to average obstruction across the sample footprint. In addition, the alignment of obstacles along the ray path (radial) may have an impact when they do not line up or "shadow" each other. Such impacts are currently neglected.

Comparison to real data – The results have been lightly compared to similar results from the ROC and SRI, with an indication of general agreement. It would be instructive to apply the radar observations themselves to see if no signals are in fact retrieved from the theoretically occulted regions of the sample pattern along each radial and for each elevation angle.

Transition from ArcView 3.x to ArcGIS 9 – move from Shapefiles and Coverages, to geodatabases and rasters (GRIDs). The newly released ArcGIS 9 speeds up the entire procedure by an order of magnitude.

8. Acknowledgments

In memory of the sacrifice made by the men and women of Space Shuttle Columbia.

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9. References

Graffman, I.A., 2004: AWIPS Map Database Home, http://www.nws.noaa.gov/geodata/

Istok, Michael, 2004: ROC standard images products, personal communication.

Leone, D.A., R.M. Endlich, J. Petročeks, R.T.H. Collis and J.R. Porter, 1989: Meteorological Considerations Used in Planning the NEXRAD Network. *Bull. Amer. Meteor. Soc.*, **70**, 4-13.

Saffle, R.E., R.S. Shriver and S.T. Shipley, 2003: NEXRAD to Shapefile Conversion and GIS Beam Propagation Analysis in 3D. Paper P1.23, 19th IIPS, AMS Annual Meeting, Long Beach, CA.

Shipley, S.T., 1999: NEX2SHP.exe utility courtesy of George Mason University, Department of Geography. Software available by contacting the author, http://geog.gmu.edu/projects/wxproject/

Shipley, S.T., I.A. Graffman and J.K. Ingram, 2000: GIS Applications in Climate and Meteorology. ESRI Internal User's Conference, San Diego, CA. http://gis.esri.com/library/userconf/proc00/professional/papers/PAP159/p159.htm