**Tropospheric Scatter (Troposcatter) Propagation for VHF, UHF, and Microwave Frequencies**

by Roger Rehr, W3SZ

Introduction. VHF and UHF frequencies have multiple potential propagation modes which include (depending on frequency) Line-of-Sight, Sporadic E, F2, Ionospheric Scatter, Field Aligned Irregularities (FAI), Meteor Scatter, Aurora, Aircraft Scatter, Tropospheric Ducting, EME, TransEquatorialPropagation (TEP), and Tropospheric Scatter (Troposcatter). At microwave frequencies Line-of-Sight, EME, Aircraft Scatter, Rain/Snow Scatter, Knife-Edge Diffraction, Tropospheric Ducting, and Troposcatter are available. The purpose of this paper is to discuss tropospheric scatter (troposcatter).
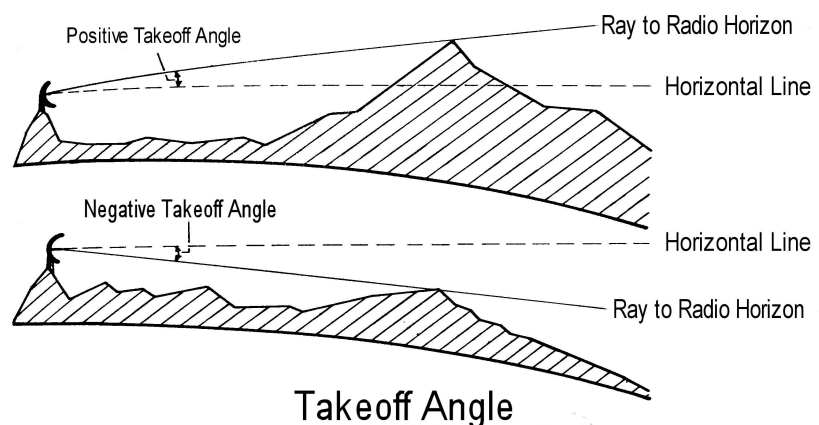
The troposphere is the lowest portion of the atmosphere. Most of our weather takes place in the troposphere. It contains 80% of the atmosphere's mass and 99% of its water vapor. The troposphere begins at ground level, and its height varies from about 20 km near the equator to 17 km in the mid-latitudes to 9 km near the poles in summer. Its height is greater in summer than in winter. The upper boundary of the troposphere is a temperature inversion called the tropopause, which separates the troposphere from the stratosphere. The pressure of the atmosphere is greatest at the surface and decreases with height. Because the temperature of the troposphere also decreases with height (by approximately 6.5 degrees C per km) and saturation vapor pressure decreases with decreasing temperature, the water vapor content of the atmosphere decreases strongly with altitude. The troposphere has irregularities in temperature, pressure, and water vapor content due to stratification and turbulance, and it is believed that these irregularities, and their effects on electromagnetic wave refraction, are the basis for tropospheric scatter.

Troposcatter occurs when two stations both point their antennas at a common volume in the troposphere, and that volume of the troposphere redirects the signal directed into it by one station towards the receiving antenna of the second station. The useful range of troposcatter is roughly 100 to 700 km, and it can be used from 144 MHz through 10 GHz.
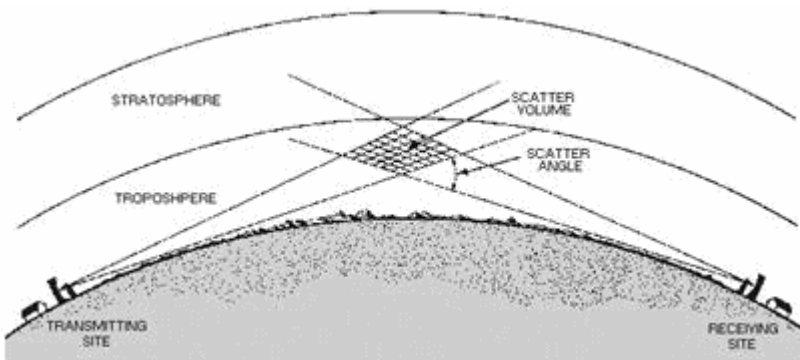
The illustration on the left shows a troposcatter path between two sites. The scatter volume is marked by cross-hatching, and the scatter angle, which is the angle between the radio horizon rays of the two stations, is labeled "scatter angle". The radio horizon ray for an antenna is the ray that marks what is called the "take-off angle" for the antenna, which is the lowest elevation angle that will clear all obstructions in the direct path to the other station. The take-off angle depends on the relative heights of the antenna and the obstruction and the distance between them. Take-off angle can be either positive or, with favorable geography, negative, as shown in the illustration on the right, taken from Roda[1].
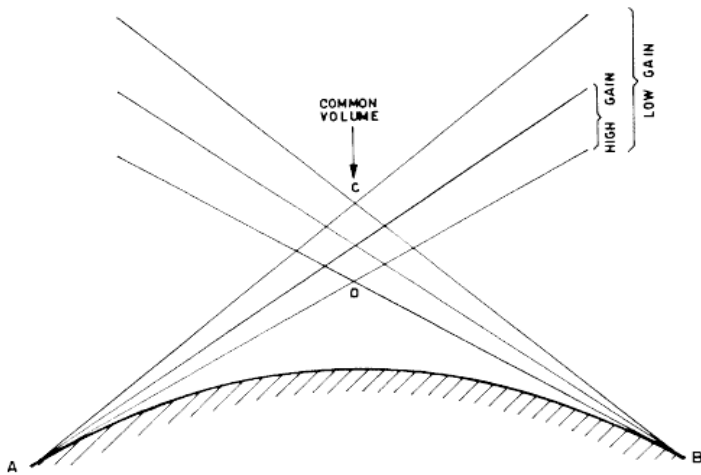

Takeoff Angle

As is shown on the left, high-gain antennas with smaller beamwidths will illuminate a smaller scatter volume than will low-gain antennas with larger beamwidths.

