Application Note
AN-33a

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TV PROPAGATION

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This application note is a major revision of the previous AN-7b [1]. It now includes the use of computer programs to predict rf path performance.

I am often asked the question by other hams. "How far can a ham TV signal go ?" My typical response is "Line-of-Sight". If you can see the other location, chances are good that you can get a TV signal to it. This has been borne out by many years of experience in ham TV. As opposed to very high power TV broadcast stations, hams are running low power (1 W to 100 W max) and our signals just don't have the oomph to get much energy diffracted over and around path obstacles.

For line of sight propagation, there also becomes the question of "Where is the radio horizon ?" If we lived on a flat earth, the answer would be infinity. Because we live on a spherical earth (radius = 6370 km), the curvature of the earth limits our horizon. It effectively puts a "hump" in the middle of our rf path. The line of sight horizon is set by pure geometry. Note this may not be your personal optical line of sight set by the resolution of your eyes, even using binoculars. The distance to the horizon is set by our observation height (or antenna height) above ground level. It is given by these equations:

optical distance (km) $\approx$ 3.57 * $\sqrt{\text{height (m)}}$ - or - in miles $\approx$ 1.23 * $\sqrt{\text{height (ft)}}$

The radio horizon is actually a bit further than the geometrical horizon. The refractive effects of the atmosphere cause a bit of bending in the radio waves and will push them typically about 15% further..

RF distance (km) $\approx$ 4.12 * $\sqrt{\text{height (m)}}$ RF distance (miles) $\approx$ 1.41 * $\sqrt{\text{height (ft)}}$

However, these atmospheric effects are totally dependent upon local weather conditions. In extreme cases, strong ducting might occur sending our RF waves far beyond the predicted RF horizon, while severe local storms might drop it back dramatically.

A few quick examples are: 5' => 3.2 miles, 30' => 7.7 miles, 100' => 14 miles, 1000 ft => 45 miles Adding antenna height at the receive site, we add the numbers for the two heights. For example transmitting from an automobile with an antenna height of 5 ft. to a remote base station with the antenna on a 30 ft. tower, the radio horizon = 3.2 + 7.7 ≈ 11 miles This calculation really only works over flat earth. On a large lake or the ocean, we do have such a flat surface. Obviously either putting up a higher tower or finding a high hill or mountain top works wonders. But of course, this is not news to us hams !

So after determining our radio horizon, the next issue to contend with is RF Path Loss. Path loss is the natural phenomena of radiating a certain amount of power but this power, again due to spherical geometry, gets spread equally over an ever expanding globe as it propagates away from the source. Thus the power density in watts/m^2 gets much smaller the further we get from the source. The formula for free space path loss based upon this geometry alone is:

Free Space RF Path Loss(dB) = 20 * log10 (f in MHz) + 20 *log10(D in Miles) + 36.6dB

Note in this equation the frequency dependency, For example, going from 70cm to 23cm bands we suffer about a 10 dB hit in path loss. A few quick calculations will give you an appreciation of the importance of path loss. As an example, for the 70cm band (430 MHz) we get: 0.1 mile => 69dB, 1 mile => 89dB, 10 miles => 109dB, etc.

To determine the best case situation for a particular rf path we need to include all of the major rf components. Calculations are done easiest in dB with power levels expressed in dBm and antenna gains expressed in dBi. To determine the power input into the distant receiver, we need to know:

Rcvr Pwr(dBm) = Trans Pwr (dBm) - Trans Cable Loss (dB) + Trans Ant Gain (dBi)
-RF Path Loss (dB) + Rcvr Ant Gain (dBi) - Rcvr Cable Loss (dB)

As an example using this calculator, let's enter the parameters of a typical 70cm ham TV station:

Transmitter Power = 5 watts (+37dBm) Cable Loss = 1dB each end
Yaggi Antenna Gain = 11dBi each end
Desired Receiver Power = -65dBm (40 dB s/n, P5 for VUSB-TV)

The calculator gives the answer of 43 miles for pure, unobstructed, free space, line of sight path. The theoretical results really only apply for outer space applications. In the real, terrestrial world, we encounter a lot of other obstacles and we would never achieve this ideal. In the fall of 2011 and again recently in Sept., 2016, several Boulder area TV hams have run TV propagation field trials. See Application Notes, AN-3 [2] and AN-32 [3] for details. We made measurements of the actual received signal strength in dBm. One observation that stood out was "Over very clear, line-of-sight paths, even with directional antennas, where multi-path was not a major issue, the actual path loss was typically 5 to 15 dB worse than the calculated, theoretical path loss." For obstructed paths, even more loss was typically encountered. Thus the likelihood of our ever experiencing just free space path loss is extremely rare.

