Using Radar Data to Predict Rain-Scatter Paths

Rain-scatter propagation has been around for a long time. Radar data is a way of predicting where rain-scatter propagation can happen and/or is happening in real time. Here KØSM discusses how to use radar data to predict rain-scatter propagation. He also discussess his software program, which is designed to be used for making such predictions.

By Andy Flowers,* KØSM

We say that an electromagnetic wave is "scattered" when it encounters some substance in its path that deflects some of its energy in a new direction. When one stops to think about it, most routine propagation at VHF and higher frequencies is a result of some sort of scattering. At VHF we often observe scattering effects from large objects close to Earth, such as buildings and aircraft. We also know that we can make use of small changes in air density in the lower atmosphere that allow for routine communication of a few hundred miles with amateur power levels. As we go higher in frequency, we find that smaller and smaller objects have a significant effect on propagation. Raindrops become an effective scattering medium in the microwave range. This article will focus on the mechanics of rain-scatter propagation and how freely available radar data can be used to predict possible propagation paths.

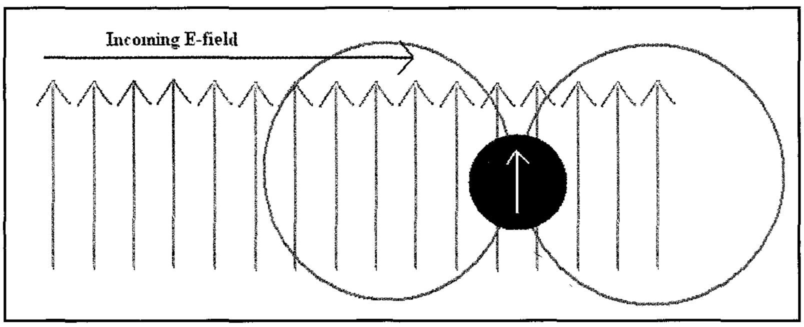

Figure 1. Induction of electric dipole in Rayleigh scattering. Arrows indicate E-field of the incoming EM wave. The two circles show the (re-)radiation pattern (H-plane) of the dipole.

Scattering Principles I: Rayleigh Scattering

There are two sets of scattering equations that are used to calculate the amount of scattering from a medium: *Rayleigh* and *Mie* scattering. The type of scattering is a function of the size of the scattering particle relative to the wavelength of the radiation. Rayleigh scattering is simpler, so we will consider it first.

Rayleigh scattering applies when the diameter of the scattering particle (d) is much smaller than the wavelength of the radiation (λ). Rayleigh scattering is the dominant scattering mode when $d < \lambda/10$. Figure 1 shows the incoming electric field from an electromagnetic wave as it passes through a particle. When this happens, an electric dipole (p) is induced in the particle.

The magnitude of p is given by equation 1:

$$p = \frac{\pi \, \varepsilon_0 \, K \, d^3 \, E_{inc}}{2} \qquad \varepsilon_0 = 8.85 \times 10^{-12} \text{ Farads/m} \quad \text{(eq. 1)}$$

K is known as *Beer's Law absorption coefficient* and is a complex number representing the scattering and absorption properties of the dielectric. It is both wavelength and temperature dependent. Typical values of $|K|^2$ at 10 GHz/0°C are ~0.92 for liquid water and ~0.19 for ice. Therefore, this confirms that ice and snow are poorer scattering media than liquid water droplets of the same size and shape.

The particle then *re-radiates* the energy as an omni-directional dipole, creating what we observe as "scattered" radiation. Because the dipole is induced in the same plane as the incoming electric field, the scattered radiation maintains the polarity of the incoming wave. From this information it becomes possible to derive the *radar equation,* which specifies how much reflected power (P_r) can be expected from an object. It relates transmitted power, antenna gain, distance, and scattering properties of the object as follows[ref. 1]:

$$P_r = \frac{P_t \, G_t \, A_r \, \sigma}{(4\pi)^2 \, R_t^2 \, R_r^2} \quad \text{(eq. 2)}$$

P_t = transmitter power
G_t = gain of TX antenna
A_r = area of RX antenna
σ = scattering coef. of target
R_t = distance from TX to target
R_r = distance from target to RX

$$\sigma = \frac{\pi^5 \, | \, K \, |^2 \, d^6}{\lambda^4} \cos\theta \quad \text{(eq. 3) [ref. 2]}$$

One of the most common uses of this formula is in weather-radar applications. If we want to know how much signal is going to be backscattered by the target (as is the case with weather radar), $\theta = \pi$ and σ becomes known as the radar *cross-section* of the target. One should also notice that the re-radiated ener-

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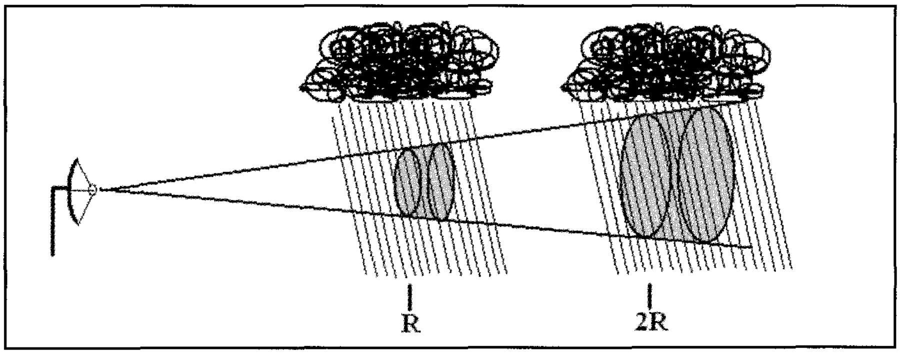

Figure 2. Reflected power is inversely proportional to R^2, not R^4, in distributed targets because the number of particles in the beam also increases with distance.