Thus high-gain antennas would be expected to result in less scattered signal due to the smaller volume, and thus more troposcatter loss, and this is in fact the case.

Fig. 4.7   Relation between antenna gain and common volume.

Troposcatter was widely used by the military prior to the availability of satellite communications systems. The figure on the right shows a NATO troposcatter circuit, and the figure below shows one of the antenna installations associated with this circuit. Large antennas and high power were typical.
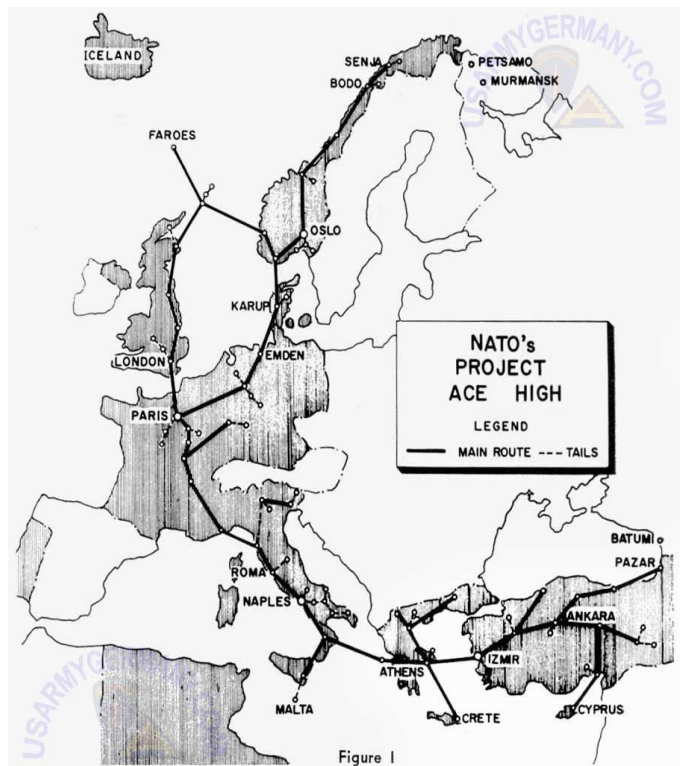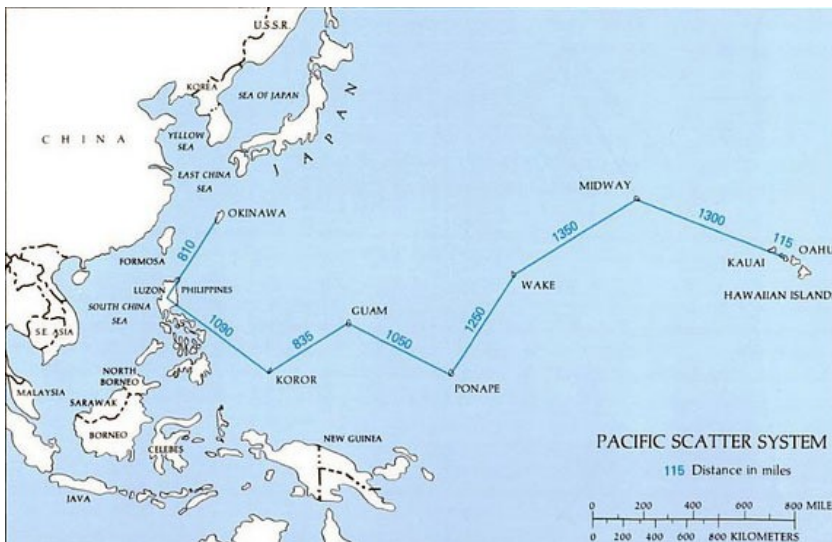

Figure I

PACIFIC SCATTER SYSTEM

The illustration on the left is of a US Military troposcatter circuit spanning the Pacific. You can see that many of the hops are in excess of 1000 km, and the longest link is 1350 km.

These troposcatter circuits were noted for their reliability, and several methods were developed for predicting troposcatter path losses so that these circuits could be properly designed.

Troposcatter on the Amateur Microwave Frequencies. Microwave contacts beyond 100 miles (160 km) are generally made with troposcatter, unless other scatter modes such as aircraft scatter or rain/snow scatter, or EME are being used. So it is important to understand the characteristics of troposcatter. Bob Atkins, KA1GT, wrote an excellent article discussing troposcatter, and in particular, the Yeh method of calculating tropscatter loss, which was published in Communications Quarterly in Winter 1991. Bob maintains an excellent webpage at http://www.bobatkins.com/radio/scatter2.html from which you can download his article, and an updated version of the software that he describes in that article[2].

The theory of tropscatter path loss is not completely settled, and there are several methods for estimating the loss, which can give quite different results for the same input data. These methods range from those that are based primarily on theoretical constructs (but still with some empirical factors) to those that are primarily empirical, being based on experimental data gathered from troposcatter circuits. Before getting into the details of those theories, I want to present a broad outline of the factors that affect troposcatter path loss, using the results of the Collins and Yeh methods for the discussion, because these models appear to provide the best agreement with experimental data.

The loss incured over a tropospheric scatter path is determined by the length of the path, the frequency used, the beamwidths of the antennas at each end of the path, and the scattering angle, which is a function of the take-off angles of the two stations and the great circle distance between the stations. From a practical standpoint, the path will be adequately defined by specifying its length, the frequency used, the beamwidths of the antennas at each end of the path, and the antenna height, height of radio-horizon-determining obstruction, and distance to that obstruction for each station. In addition, some formulas make use of Ns, the atmospheric refractive index, but it turns out that these formulas perform more accurately if the value of Ns is set to a constant value.