OBSTACLES to RF PROPAGATION: The above equations were for ideal, unobstructed, line of sight situations. What can limit us in the real world ? Lots of things including: ground reflections, vegetation, tall buildings, urban building clutter, hills, ridge lines, mountains, etc. The absorption by vegetation, due to water content, goes up with increasing frequency. I have noticed a significant difference in the signal strength hitting our local TV repeater between summer and winter. When the leaves were gone from the trees between my former qth and the repeater, my signal strength at the repeater, especially on 23cm significantly improved. Getting over obstructions to our line of sight path involves diffraction which can introduce considerable extra dB loss. Most of the rest of the losses result from Multi-Path. This is reflected waves from other objects which arrive at the receive site later in time and can cause standing wave patterns in the receive signal which at certain frequencies might totally null out the desired direct path signal. Another perturbing effect can be "Doppler" shift due to moving objects disturbing the various multi-paths.

A pure, free space, channel is called a "Gaussian". If there is a direct line-of-sight path, but also multi-path signals arriving at the receive antenna, then this is called a "Ricean" channel. If there is no direct line-of-sight path, but multi-path signals arrive at the receive antenna, this is then called a "Rayleigh" channel.

RF PATH PREDICTIONS: Pioneering radio propagation research was done right here in Boulder, Colorado in the late 50s and 1960s at the USA Govt., National Bureau of Standards, Central Radio Propagation Labs (CRPL) [4]. By 1968, a computer program was available for making predictions of rf path performance based upon this research [5]. This pioneering work was led by Phillip Rice and A.G. Longley. It is now today, universally referred to as the Longley-Rice propagation model. It is also sometimes referred to as the ITM model, or Irregular Terrain Model. The model works for frequencies above 20MHz, i.e. VHF and higher. It does not include HF, over-the-horizon, ionospheric effects. The model contains a lot of statistical estimates for the many variables, including diffraction and scattering from topography, urban clutter, vegetation clutter, atmospheric changes, etc. The results are not an absolute, guaranteed value, but a statistical estimate.

COMPUTER PROGRAMS: There are several computer programs presently available which use the Longley-Rice model [6]. They include: *CRC-COVWEB, Radio Mobile, SPLAT!, QRadioPredict, and Pathloss*. Most of these are programs must be installed on your computer along with a massive topographical data base. *CRC-COVWEB* and *Radio Mobile* provide on-line calculator versions and use Google Earth maps. [7, 8]. The author's only experience is with these two on-line calculators. My personal preference is now *Radio Mobile-Online*. It has much better spatial resolution than *COVWEB* and also provides in addition to coverage maps, a detailed point-to-point rf path profile analysis. The remainder of this app. note will be devoted to using *Radio Mobile-Online*.

Radio Mobile Online: This program was written and copyrighted by Rodger Coudé, VE2DBE. The on-line version is dedicated to amateur radio use and as such will only accept input frequencies in the amateur radio bands. The mathematical model is a mix of the Longley-Rice model, the two rays method, and the land cover path loss estimation. Radio Mobile first calculates the free space path loss. It then adds estimates for the excess path loss contributions from: Obstruction Loss, Forest Loss, Urban Loss, and Statistical Loss (typically always set to about 6.5dB). To demonstrate this program, the coverage area of the new, Boulder, Colorado DTV/ATV Repeater transmitter will be used [9]. Comparing *Radio Mobile's* point-to-point predictions with the results from actual, mobile, field measurements has shown agreement. The TV repeater coverage maps also correlate well with the field measurements [10].