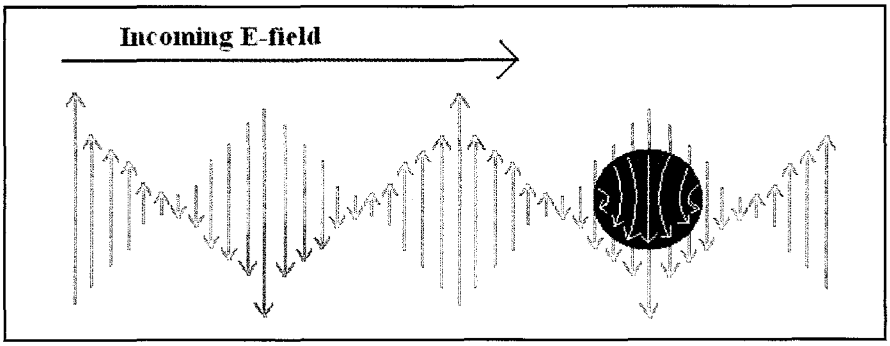

Figure 3. Distribution of electrical charge in Mie scattering.

gy is inversely proportional to λ^4. This, in combination with the power and antenna gain readily available to amateur operators, explains why 10 GHz is an ideal frequency for rain-scatter communication.

In radar applications $R_t = R_r$ so the reflected power varies with R_t^4. Scattered power that is inversely proportional to R^4 seems like a bad situation for long scatter paths. Fortunately, it is not *quite* as bad as that. Equation 2 is for *single* Rayleigh-scattering particle in the volume of the transmitted beam. In the case of a rainstorm, the radar beam is filled with many such particles, so the scattered radiation can be thought of as the sum of all their radiated powers. As the storm moves farther away from the transmitter, the number of particles in the transmitter's path increases proportionally to the square root of the distance (figure 2). Assuming that the transmitter does not under-illuminate the scattering medium, the scattered radiation becomes inversely proportional to R^2, not R^4.

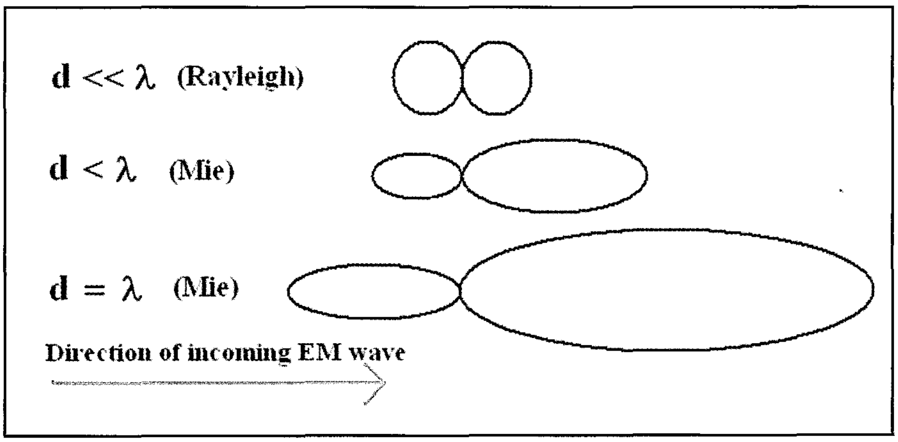

Figure 4. Approximation of radiation pattern as a particle progresses from Rayleigh to Mie scattering (H-plane).

Given the symmetry of Rayleigh scattering, this is true for both the forward-scatter and backscatter paths.

Scattering Principles II: Mie Scattering

Mie scattering occurs when the particle is of significant size that we can no longer assume that the E-field is constant across it (figure 3).

Given the complex interaction of the electric field inside the particle, the mathematics of Mie theory are quite rigorous and will not be covered here. The resulting radiation pattern can become equally complex, particularly when $d > \lambda$, but for a (roughly) spherical particle we can make some generalizations. Under most conditions there is a major lobe in the forward direction, and a lesser backscatter lobe—very much like the radiation pattern from a Yagi or log-periodic antenna. Because Mie scatterers have a larger volume than Rayleigh scatterers, the overall strength of the scattered signal tends to be larger. Mie scattering suggests the possibility for very strong *forward-scatter* propagation. Figure 4 illustrates these rough generalizations.

Both Rayleigh and Mie scattering have effects at amateur radio frequencies. The diameter of raindrops can vary between 0.5 mm in a light sprinkle to up to 5 mm in an extreme downpour. This means that the Rayleigh equations will apply to most propagation below 10 GHz (3 cm). Mie scattering will play a significant role mostly at 10 and 24 GHz, where thunderstorms can produce large raindrops and hail that are more accurately modeled by Mie scattering.[ref. 3]

Figure 5 shows the relationship between radiation pattern and drop size at 10 GHz. As one can see, larger drop sizes result in stronger signals in all directions. Mie effects begin to warp the dipole pattern when the drop size approaches 3 mm.

Since terrestrial amateur communication uses almost exclusively horizontal polarization, the scattered radiation pattern from a raindrop will look very much like that of a horizontal dipole (lefthand side of figure 5). We can treat a rainstorm as the sum of all of these particles such that the radiation pattern of an entire thunderstorm looks like that of figure 5. Using horizontal polarization will result in the strongest signals when the angle between the two stations (with the storm at the vertex) is closest to 0° (backscatter) or 180° (forward scatter). If one wishes to work