Troposcatter loss is very strongly dependent on takeoff angle, and so choosing optimal siting of the antennas at both ends of the path is essential to minimize path loss, as the graph and discussion below demonstrate. Optimal siting means getting the antenna as high as possible, and minimizing the height of the radio-horizon-determining obstruction, and maximizing the distance to that obstruction, thus minimizing the take-off angle at both ends of the path.

You can see from the graph below that according to the Collins formula for troposcatter loss, as the total takeoff angle (sum of the takeoff angles for the two stations) increases from -1 degree to 0 degrees, 11 dB of signal is lost. As the total takeoff angle increases further, from 0 to 1 degree, the loss increases to 20 dB. Increasing the total takeoff angle to 2 degrees increases the loss to 28 dB, and increasing the total takeoff angle to 3 degrees brings the total signal loss compared with a total

Troposcatter Loss vs Total Takeoff Angle
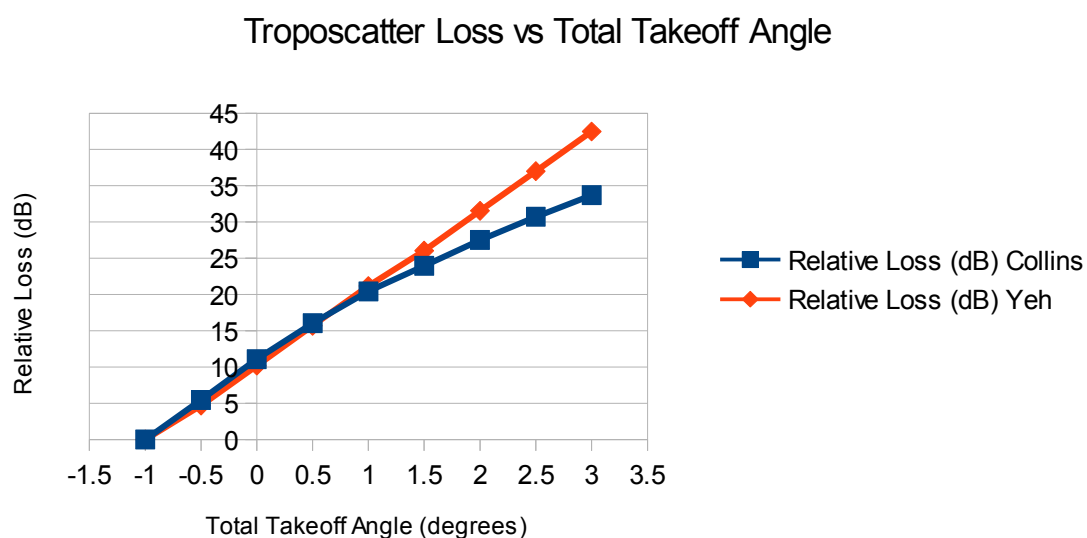
takeoff angle of -1 degree up to 34 dB. The Yeh formula predicts even greater losses with increasing total takeoff angle, with the loss at a 3 degree takeoff angle predicted to be 43 dB greater than with a -1 degree take-off angle. Clearly, optimizing one's takeoff angle is essential! Under ideal circumstances, takeoff angle will be horizon limited; that is, there will be no obstruction between your antenna and the horizon. The higher you can place your antenna, the lower (better) will be your takeoff angle, whether or not it is horizon limited.

The table on the right shows the additional scattering loss caused by increasing antenna gain (decreasing beamwidth). While this signal loss must be taken into account

Gain per array (db)	Beamwidth total (degrees)	Relative Loss (dB) Collins	Relative Loss (dB) Yeh
0.1	162.44	0	0
10	52.96	0	0.1
20	16.43	0.03	0.4
30	5.2	0.32	1.34
40	1.64	4.64	4.06
50	0.52	18.63	10.25

when calculating link budgets, the extra scattering loss that is accrued as antenna gain increases is clearly outweighed by the extra signal strength achieved with the greater antenna gain. For example, with 50 dB gain antennas at each end of the circuit, 100 dB of signal is added by the antennas (50 dB at each end), and only 10.25 to 18.63 of extra scattering loss is incurred.
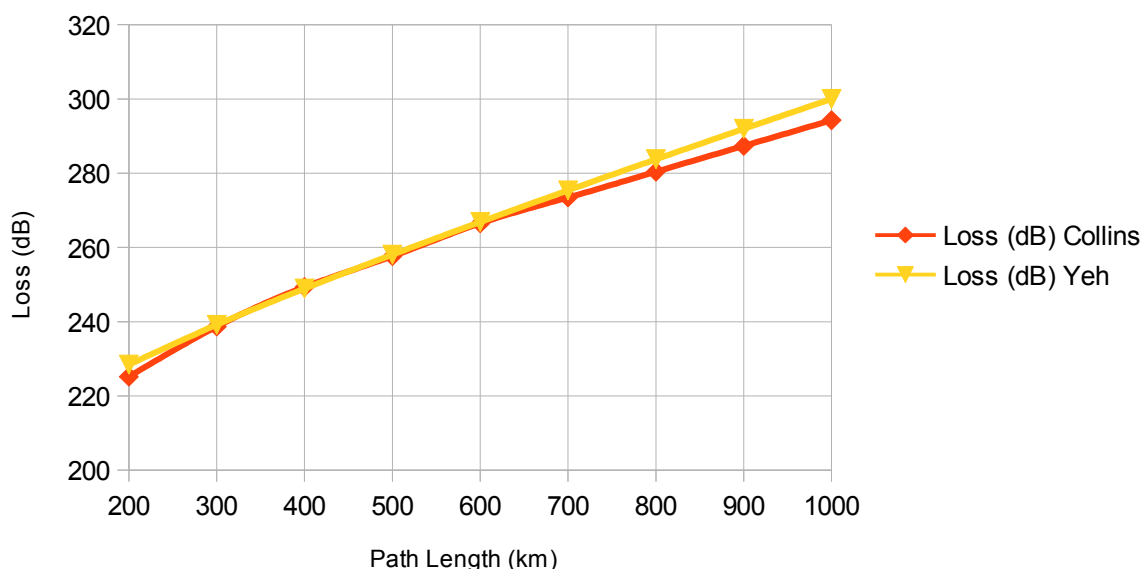
As frequency increases, troposcatter path loss increases by 30 log f2/f1 according to both the Yeh and Collins formulas. This is shown in the graph below, for the amateur radio bands from 144 through 10368 MHz. Remember that for constant aperture, antenna gain goes up by 20 log f2/f1 at each end of the circuit. This will mitigate the increasing troposcatter path loss with increasing frequency, if antenna aperture size is kept constant with increasing frequency.