Input Parameters: ***Radio Mobile*** requires one to input to the on-line program, all of the following parameters: *(note the values listed are those used for the Boulder TV repeater)* Tx Ant Height (10.7m = 35ft); Tx Ant Type (cardiod); Tx Ant Azimuth (67^o); Tx Ant Tilt (0^o); Tx Ant Gain (11.2dBi); Tx line loss (1dB); Tx Frequency (423MHz); Tx Power (4 Watts); Rx Ant Height (1.5m - for mobile); Rx Ant Gain (2.2dBi - for mobile); Rx line loss (1.1dB); Rx threshold (5.6μV = -92dBm, adjustable as desired); Required Reliability (70% - default); Strong Signal Margin (10dB - default, adjustable as desired); Strong Signal map Color (light green - default); Weak Signal map Color (light yellow - default), Opacity (50% - default); Max. Range (choices are - 10, 25, 50, 150, 200, 250 & 300km); Resolution { choices are low (601x601), med (1001x1001) or high (1668x1668 pixels)} & selection of using either or both "land cover" and/or two rays modeling (I used both).

Receiver Sensitivity: The value used for sensitivity is strongly dependent upon the receiver bandwidth and type of modulation used. The receiver noise floor is set by the laws of physics and is a function of the receiver noise temperature. The noise power is given by: Pn = K*T*BW, where K is Boltzman's constant (1.38 x 10^{-23} J/^{o}K), T is absolute temperature in Kelvins, and BW is the receiver bandwidth in Hz. For typical bandwidths, at 290^{o}K (room temp.), the results are: (CW) 300 Hz => -149dBm, SSB 2.4kHz => -140dBm, FM (15 kHz) => -132dBm, Broadcast FM (200kHz) => -121dBm, TV (6 MHz) => -106dBm. The noise figure of a receiver then adds additional noise. Just from these numbers alone, it is seen that the coverage area of a TV repeater vs. an FM voice repeater with similar output powers and antennas will be dramatically different.

Lab measurements on TV receivers using various modulation methods typically gave sensitivities in the -90 to -100dBm range [11-12]. However, for all analog receivers, signals at these levels result in extremely poor, P1 to P2 images [13]. For digital TV receivers, with the digital cliff effect, it is either a perfect P5 image or none at all. The cliff effect width is typically about 1dB, with pixelization and/or freeze frames occurring at threshold. Typical receiver sensitivities are listed in Table I below. Adding a low noise, pre-amplifier typically improves these values by about 3 to 6dB.

Table 1 - TV Receiver Sensitivities

Modulation	P1	P2	P3	P4	P5
VUSB-TV	-94dBm	-88dBm	-80dBm	-74dBm	-60dBm
FM-TV	-100dBm	-95dBm	-93dBm	-89dBm	-84dBm
DVB-T QPSK	na	na	na	na	-95dBm
DVB-T 16QAM	na	na	na	na	-90dBm
DVB-T 64QAM	na	na	na	na	-82dBm

For the Sept. 2016, mobile field survey [3] of the new Boulder DTV repeater in the DVB-T QPSK mode, I never was able to receive any pictures with receiver signal strengths less than -92dBm. This was while using a low noise pre-amp in front of the DVB-T receiver. Thus, for the calculation of repeater coverage maps, the threshold was set to -92dBm.

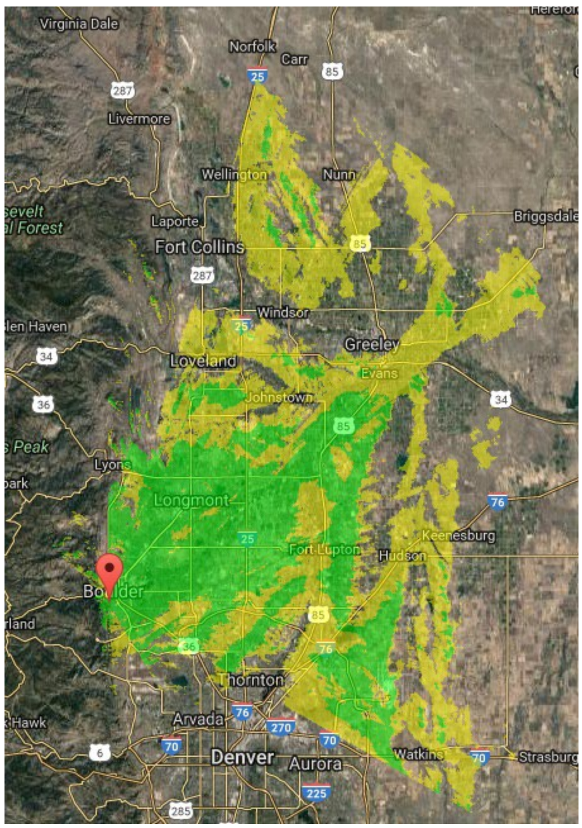

Fig. 1 Boulder, Colorado TV repeater maximum coverage area with an excellent receiving antenna, 11dBi yaggi at 30 ft -- Yellow = >-92dBm, Green = >-82dBm, 100km radius, resolution = 200m/pixel. The red tear-drop indicates the location of the transmitter.