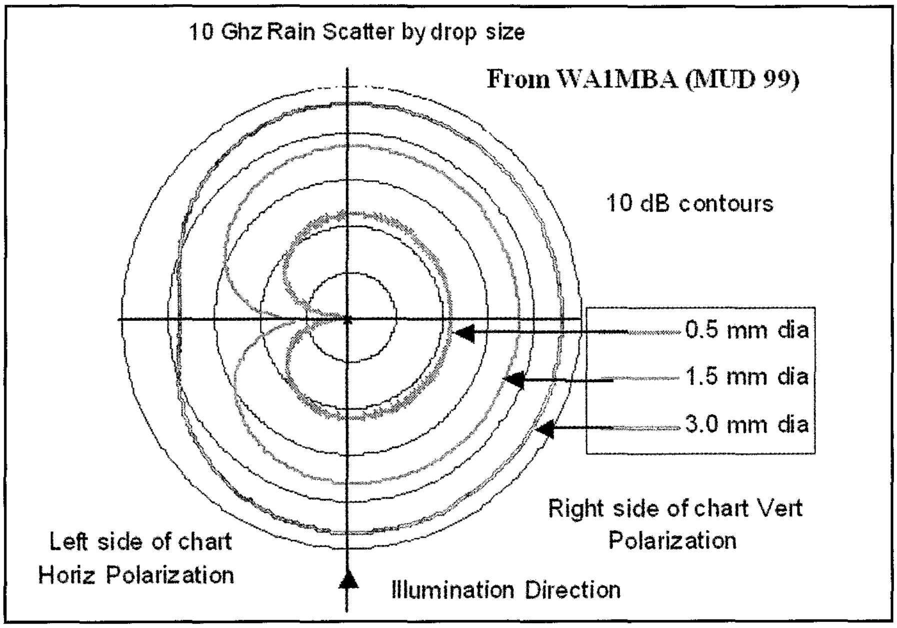

Figure 5. Scattering from spherical water droplets of different diameters at 10 GHz (from WA1MBA's presentation, MUD 99). Notice the large null at 90° with horizontal polarization.

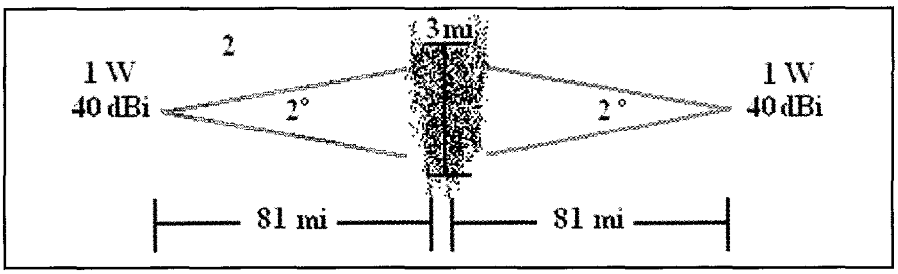

Figure 6. Two stations maximize signals when the same amount of scattering volume is illuminated.

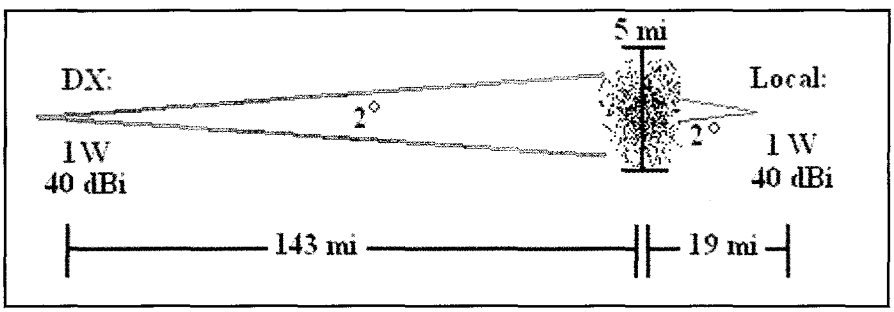

Figure 7. The storm in figure 6 has drifted to the right. The local station now under-illuminates the scattering volume of the DX station.

someone at a 90° angle, vertical polarization would probably work better.

Rain Scatter and Antennas: Bigger May Not Be Better!

Rain scatter has some propagation characteristics that may be counterintuitive to even experienced VHF operators. When making traditional link-budget calculations, we assume that the amount of power at the target is inversely proportional to the square of the distance between the source and the target. However, when we have a large distributed target such as a thunderstorm, it is possible to fully illuminate the target with the transmitter's beam. Because the target is sufficiently large, there is a point at which further narrowing of the transmitted beam (e.g., using a bigger dish) will only serve to under-illuminate the target, causing no increase in the scattered signal to the other station. This is a situation all too familiar to microwave EMEers.

To illustrate this point, figure 6 shows a situation in which the storm is equidistant from both stations. Both stations illuminate the storm equally with the same amount of power. This means that the average power density at the storm is equal from both stations. The E-field striking the water droplets is also the same and therefore their re-radiated (scattered) signals will be equal. If we assume Rayleigh scattering, we end up with equal signals at both stations.

Something interesting happens if the storm drifts to the right over time: The stations no longer illuminate an equal share of the scattering volume (figure 7). The DX station illuminates about 5 miles of the storm, while the local station only illuminates a little more than 0.5 miles. Both stations are still illuminating the storm with the same amount of power. The DX station still sees the same power density radiating from the storm, although it is unevenly distributed in his antenna's beamwidth. The local station is only able to see a fraction of the scattered signal from the DX station, but this loss in signal is made up by the local station's effective antenna area and proximity to the storm.

It turns out that to illuminate the same scattering volume using the distances in figure 7, the local station could use an antenna with a 15° beamwidth. This would result in no noticeable change in signal strength at the DX station, because the average power scattered by the storm within the DX station's beamwidth remains the same (figure 8). This means that a station using an 18-dBi horn held out of a window could be just as effective as a tower-mounted 1-meter dish for the local station, provided that each has an unobstructed view of the storm. This is almost certainly the case at the distances involved, as the common scattering volume is likely thousands of feet in the air and well above the horizon for the local station.