Relative Loss vs Frequency (dB)
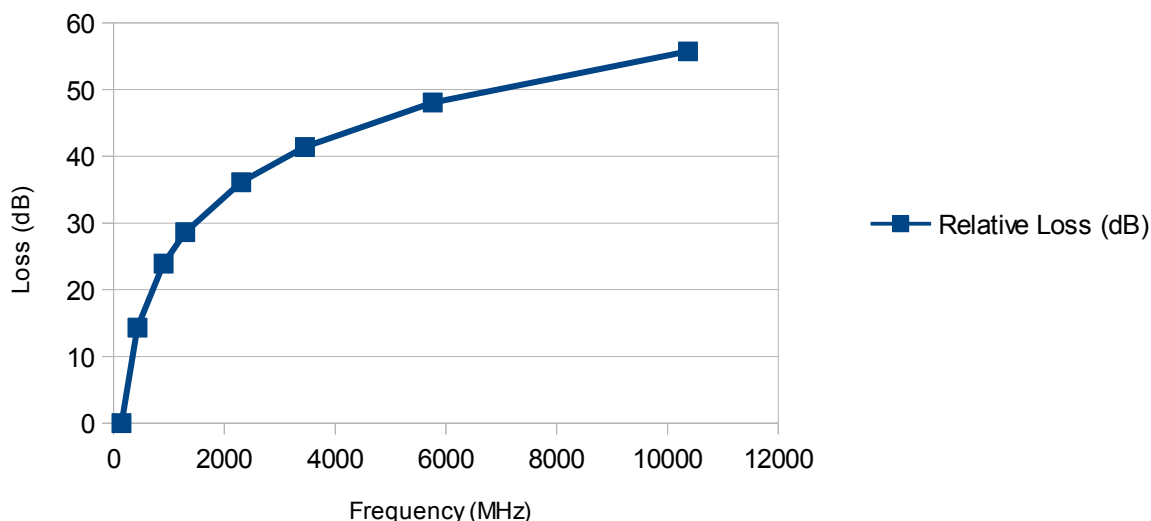
The behavior of troposcatter path loss as a function of path length is complex, because it depends not only on free-space loss directly, but also on scatter angle, which is a function of path length as well as take-off angle of each of the two stations. At the extremes of distance, the Collins formula predicts less loss than does the Yeh formula. For example, at a distance of 200 km, the Collins formula predicts 3.2 dB less loss than does the Yeh formula, and at 1000 km the Collins formula predicts approximately 5.7 dB less loss than does the Yeh formula. However, for intermediate distances the two formulas provide similar estimates of path loss. These differences are small when looked at as a percentage of the overall loss, which is on the order of 220-230 dB at 200 km, and on the order of 290-300 dB at 1000 km. Path parameters used to generate the values just presented and the graph below include a total take-off angle of 1.025 degrees, antenna gain 37 dB at both ends of the path, Ns = 310, and frequency 2304 MHz. Height parameters for both stations are antenna = 188 m, obstruction = 197 m, and distance to obstruction = 1 km. These parameters give a take-off angle of 0.512 degrees for each station, and thus the total take-off angle of 1.025.
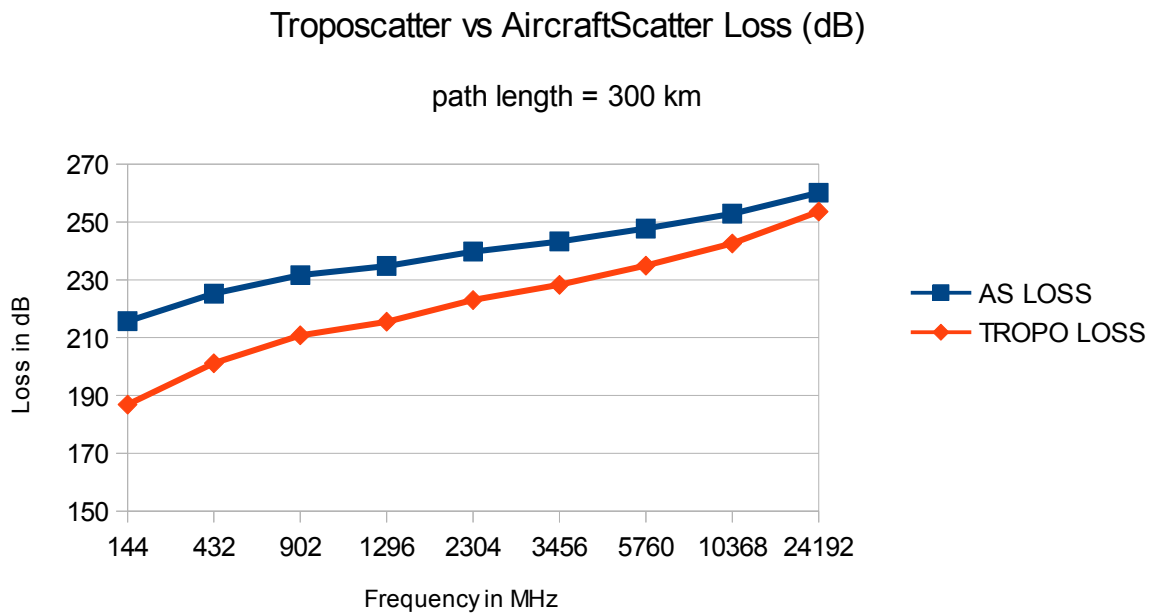
Troposcatter Loss vs Path Length