RF COVERAGE MAPS: *Radio Mobile* can generate very detailed maps showing the coverage area of a transmitter, Fig. 1. The on-line version of the program only allows one to plot two different rf levels. The master program which needs to run on your own computer is capable of plotting a rainbow of colors denoting many different rf levels. The computed results are overlaid onto a Google Earth map or aerial photo. *Radio Mobile* generates these maps by performing a point-to-point path profile analysis for each and every pixel within the designated max. radius. The pixel resolution in meters is dependent upon the selected resolution (low, med. or high) and max. radius in km.

The furthest distance for a -92dBm contour predicted was about 100km (60 miles), primarily to the north-north-east, extending a bit beyond Ft. Collins and Greeley. The farthest distance confirmed by the Sept. 2016 mobile field survey was 34 miles south-east to the Denver International Airport. More detailed repeater coverage maps are found in AN-34 [10].

POINT - TO - POINT PATH PROFILE: Radio Mobile can also generate a single point-to-point profile and display the actual path, along with a tabulation of the results. The transmitter and receiver locations are spotted precisely using an interactive Google Earth map or aerial photo in which the map location and magnification are controlled by the mouse. When the cursor is located at precisely the correct latitude and longitude, the mouse is clicked and the location stored in memory. Figs. 2-8 show some typical examples calculated for the Boulder TV repeater to various locations.

The first test run to verify the accuracy of the ***Radio Mobile*** program was to calculate the signal strength received from the Boulder TV repeater at my own QTH which was 5.3 miles distant. I input my particular receive antenna parameters into the p-t-p program along with the repeater parameters and the computed results are shown in Fig. 2. I use a KLM, 70cm, 6 element yaggi (11dBi) at 25ft.(6.4m) with 47ft. of 3/8" hardline coax (1.4dB loss). I have a good line-of-sight path to the repeater, as verified by *Radio Mobile*. Fig. 2 plots both the intermediate terrain and obstacles, and also gives a table listing all the input data, plus the results of various computations.

Radio Mobile — Par/By Roger Coudé VE2DBE — Information

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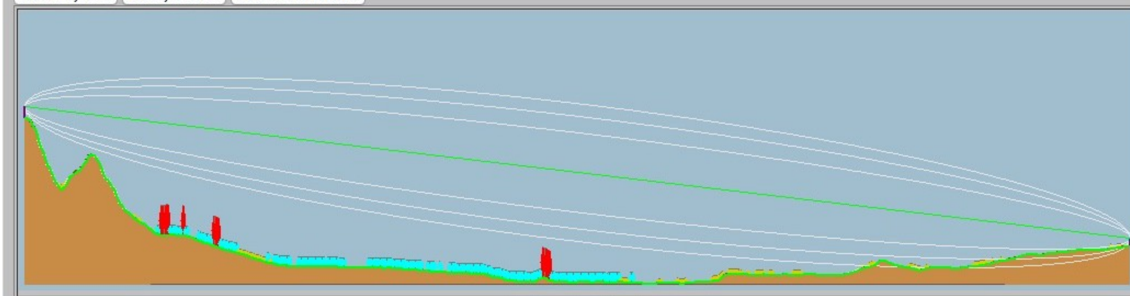

TV Rptr-KH6HTV

CP TV RPTR (1)		(2) KH6HTV-BLDR-QTH	
Latitude	39.994531 °	Latitude	39.978462 °
Longitude	-105.279311 °	Longitude	-105.181378 °
Ground elevation	1788.2 m	Ground elevation	1664.6 m
Antenna height	10.7 m	Antenna height	6.4 m
Azimuth	102.06 TN | 93.75 MG °	Azimuth	282.12 TN | 273.87 MG °
Tilt	-0.90 °	Tilt	0.82 °