The point of this discussion is that more gain is not always better. The ability to switch to a medium-gain horn may actually help one make more contacts, as it is much easier to point, particularly in elevation, which will be necessary when the scattering volume is nearby. This should be encouraging news to people who live in areas with poor horizons. It also suggests that a big dish and a low noise fig-

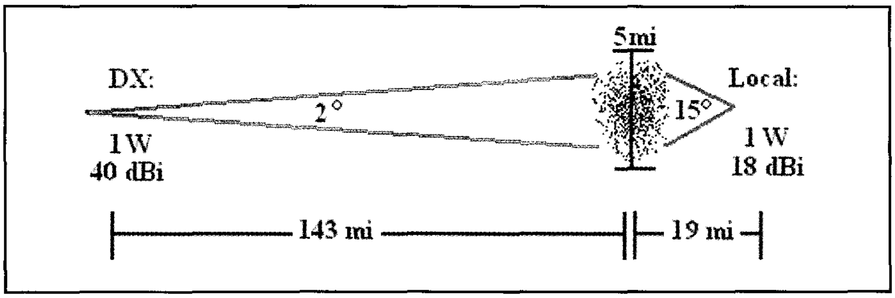

Figure 8. Local station switches to a medium-size horn antenna with no loss in signal at either end of the path.

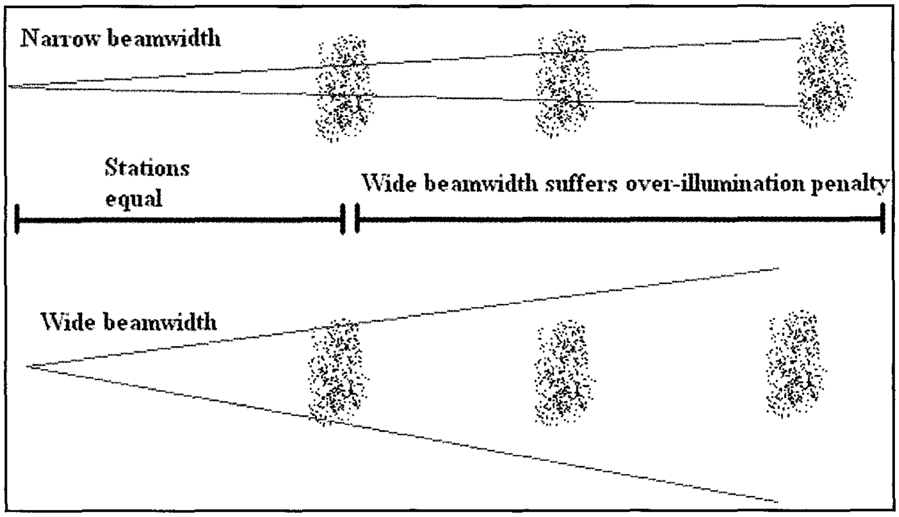

Figure 9. Over-illumination will cause extra path loss in the amount of power striking the scattering volume for increasing distance. A large dish with a narrow beamwidth will not incur these penalties as long as the storm remains under-illuminated.

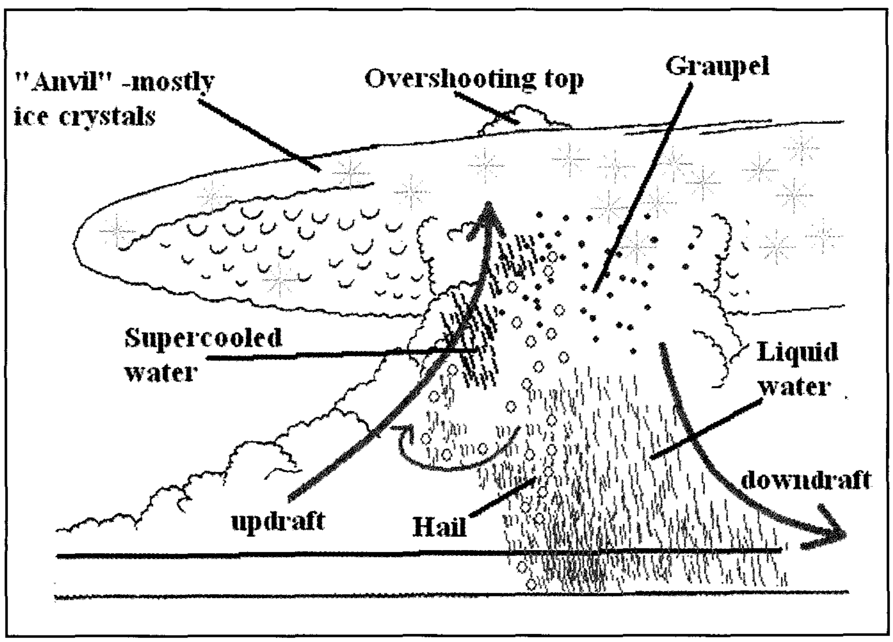

Figure 10. The anatomy of a supercell thunderstorm (view from south). (Adapted from NWS image)

ure are likely to be more helpful than a big amplifier for the stations who are located far from microwave population centers. Large dishes will not suffer over-illumination penalties except for storms at the fringes of its range (figure 9).

Anatomy of a Thunderstorm

Thunderstorms come in many shapes and sizes across the country. When it comes to rain-scatter communication, we would like to identify those storms that are likely to provide the strongest signals over the longest paths. Supercell thunderstorms are likely candidates to satisfy these criteria, as they tend to be quite tall and provide a large amount of moisture at high altitudes, thus increasing the potential scattering range. In addition, they tend to persist much longer than other single-cell thunderstorms, allowing them to be tracked by radar for long periods of time.

Figure 10 shows a supercell thunderstorm viewed from the south. This diagram also shows the primary forms of precipitation and where they can be found. The most effective scattering particles—large raindrops and hail—can be found in what is known as the *storm core*. The updraft can bring this reflective material very high into the storm, resulting in an "overshooting top" that penetrates the tropopause.