So you can see that to minimize troposcatter path loss, you want to minimize take-off angle, minimize antenna beamwidth, minimize frequency, and minimize path length. But as noted, the increased scattering loss produced by increasing antenna gain, within the range of antenna gains likely to be used by radio amateurs, is more than compensated for by the greater signal delivery to and from the antenna when higher gain antennas are used at each end of the circuit. And with increasing frequeuency you get greater array gain for a given aperture, mitigating the increased path loss with increasing frequency. In general, for the greatest chance of successful communications at a given frequency and over a given path length, one will want to use the highest gain antennas available, and place those antennas as high as possible, so that the lowest possible take-off angle is achieved at both ends of the circuit.

To give you a sense of how well troposcatter does relative to, for example, aircraft scatter, I used my program AircraftScatter Sharp[3][4][5] to calculate predicted path loss for troposcatter and aircraft scatter over identical paths of 300, 677, and 948 km, to represent short, medium, and long paths. The distance of 677 km was chosen for a medium path because that is the length of the path between W3SZ and W4DEX, which is a busy aircraft scatter path. Results will be shown below.

Note that these comparisons do not include the effect on the aircraft scatter signal of Forward Scatter Enhancement, which can add up to 15-20 dB to the strength of the aircraft scatter signal, if the forward scattering angle (in 3 dimensions) is less than about 6 degrees. As the forward scatter angle increases, the Forward Scatter Enhancement drops off dramatically, so that by a forward scatter angle of 30 degrees (which represents a skew angle of only 15 degrees at each station), the maximum Forward Scatter Enhancement is reduced to only 6 dB.

All of the following analyses will use path parameters of total take-off angle -0.45 degrees and antenna gain 34 dB at both stations.

At a path length of 300 km, troposcatter loss is always less than aircraft scatter loss, with the difference in loss being 29 dB at 144 MHz and 7 dB at 24192 MHz. This is illustrated in the figure below.

Troposcatter vs AircraftScatter Loss (dB)
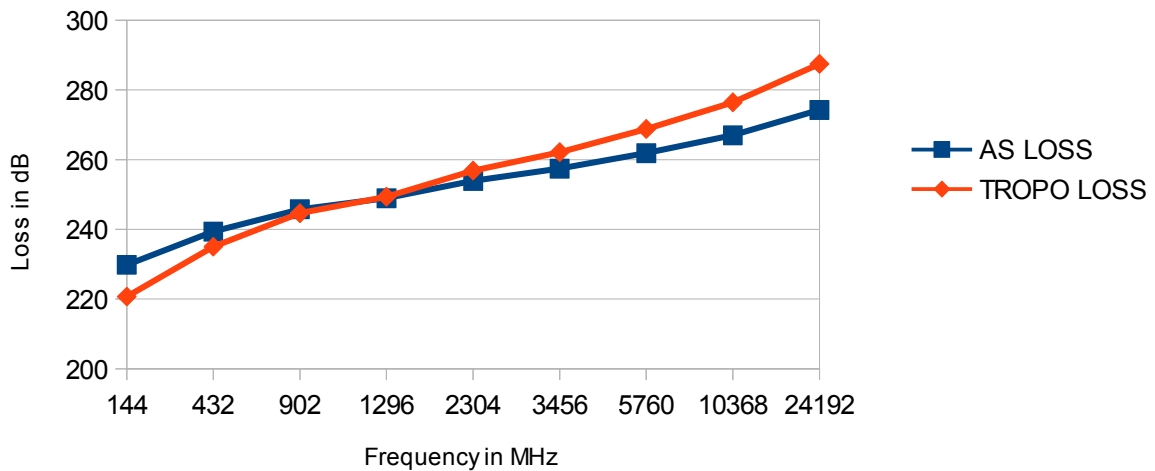
path length = 300 km

For a path length of 677 km, troposcatter has 9 dB less loss at 144 MHz, but 13 dB more loss at 24192 MHz, with the cross-over occurring at 1296 MHz. This is shown in the graph below.

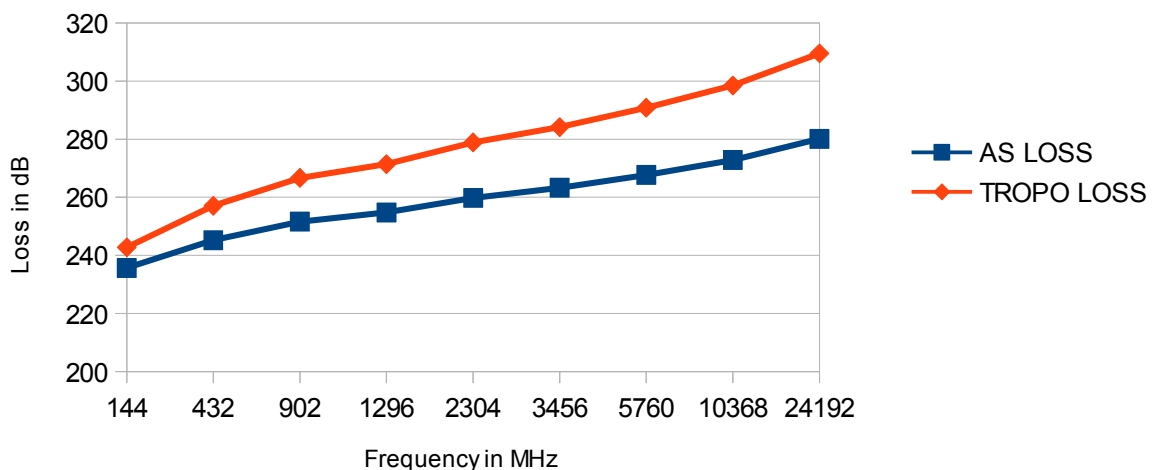## Troposcatter vs AircraftScatter Loss (dB)