Radio system		Propagation	
TX power	36.02 dBm	Free space loss	103.55 dB
TX line loss	1.00 dB	Obstuction loss	-5.15 dB
TX antenna gain	11.00 dBi	Forest loss	0.00 dB
RX antenna gain	11.00 dBi	Urban loss	1.00 dB
RX line loss	1.40 dB	Statistical loss	6.54 dB
RX sensitivity	-94.96 dBm	Total path loss	105.94 dB

Performance	
Distance	**8.533 km**
Precision	10.0 m
Frequency	423.000 MHz
Equivalent Isotropically Radiated Power	40.000 W
System gain	150.58 dB
Required reliability	70.000 %
Received Signal	-50.32 dBm
Received Signal	682.18 µV
Fade Margin	**44.64 dB**

Fig. 2 ***Radio Mobile*** - Path Profile prediction for TV Repeater to KH6HTV-QTH. Direct line-of-sight, 5.3 mile path between transmitter and receiver. The transmitter is always plotted on the left and the receiver is always plotted on the right side. The green trace is the direct ray. Note: 1st, 2ed & 3ed Fresnel zone ellipsoids (white lines) and intermediate path obstructions are shown.

The DVB-T/QPSK DTV signal from the TV repeater received in the KH6HTV ham shack was received with a low noise preamp (18.5dB gain, < 1dB NF), 4:1 splitter (-7dB loss) and a Hi-Des model HV-120A DVB-T receiver and also simultaneously a Rigol DSA-815 Spectrum Analyzer. The on-screen-display (OSD) of the HV-120A measured (with suitable offset, correction factor of -14dB) the input signal strength to be -40dBm. The OSD also showed a perfect s/n of 23dB. Correcting for the preamp/splitter gain, the actual measured input power was thus -51.5dBm. This compares very favorably, within about 1dB, with the -50.3dBm predicted by ***Radio Mobile***, see Fig. 2.

As further verification, the incoming repeater DVB-T signal was also displayed and measured on the Rigol DSA-815, see Fig. 3 below. The analyzer settings were as recommended by the EU-ITU [14]. Due to the wideband (6MHz BW) nature of the DVB-T signal and the narrow resolution bandwidth of the analyzer (30kHz), a correction factor of +22dB must be applied to the signal levels displayed. The actual received signal does not have the transmitted flat spectrum but instead shows evidence of some multi-path distortion. The highest level seen is about -75dBm. With the correction factor of +22dB, the received signal level is thus about -53dBm which is still in excellent agreement with both the HV-120A measurement (-51.5dBm) and the ***Radio Mobile*** prediction (-50.3dBm).