The storm core can extend tens of thousands of feet in altitude, especially if the updraft is strong. Hail forms in the storm core when supercooled water collides with (and instantly freezes to) either ice crystals or graupel (snow pellets) from above. The hailstone gains mass and starts to fall as more and more water droplets collide with it. Storms with very strong updrafts are able to circulate some of the hail back to the top of the storm many times, each time adding a new layer of water. This process results in very large hail sizes and the potential for strong scattering at lower microwave frequencies.

Figure 11 is an RHI (*range height indicator*) scan of an actual supercell thunderstorm. This is a 0.5° vertical slice of the storm showing the location of the most intense scattering material in the storm. This correlates well with the schematic drawing in figure 10. Hail shows up as the highest reflectivity because it is the most effective scattering medium. One can see that there is a large amount of water and hail held aloft

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Radar Data... *(from page 14)*

between 4,000 m and 12,000 m (13,000–40,000 ft). However, the *hail shaft*—where the hail actually reaches the ground—is only one or two miles across.

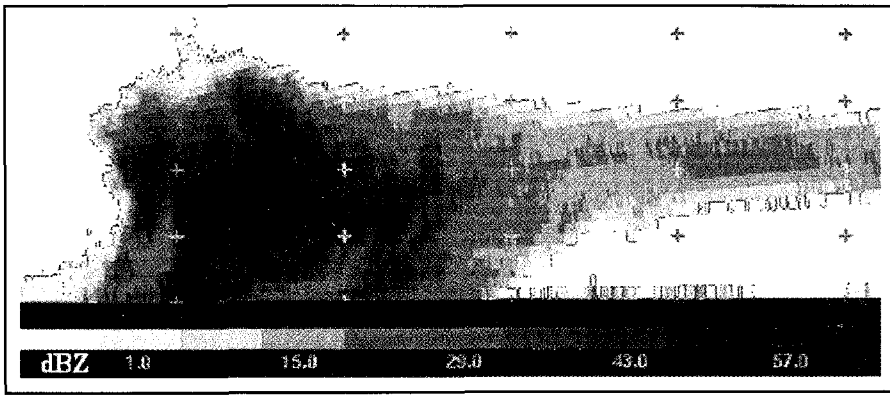


Figure 11. RHI scan of a supercell at 3 GHz showing a storm core of hail and rain. Darker colors represent stronger radar returns. Vertical divisions are 4000 m. View is from the south.

Using Radar Data to Predict Propagation

Most of the continental United States is covered by the NEXRAD (Next Generation Radar) network shared by the FAA, NOAA, and the Department of Defense. The raw data from these radar sites is made freely available to anyone on the internet. The most familiar manifestation of this data is presented in the form of the color radar maps available on the web. [ref. 4]

The NEXRAD radars operate at 3 GHz and record three sets of raw data: reflected power from the target, the "spectral width" of that reflection, and wind velocity data. The first is an indication of *how much* precipitation the target contains, and the latter two are used in determining wind velocity information. Precipitation particles are smaller than $\lambda/10$ at this frequency (i.e., < 1 cm), so meteorologists can use the NEXRAD with Rayleigh scattering equations to estimate rainfall. Meteorologists apply complex algorithms to these sets of raw data (often programmed into the radar itself) to detect severe-weather events such as large hail, damaging winds, and tornados. This same data has the potential to provide information to amateur radio operators wishing to attempt forward-scatter communications. In order to adapt it for that purpose, we need to understand how the radar operates and how to interpret the information it provides.

The NEXRAD makes *plan position indicator* (PPI) scans. These are scans in which the elevation angle of the radar is fixed while making a 360° azimuthal sweep. This is similar to how aircraft radars work, except that the scan rate is much slower. The radar can reconstruct RHI scans (similar to the one in figure 11) by making several such sweeps at different elevation angles. The different scans can be combined like an onion peel to produce a 3-D picture of the weather. [ref. 5] The collection of all scans at all elevations is called a *volume coverage pattern (VCP).*

The NEXRAD has two main VCPs: *clear-air* mode and *precipitation* mode (figure 12). Clear-air mode is the most sensitive and is used to detect weakly reflective objects. The radar moves more slowly in this mode in order to integrate more reflected energy from a given volume of air. When the radar is clear-air mode, most of what is displayed is airborne dust, insects, and birds. Fine snow is also a very poor reflector, so the clear-air mode is often used in the winter to detect snowfall. It takes about 10 minutes for the NEXRAD to complete a VCP in clear-air mode.

The precipitation mode is used for analyzing the vertical structure of storms. It makes many scans from 0.5 to 19.5 degrees to give information on vertical storm structure. The National Weather Service provides this information in two different forms on its web server—either as a *base reflectivity* or *composite reflectivity* image. The base reflectivity shows the reflectivity of the lowest elevation scan (usually 0.5°). The composite