path length = 677 km

For a long path length of 948 km, troposcatter is always worse than aircraft scatter. Troposcatter gives 7 dB more loss than aircraft scatter at 144 MHz, and 29 dB more loss at 24192 MHz. This is demonstrated in the illustration below.

Troposcatter vs AircraftScatter Loss (dB)

path length = 948 km

If you are trying to determine the likelihood of successful communications with another station, or trying to decide where to locate a portable station or rover stop, you need to have some idea of your path loss. The first step in determining your path loss is to accurately determine the location of both stations. You then need to determine the path length, which is generally easily done using GPS localization. The most crucial, but most difficult, part of the data collection is accurately determining your take-off angle. AircraftScatter Sharp will help you to do this, if you have downloaded the necessary SRTM3[6] datafiles that AircraftScatter Sharp uses to determine path

profiles. If you have downloaded the SRTM3 files, then you can just set up your Home and DX station parameters in the program and it will give you predicted path loss for both aircraft scatter and troposcatter paths for the amateur bands between 144 and 24192 MHz.

This is shown in the illustration below, which shows the portion of the AircraftScatter Sharp display that gives this information:

You can see that with the station parameters given, this gives a signal margin of 3-4 dB for a troposcatter 3 GHz contact between W3SZ and W4DEX. Note the negative take-off angles at each end of the communications link. This is essential to keeping the loss to a minimum, as already noted. "km" is distance to obstruction in km, and "Alt" is height of the radio-horizon-determining obstruction in meters. Note that AircraftScatter Sharp does not know about trees.

Above is the entire AircraftScatter Sharp display, from which the excerpt shown on the preceeding page was taken. With AircraftScatter Sharp, you can "fiddle" with station location, antenna height, antenna gain, power, etc. in order to determine what you need to do to have an adequate link budget, using either troposcatter or aircraft scatter.

Theory and Modeling of Tropscatter Path Loss. Variability of the refractive index of the atmosphere, caused by variations in water vapor content of the troposphere, is believed to be the cause of tropospheric scattering. Some models assume that the variability occurs due to the random distribution of "blobs" of different dielectric constant. Other models assume that stratification of the refractive index into layers is important, and that there is either scattering or reflection from these layers[7]. Some experimental studies suggest that above 1000 MHz the mechanism is predominantly scattering, but that at lower frequencies at least some of the received signal is due to reflection[8].

Seasonal and diurnal changes in the height and composition of the troposphere and the respective variations that these changes produce in scattering volume and refractive index cause summer troposcatter signals to average about 10 dB higher than winter signals, and mid-afternoon signals to be about 5 dB lower than early morning or evening signals[9]. In addition, there is both slow[10] (minutes to hours) and rapid[11] (4-7 Hz) fading of tropospheric scattered signals. The rapid or short term fading is attributed to the summation of what is for practical purposes an infinite number of signals of random phase and amplitude emanating from the scattering volume. The slow or long term fading is due to gradual changes in the value of the refractive index and the scattering volume over time. Several models for calculating tropospheric loss attempt to account for these changes by incorporating the value Ns, the surface refractivity into the calculation, but these methods actually prove to be more accurate in practice when this factor is <u>not</u> included as a variable.

The loss of system gain that occurs due to the obligatory decrease in the size of the scattered volume as beamwidth decreases is termed the "Aperture-Medium Coupling Loss", and there are various models for this loss factor[12]. Phase incoherence of the signal coming from the scattering volume, which does not appear as a point source to the receiving antenna, is also believed to contribute to this additional signal loss that is incurred with larger antennas[13].

There are six commonly used methods for calculating troposcatter path loss. These are termed the National Bureau of Standards (NBS) method, the ITT method, the CCIR method, the Yeh[14] method, the Rider method, and the Collins[15] method. There is an excellent comparison of the accuracy of all of these except for the ITT method by R Larsen[16], much of which is reproduced in Panter's text.

The NBS method is complex. It defines the loss L as:

$$30 \log f - 20 \log d + F(Theta) + Lc - V(de) - Fo + Ho + Aa$$

where

f = frequency in MHz
d = distance in km
Theta = scattering angle in radians
de = effective distance
F(Theta) = attenuaton function
Lc = aperture-medium coupling loss
V(de) = climate variation factor
Fo = scattering efficiency correction

Ho = frequency gain function
Aa = atmospheric absorption factor

This method is not practical for us to attempt to use for calculating troposcatter loss.

The CCIR method is essentially a simplified version of the NBS method. It defines the loss L as:

30 log f – 20 log d + F(Theta) + Lc – V(de)

where the variables are as listed for the NBS method, and the functions F and V are plotted in the CCIR report. Larsen estimated the coupling loss Lc as

0.7 exp(0.055(Gt + Gr))

where Gt and Gr are the gains of the transmitting and receiving antennas.