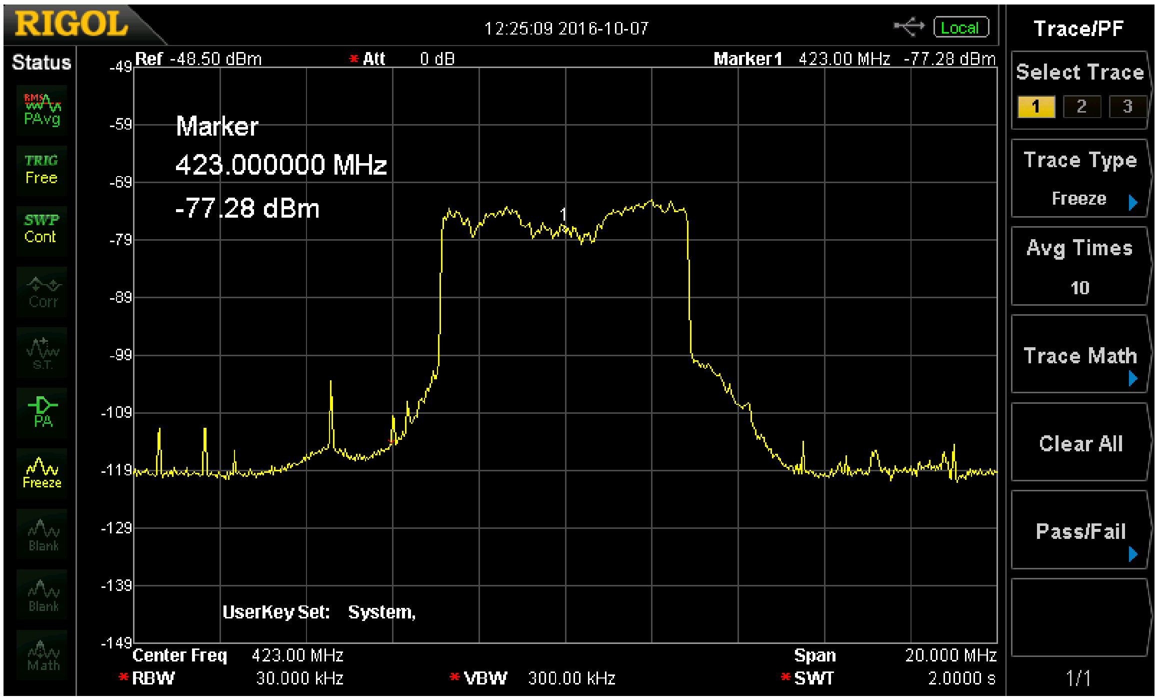

Fig. 3 TV Repeater signal received at KH6HTV QTH as displayed on the Rigol DSA-815 spectrum analyzer. Spikes seen outside the 6 MHz channel (420-426MHz) are other narrow-band signals. Non-flat spectrum is due to some multi-path distortion.

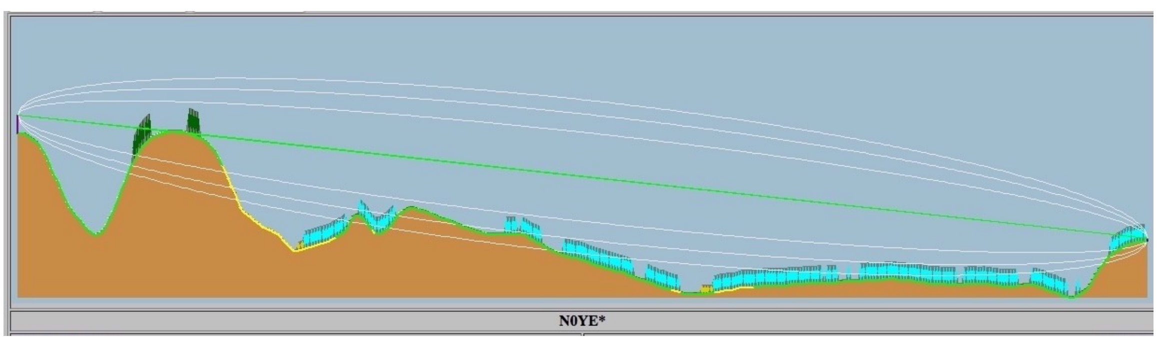

Fig. 4 TV repeater to N0YE --- this is an example of the direct, 2.3 mile path making a grazing pass over an intermediate obstruction. Also note the presence of forested areas on this ridge line (dark green trees). Also noted is urban clutter represented by the small turquoise colored cubes down in the valley and also at the receive site. Pr = -70.7dBm (calculated) & -70dBm (measured). +0.7dB difference

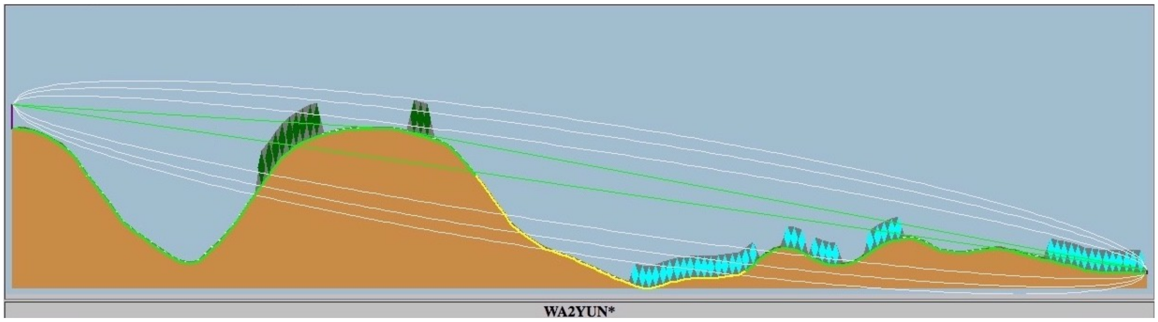

Fig. 5 TV repeater to WA2YUN -- this is an example of an obstructed, short, 1 mile path in which a signal can still be received via diffraction. Pr = -85.9dBm (predicted) & -81dBm (measured) +4.9dB difference