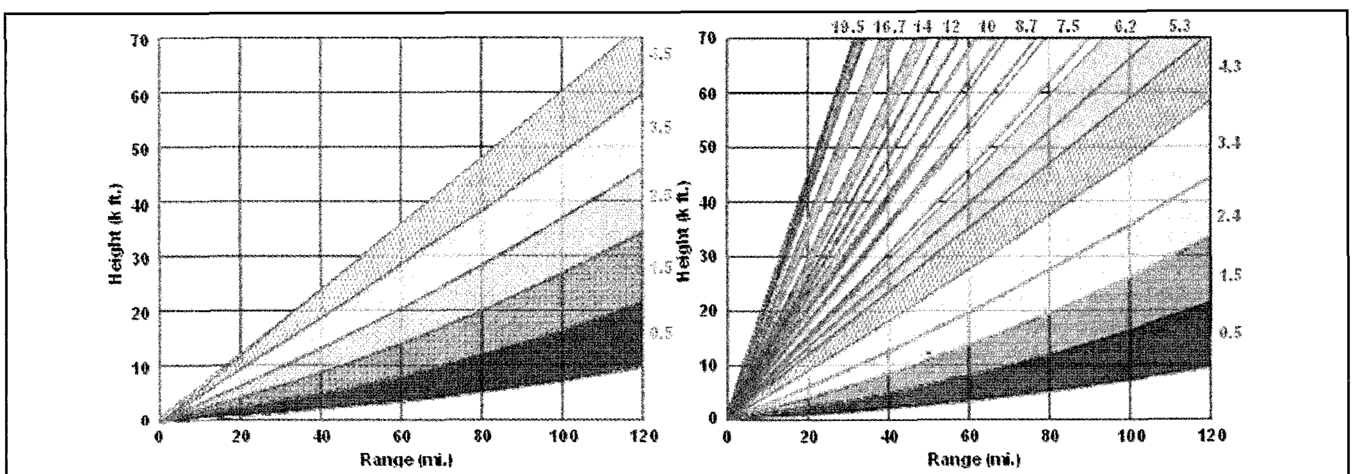
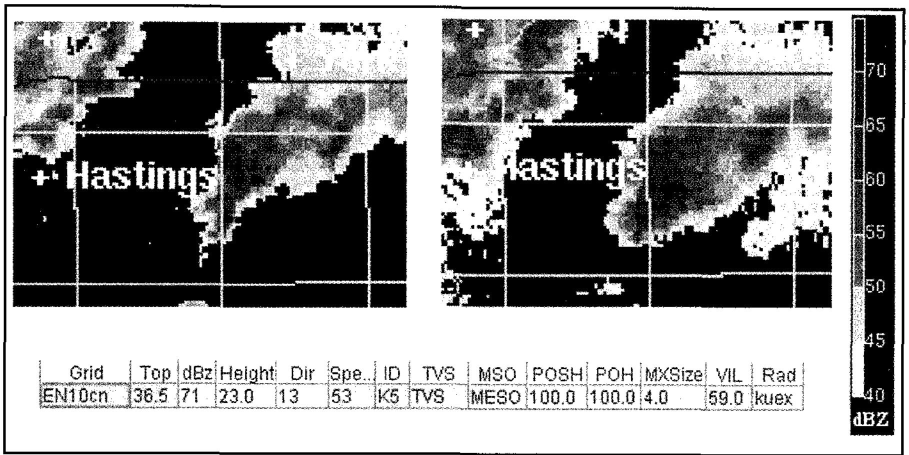


Figure 12. (Left) VCP for clear-air mode. (Right) VCP in precipitation mode. Numbers on the top and right of the figures indicate the elevation of the scans in degrees. The curvature of the Earth limits the lowest visible altitude at long distances. (National Weather Service images)



Grid	Top	dBz	Height	Dir	Spe..	ID	TVS	MSO	POSH	POH	MXSize	VIL	Rad
EN10cn	36.5	71	23.0	13	53	K5	TVS	MESO	100.0	100.0	4.0	59.0	kuex

Figure 13. (Left) Base reflectivity of severe storm east of Hastings, NE. (Right) Composite reflectivity of same storm showing a large amount of hail and water held aloft by a very strong updraft that is not visible on the base reflectivity scan (11 May 2005). Entry from the storm attribute table suggesting extremely large hail and a possible tornado.

reflectivity image displays the highest reflectivity out of all of the elevation scans. [ref. 6] The NEXRAD is able to complete a precipitation-mode VCP in about 5 minutes. A comparison between the base and composite reflectivity can reveal a large scattering volume at high altitudes (figure 13).

The measurable reflectivity from objects in the atmosphere can vary over eight orders of magnitude (e.g., from air turbulence on a clear afternoon to large hail in a severe thunderstorm), so the NEXRAD reports reflectivity on a logarithmic scale. This value is measured on a scale from –20 to +75 *dBZ*. *Z* is a measure of reflectivity per unit volume, and it is a way of taking the distance between the radar and the target out of the equation. That is to say, a distributed target that has a reflectivity of 55 dBZ is 55 dBZ if it is 20 miles or 200 miles from the radar site, provided that the target fills the entire beam path. This is important to know when reading a radar chart labeled in dBZ, as large reflectivity values far from the radar are not any more reflective than those same values near to the radar, even though the echoes themselves are weaker in terms of total reflected power. This dBZ value is derived from the Rayleigh equations and assumption discussed above, summed over all of the particles (assumed to be many little electric dipoles) present in the volume of the radar beam. The following offers a rough guide to the dBZ scale:

1-mm diameter raindrop per m^3 = 0 dBZ
2-mm diameter raindrop per m^3 = 3 dBZ
Light rain = 20–30 dBZ
Moderate rain = 30–40 dBZ
Heavy rain = 40–50 dBZ

Avid radar watchers will recall seeing values of 60+ dBZ regularly in severe thunderstorms. These abnormally high values are usually a sign of medium to large hail. While ice itself is a poor scattering medium (about 5 dB weaker than a raindrop of the same volume), hailstones can grow much larger than water droplets. This can easily make up the difference between the two. Moreover, a hailstone can get a coating of water as it is hurled around inside the storm below the freezing line. This gives it the appearance of a *very* large raindrop. Hail is bad news for meteorologists trying to predict accurate rainfall amounts using radar reflectivity (not to mention to hapless automobiles below), but great for hams wishing to work DX on the microwaves. This effect of hail is readily seen in the large reflectivity values in the supercell of figure 13.