The Yeh method defines the loss L as:

30 log f + 20 log d + 10 Theta – 0.2(Ns – 310) + Lc + 57

where

f = frequency in MHz
d = distance **in miles**
Theta = scattering angle **in degrees**
Ns = surface refractivity
Lc (aperture-medium coupling loss) is estimated from a graph in Yeh's paper, based on experimental data. In his excellent paper, Bob Atkins notes that this graph can be approximated by the equation

Lc = 2.5 + 1.8(Theta/alpha) – 0.063(Theta/alpha)**2

where

Theta is scattering angle in degrees
alpha = (bw1 * bw2)**0.5
bw1 = beamwidth of antenna 1
bw2 = beamwidth of antenna 2

Thus the Yeh method is easily adapted to a software-based solution.

Note that the CCIR method and the Yeh method use different formulas to calculate the aperture-medium coupling loss.

The Rider method defines loss L as:

30 log f + 30 log d + 50 log Theta – 0.43 (Ns – 330) + Lc + 49

f, d , Theta, and Ns are as defined for Yeh's method. Rider did not specify how to calculate Lc, the aperture-medium coupling loss, so Larsen used the graph from the CCIR method to calculate it for the Rider method.

The original Collins method is entirely graphical. I have adapted it to a software-based method,

which is the subject of a companion article[17]. The Collins method is based on experimental data, and its accuracy may be reduced it if is used for datapoints that are outside the bounds of that original dataset. If it is applied to datapoints that are not within the bounds set by the original experimental dataset, then some method of extrapolation must be used. In the companion paper I discuss what methods I used for such extrapolation.

The limits of the dataset are:

interstation distance must be between 50 and 350 miles
sum of the horizon angles (take-off angles) must be between 0.5 and 4 degrees
scatter angle must be between 0.5 and 5 degrees
sum of antenna beamwidths must be between 0.5 and 4 degrees

Thus one can see that the distance range over which the Collins formula can be applied without extrapolation is quite small; 50-350 miles, and there are additional limitations on scatter angle and the sum of the take-off angles that must also be met.

There are four graphs used for the Collins method:

Figure 10.7 is titled "Basic Propagation Loss Curve for 1000 Megacycles". It is a plot of "Loss Between Two Isotropic Radiators in dB vs Distance in Statute Miles". It is linear in y and log in x. Using the graph, one reads the loss in dB for a given distance in miles.

Figure 10.8 is "Frequency Correction Curve for Basic Propagation Loss". It is a plot of "Frequency Correction Factor in dB vs Frequency in Megacycles". It is linear in y and log in x. One reads the additional (or reduced) loss in dB due to frequency for a given frequency in MHz, as compared to the reference frequency of 1000 MHz.

Figure 10.9 is "Loss Due to Elevated Horizon Angles". It is a series of curves, for 50, 75, 100, 150, 200, 250, 300, and 350 miles for "Loss Due to Horizon Angles" in dB vs the sum of the horizon angles of the two communicating stations, in degrees. It is linear in y and x. One reads the loss in dB for a given total horizon angle by selecting the appropriate distance curve, or interpolating between curves if necessary.

Figure 10.10 is "Nomogram for Determining Aperture-to-Medium Coupling Loss". The leftmost scale is "Equivalent Smooth Earth Statue Miles and Scatter Angle (Degrees)". The rightmost scale is "Antenna Beamwidth (Degrees)". The middle (result) scale is "Aperture to Medium Coupling Loss (dB)". None of these scales is linear. One selects the sum of scatter angle due to the combination of inter-station distance and take-off angles of the two stations on the left scale, and the antenna beamwidth on the right-hand scale. One then reads the aperture-to-medium coupling loss off the center scale where the line so drawn connecting the two points just described on the outer two scales intersects the middle scale. Note that this nomogram assumes identical beamwidths for the antennas at the two ends of the circuit, and this number, the "antenna beamwidth" on the right-hand scale of the nomogram represents the beamwidth of a single antenna. To use this nomogram with a circuit where the antennas of the two stations do not have the same beamwidths, some assumptions or compromises must be made.

These graphs are included in the appendix of the companion paper that details how I converted the graphical Collins method to a software-based method.

To use the Collins method, one simply reads the path loss off of each graph and adds the losses so obtained together to get the total troposcatter path loss.

Larsen compared the five methods noted above using 15 troposcatter circuits for which both the necessary input variables for the methods and actual path loss data were available. The paths and the predicted and measured trospheric path loss data in dB for each troposcatter circuit from Larsen's article are shown in the appendix, as is the error in dB for each measurement included in that article.

The errors of the five methods, in dB, as reported by Larsen, are shown in the table below:

		NBS.101	CCIR	Yeh	Rider	Collins
RMS Error		8.1	8.1	7.4	16.8	5.1
Mean Error		-4	-4.5	-3	7.8	0.9
Mean Absolute Error		5.8	6	5.9	14	3.8

You can see that the Collins method gave the best results, and that the Yeh method was second best. However, all of the methods except for the Rider method were of very similar accuracy. The Rider method was inferior to the other methods.

Some of the data for three paths, the Trinidad-Barbados, Round Hill-Winston Salem, and Johore Bahru-Kuching paths, were outside the boundaries of the original Collins dataset, and so Larsen had to extrapolate to obtain Collins-method-based results for those paths. When he excluded those paths, the Collins dataset performed even better, with an RMS error of only 2.5 dB, a mean error of only 0.5 dB, and a mean absolute error of 2.1 dB.

As was alluded to earlier in this paper, the models that included a climactic variability term, Ns, actually performed better when Larsen set Ns to an arbitrary constant for each method. Unfortunately, he did not report what those constant values are. When he set Ns to an arbitrary value that maximized the accuracy of each method that included this variable (i.e, all but the Collins method), the accuracy of each of these methods improved, although the Collins method still retained a slight advantage. This is shown in the table below. As before, all values are in dB.