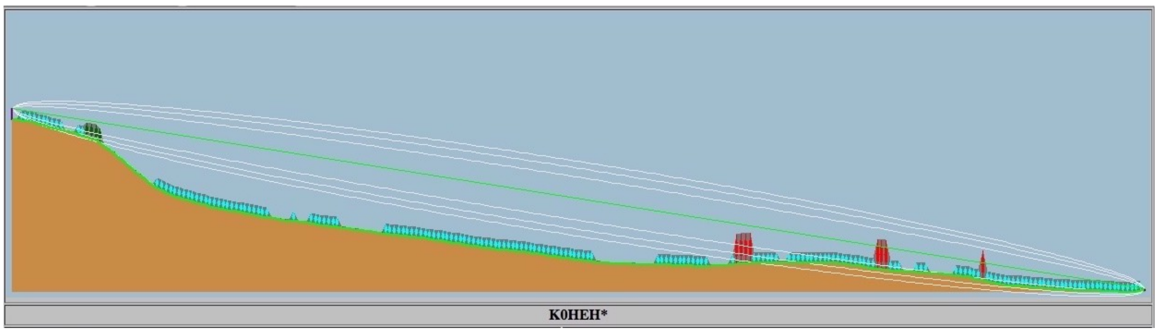

Fig. 6 TV repeater to K0HEH -- this is an example of the direct, 1.6 mile path being obstructed by tall buildings on the Univ. of Colorado campus. They are indicated by the bright red structures. In this case reception was possible due to diffraction in the first Fresnel zone. Pr = -53.7dBm (predicted)

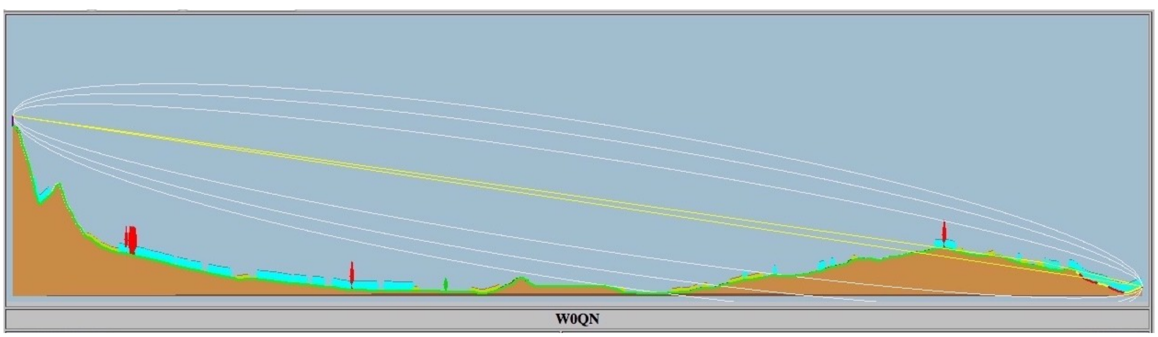

Fig. 7 TV repeater to W0QN -- this is an example of an obstructed, 8.2 mile path in which the received signal is within ±3dB of receiver sensitivity threshold. This is indicated by the direct rays being plotted in yellow. Pr = -89.3dBm (predicted) & -92dBm (measured) -2.7dB difference