For our purposes, we can think of the dBZ values reported by the NEXRAD as a measure of backscatter at 3 GHz. We can use that measure of backscatter to extrapolate what propagation might be like at other frequencies. If we assume the storm has no hail in it, we can count on Rayleigh scattering to give us a fairly accurate model of propagation through 10 GHz. Since the scattered signal is inversely proportional to λ^4, 10 GHz should be about 12 dB stronger than at 5 GHz, *ceteris paribus*. This is indeed something that has been observed in prac-

Storm Table

Grid	Top	dBz	Height	Dir	Speed	ID	TVS	MSO	POSH	POH	MXSize	VIL	Rad
EM44pv	18.4	51	4.2	74	19	V8	NONE	NONE	0.0	0.0	0.0	10.0	knqa
EM45sd	11.3	53	5.4	45	8	A8	NONE	NONE	0.0	0.0	0.0	9.0	knqa
EM44rv	12.2	48	8.0	60	24	R7	NONE	NONE	0.0	0.0	0.0	7.0	knqa
EM44pu	10.1	48	4.7	NEW	NEW	K1	NONE	NONE	0.0	0.0	0.0	6.0	knqa
EM44lm	16.3	44	8.4	NEW	NEW	A2	NONE	NONE	0.0	0.0	0.0	5.0	knqa
EM45uc	12.0	51	7.1	NEW	NEW	G2	NONE	NONE	0.0	0.0	0.0	4.0	knqa
EM44ru	8.4	46	3.8	NEW	NEW	B8	NONE	NONE	0.0	0.0	0.0	4.0	knqa
EM45tj	8.5	45	8.5	84	16	J1	NONE	NONE	0.0	0.0	0.0	3.0	knqa
EM44wl	10.5	39	5.1	69	16	G0	NONE	NONE	0.0	0.0	0.0	2.0	knqa
EM44wn	9.6	40	4.4	57	16	Z1	NONE	NONE	0.0	0.0	0.0	2.0	knqa
EM44qx	8.3	41	3.8	NEW	NEW	E2	NONE	NONE	0.0	0.0	0.0	2.0	knqa
EM44nu	17.3	41	11.9	125	10	A0	NONE	NONE	0.0	0.0	0.0	2.0	knqa
EM45wg	9.1	45	9.1	NEW	NEW	T1	NONE	NONE	0.0	0.0	0.0	2.0	knqa
EM45pe	7.5	42	7.5	47	21	N0	NONE	NONE	0.0	0.0	0.0	2.0	knqa
EM45wl	9.0	43	9.0	33	20	Y9	NONE	NONE	0.0	0.0	0.0	2.0	knqa
EM45th	8.5	46	8.5	6	2	C2	NONE	NONE	0.0	0.0	0.0	1.0	knqa
EM44xr	10.4	39	10.4	80	22	Z8	NONE	NONE	0.0	0.0	0.0	1.0	knqa

Figure 14: Example storm table from Memphis NEXRAD Radar (KNQA) on 5 May 2005 at 11:50 AM as displayed by RainScatter.

tice. We can expect signals on 3.4 and 2.3 GHz to be accordingly weaker.

Very high dBZ values from the NEXRAD are indications of hail and that Mie scattering is starting to take effect at the higher microwave frequencies. Propagation will probably be strongest when the storm is located on the great-circle path between the two stations. Very high dBZ values are also an indication that rain-scatter QSOs may possible at 3.4 and 2.3 GHz—not something very common with the ERP of most ham stations.

For a propagation path to exist, the scattering volume must be above the horizon for both stations. Fortunately, each NEXRAD provides a *storm attribute table* that includes information about each storm cell within 214 miles of the radar site. This table includes information about maximum reflectivity, height, location, speed, direction, estimated precipitation (both rain and hail), as well as information for severe weather prediction. Figure 14 shows the storm attribute table for the Memphis radar during an outbreak of small, convective thunderstorms.

Of particular interest are the "top" and "height" categories. The echo top is the highest altitude (in 1000's of feet) that the radar detects precipitation (>18.5 dBZ reflectivity). The "height" category is the altitude at which the maximum reflectivity (the dBZ value) was recorded, and is a rough indication of how much scattering material is present in the storm core. It becomes possible to calculate the visible "footprint" of a storm to estimate its useful scattering range at microwave frequencies.

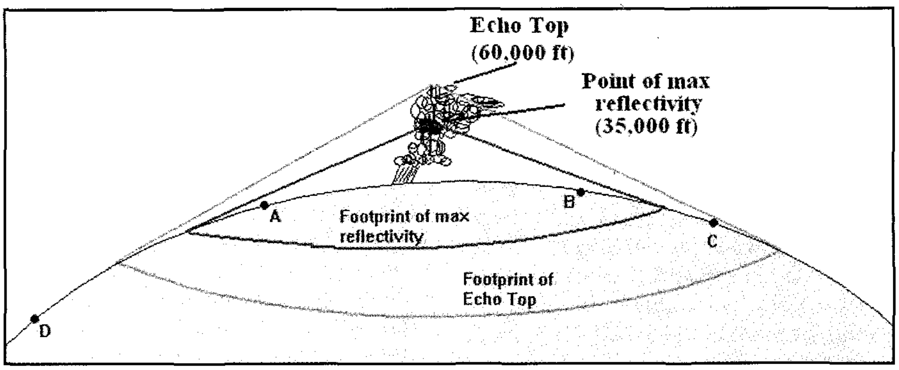


Figure 15. Footprint of a supercell thunderstorm with echo tops at 60,000 ft.

Figure 15 shows how the "top" and "height" data can be used to predict propagation paths. Stations A and B can both see the point of maximum reflectivity and have the potential for very strong signals. C can communicate with both A (forward scatter) and B (backscatter). D is unable to participate because the storm is below the horizon. The diameter of echo top's footprint is more than 600 miles for a 60,000-ft storm. [ref. 7]

Another useful category is the *vertically integrated liquid* (VIL) estimation. This is a measure of the amount of liquid water that could be condensed out of the storm core measured in kg/m^2. Large VIL numbers in a convective thunderstorm are indicative of a large amount of water, thus larger water droplets and more effective scattering at microwave frequencies. The TVS and MESO categories provide information on severe weather events. TVS stands for *tornadic vortex signature*—a sign of a possible tornado. MESO stands for *mesocyclone*—a term for large-scale storm rotation. Both of these phenomena correlate with strong updrafts in the storm core.