		NBS.101	CCIR	Yeh	Rider	Collins
RMS Error		7.4	7.9	5.4	9.3	5.1
Mean Error		-4	-4.4	-0.3	0.1	0.9
Mean Absolute Error		5.4	5.7	4.3	6.7	3.8

The message the Larsen article gives us is that our best choice for calculating troposcatter loss is the Yeh method. If input datapoints are within the boundaries of the original Collins dataset, then the Collins method is an excellent choice. But the difference in accuracy between the two methods is small enough that using only the Yeh method is quite reasonable. Bob Atkins' program, which you can download from his website, does calculations for the Yeh, ITT, CCIR, Rider, and Collins methods. AircraftScatter Sharp uses the Yeh method for its troposcatter loss calculations. I

considered adding the Collins and other methods to it, but I did not do so as I was not convinced that this would increase the acccuracy of the program. I also wrote a program that calculates troposcatter loss using the Yeh and Collins methods, and it is available at the URL listed in the bibliography[18]. Use the Collins results with caution if any of the datapoints you are evaluating are outside the range of the original Collins dataset.

So if you want to evaluate a path for possible troposcatter, I suggest that you:
1. Download and install AircraftScatter Sharp[19]
2. Download the SRTM3[20] files that cover your planned path
3. Carefully enter the locations of the two ends of the path into AircraftScatter Sharp
4. Carefully enter the antenna heights above sea level (in meters) for each station
5. Enter the remaining station parameters including antenna gain (dBi), power (watts), receive system noise figure (dB) for each station

Then AircraftScatter Sharp will give you not only troposcatter path loss, but also your received signal strength, your signal margin in a 100 Hz bandwidth, and also your take-off angles and the troposcatter angle.

Conclusion. Troposcatter is the method most commonly responsible for beyond-line-of-sight microwave amateur contacts. Troposcatter losses increase with distance and frequency, and decrease dramatically as take-off angle decreases. <u>With a good takeoff angle</u>, troposcatter will always be superior to aircraft scatter on short paths, and troposcatter will always be inferior to aircraft scatter on very long paths. On paths of intermediate length there will be a crossover frequency below which troposcatter is superior, and above which it is inferior. Several troposcatter loss calculation models are discussed. Of the models discussed, the Yeh model is recommended for general use, although the Collins model is superior when used within the limits of its original dataset. Several software packages that allow the amateur to calculate the expected troposcatter loss for a given path are discussed, including one, AircraftScatter Sharp, that allows a digital map-based approach to path analysis.

Roger Rehr
W3SZ
July 27, 2014

I would like to thank Dick Frey WA2AAU for first suggesting that I look into adding troposcatter path loss to my program AircraftScatter Sharp.

Appendix

The table below shows the path characteristics and predicted and measured path losses in dB from the Larsen article described in the text and listed in the bibliography.

Path	dist (km)	freq (MHz)	NBS.101	CCIR	Yeh	Rider	Collins	Measured
New York-New Jersey	275	460	191.8	192.4	200.9	217.1	197.3	196
Tokyo-Sendai	310	2120	221.5	222.6	219.8	237.9	224.5	224.4
Start Pt – Wembley	278	3480	218.7	220.3	221.6	234	224.1	220.9
Miyazaki – Murato-Misaki	300	1310	204.1	206	207.2	216.9	211.9	211
Cyprus – Israel	319	77.5	147.5	146.3	165	152.7	158	163.3
Penang – Singapore	595	1900	261	254.8	243.9	247	260.3	260.9
New Jersey – Massachusetts	302	3670	233	233.7	233.8	256.9	236.5	233.5
Bromley – Catterick	322	858	204.4	202.8	204.1	213.7	209.1	211
Trinidad – Barbados	314	900	184.7	186	186.8	178.9	201.3	189
Feldberg – Montebaldo	322	957	223.1	218.2	232.7	264.4	221	223.1
Canada – New York	465	468	218.2	218.7	223.9	237.7	225.6	229.6
Round Hill – Winston Salem	994	412	238.2	239.2	243.9	249.7	249	257
Tokyo – Nihonmatsu	226	2120	214.3	213.7	218.2	234.7	218.5	214
Johore Bahru – Kuching	738	1840	255	254.5	236.8	240.9	254.5	245.7
Riyadh – Dahran	390	900	220.7	219.3	212.4	230.8	218.7	217.2

The table below shows the error in dB for each of the measurements above as compared with the actual measured path loss, taken from the Larsen article described in the text and listed in the bibliography.

Path	dist (km)	freq (MHz)	NBS.101	CCIR	Yeh	Rider	Collins
New York-New Jersey	275	460	-4.2	-3.6	4.9	21.1	1.3
Tokyo-Sendai	310	2120	-2.9	-1.8	-4.6	13.5	0.1
Start Pt – Wembley	278	3480	-2.2	-0.6	0.7	13.1	3.2
Miyazaki – Murato-Misaki	300	1310	-6.9	-5	-3.8	5.9	0.9
Cyprus – Israel	319	77.5	-15.8	-17	1.7	-10.6	-5.3
Penang – Singapore	595	1900	0.1	-6.1	-17	-13.9	-0.6
New Jersey – Massachusetts	302	3670	-0.5	0.2	0.3	23.4	3
Bromley – Catterick	322	858	-6.6	-8.2	-6.9	2.7	-1.9
Trinidad – Barbados	314	900	-4.3	-3	-2.2	-10.1	12.3
Feldberg – Montebaldo	322	957	0	-4.9	9.6	41.3	-2.1
Canada – New York	465	468	-11.4	-10.9	-5.7	8.1	-4
Round Hill – Winston Salem	994	412	-18.8	-17.8	-13.1	-7.3	-8
Tokyo – Nihonmatsu	226	2120	0.3	-0.3	4.2	20.7	4.5
Johore Bahru – Kuching	738	1840	9.3	8.8	-8.9	-4.8	8.8
Riyadh – Dahran	390	900	3.5	2.1	-4.8	13.6	1.5

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