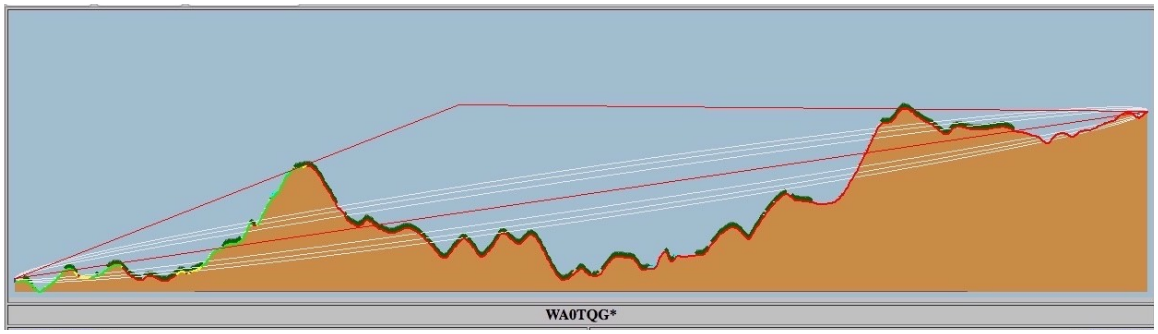

Fig. 8 TV repeater to WA0TQG -- This is an example of an impossible, 6.2 mile path over tall mountains. Transmitter on left at 5,900ft. Receiver on right at 7,400ft. When the direct rays are plotted in red, it indicates the signal strength is below threshold by more than -3dB. Pr = -130dBm (predicted)

FIELD SURVEY In Sept, 2016, a mobile field survey was performed to verify the coverage area of the new Boulder, CO, DVB-T repeater [3]. Field strength data was recorded at over 150 different locations. The farthest distance tested was out to 35 miles from the TV repeater. Data was recorded for both "in motion" and "fixed" locations. At fixed locations, the actual OSD values for dBm and s/n were recorded along with GPS latitude and longitude For the in-motion situation, the nominal value and the max./min. values in the OSD were noted while driving in particular areas. The coverage area of the repeater is the city of Boulder and the eastern half of Boulder County with predominantly prairie land with rolling hills. Due to the transmitter location, it's signal does not penetrate into the mountains in the western half of the county. While driving through relatively flat, rural areas without a lot of trees, the signal level was fairly steady. In urban environments with lots of houses and trees, signal variations of up to ± 10dB were very commonly encountered within a relatively short distance. While driving, the vehicle sometimes reached speeds up to 65mph. In strong signal areas, no dropouts were observed even at high speeds. In no case was a signal weaker than -92dBm ever able to produce a picture. This was 7dB worse than the sensitivity of the receiver measured in a perfect signal (i.e. no multi-path), lab environment.

The extensive field survey data has been carefully analyzed. The first analysis was to determine the excess loss over that predicted by the free space path loss equation. The second analysis was to compare the received signal strength (in dBm) predicted by *Radio Mobile* vs. the actual measurement. The data was broken into three distinct groups. The first was for true Line-of-Sight paths. The second was for Rural (prairie) areas. The third was for Urban (Boulder, Colorado) areas. The results are summarized below:

EXCESS PATH LOSS:

1. Locations with true Line-of-Sight paths, the excess loss mean was -7.9dB with a standard deviation (σ) of 4.5dB for 13 observations. Worst case was -16dB, Best was +4dB (meaning 4dB higher enhancement than predicted for free space propagation)
2. For Rural (prairie) Areas the excess loss mean was -13.9 dB with a σ of 7.8dB for 47 observations. Worst case was -29dB, Best was +4dB.

3 For the Urban (Boulder) Area, the excess loss was 21.8dB with a σ of 10.7dB for 37 observations. Worst case was -39dB, Best was +2dB.

RADIO MOBILE Predictions vs. Measurements
[difference in Prcvr (measured) - Prcvr (predicted)]

1. Locations with true Line-of-Sight paths, the mean difference was +8dB with a standard deviation (σ) of 5.7dB for 13 observations. The extremes were -3.4dB and +17.5dB i.e. *Radio Mobile* was pessimistic by about -8dB for true line of sight paths.
2. For Rural (prairie) Areas the mean difference was +4.8 dB with a σ of 7.3dB for 43 observations. The extremes were -14.5dB and +17.5dB. i.e. *Radio Mobile* was pessimistic by about -5dB for rural environments.
3 For the Urban (Boulder) Area, the mean difference was -6.4dB with a σ of 9.9dB for 37 observations. The extremes were -21dB and +14dB. i.e. *Radio Mobile* was optimistic by about 6dB for urban environments.

CONCLUSION: *Radio Mobile* can give you valuable insight into the various obstructions in a particular rf path. However, it is a statistical estimate of path loss and not an absolute answer.

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note: KH6HTV Video Application Notes are available for free download as .pdf files from the web site: www.kh6htv.com