RainScatter Software

Storm Attribute Tables usually can contain a massive amount of data on a stormy day; a single radar site may have 50 or more storm cells identified. Calculating footprints for each one becomes a

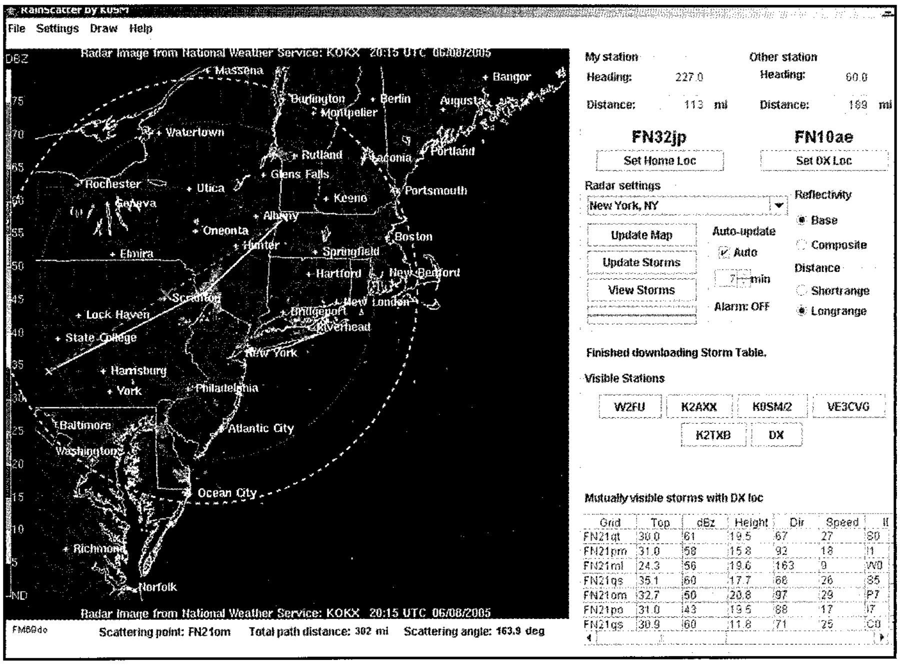


Figure 16. Screenshot of RainScatter *version 1.0. The window at the left is the radar image provided by NWS with the storm's footprint overlayed. Bearing and distance information is in the upper right. The storm attributes table is shown at the bottom right. Above the storm attributes table are buttons that will filter the storm table to show only storms that are mutually visible with that station.*

chore if it is done manually, and since large storms often move at 50 mph or faster, time is of the essence. Sorting out the possible propagation paths is something best done with a computer.

This is where the *RainScatter* software comes in (figure 16). [ref. 8] *RainScatter* downloads the Storm Attribute Tables and quickly calculates the footprint for each storm. This data can be overlaid onto the radar reflectivity maps provided by the National Weather Service, also available on the internet. This makes finding and tracking potential paths much easier for the operator. In addition, one can store locations of other stations and filter only the storms that are mutually visible to both. *RainScatter* does not take all of the guesswork out of rain-scatter communication, but it does provide the operator with data to make informed decisions.

RainScatter has the potential to mobilize activity on 10 GHz and other microwave bands when it may have otherwise gone unnoticed. A large supercell can persist for hours, opening up the possibility for QSOs over an entire region of the country. Everyone running the software will be able to see the same accurate picture of the weather and know which storm is in range and how much potential it has for rain-scatter propagation.

RainScatter can reduce our reliance on VHF liaison for 10-GHz DX. First of all, the path for the 2-meter liaison is often not the same as the skewed microwave path. Given the footprint of a very large storm, two stations may have a harder time finding each other on VHF than they would on 10 GHz. Secondly, large thunderstorms can provide scatter communication well beyond what a VHF station can provide, especially when one considers the amount of noise generated by a thunderstorm. This is even more the case for those operating portable 10-GHz stations. One can imagine the awareness of large thunderstorms adding an exciting twist to the summer contests, or just spicing up a lazy summer afternoon.

Notes

1. A_r is the *effective area* of the antenna. This can be calculated from the gain: $A_r = (\lambda^2/4\pi)\log(g)$ where g is the gain in dBi.

2. θ is the scattering angle measured in the plane of polarization. This creates the dipole radiation pattern we see in figure 1.

3. WA1MBA provides the radiation patterns for all amateur bands above 10 GHz. At the time of this writing I am not aware of any rain-scatter communication on amateur radio frequencies at 47 GHz or above. However, the radiation patterns have very strong forward-scatter lobes at millimeter wavelengths. (See T. Williams, WA1MBA, "Rain Scatter, SHF and EHF," in *Proceedings of Microwave Update '99,* ARRL, 1999, pp. 150–163.)

4. The national radar mosaic showing the coverage of all ~140 radar sites is available from the National Weather Service at <http://weather.noaa.gov/radar/mosaic/DS.p19r0/ar.us.conus.shtml>. A description of the available radar products is provided by the NWS's Telecommunication Operations Center at <http://www.nws.noaa.gov/tg/rpccds.html>. This site provides a link to the FTP server.

5. The National Weather Service does not provide RHI scans on its web server. Such information is usually reconstructed from the raw data by third-party programs in use by researchers and severe-weather analysts.

6. For more information on the NEXRAD radars and the NWS's web-based products, see <http://radar.wrh.noaa.gov/radar/radinfo/radinfo.html>.

7. It will be interesting to see which numbers have a greater effect on propagation. The echo top measurement may only have reflectivity of 18.5 dBZ, which is not a very strong reflection. This suggests that the height of maximum reflection might be a more useful indicator.

8. *RainScatter* is freely available under the GNU Public License at <http://frontiernet.net/~aflowers/rainscatter>. It requires a Java Runtime Environment (JRE) 1.4.2 or later.