Radio Line-of-Sight Paths from the USGS Digital-Elevation Database

Looking for UHF/VHF terrestrial DX? Let this Web server and the USGS check proposed propagation paths for you.

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Eventually, every microwave operator is left scratching his head wondering about the "contact that got away." Was it the local QRM? Was it an inversion? Was it gremlins in the receiver? Was there a big hunk of rock in the way?

It is hard to know if the local QRM made a difference. Weather comes and goes: who knows what the atmosphere was doing at the time? Of course, there were gremlins in the receiver—that's where they live—but you've made many contacts with that receiver. We'll never know the answer to the imponderables, but we can find out if there was a big rock in the way.

The United States Geological Survey has provided access (via the Web) to a huge database of digitized topographic maps. While one could show that two points are on a line-of-sight path by drawing lines on paper topographic maps (many of us have done this), digitized maps offer us the opportunity to automate what is normally a very tedious job. There is a Web-based service that produces line-of-sight plots for paths between any two points in the continental United States.

What is "Line-of-sight"?

In general, a directional radio wave propagating in a vacuum travels in a straight line. Like light, however, the paths of radio waves can be bent when they pass through non-uniform media. This effect can be demonstrated quite simply with light, by looking through a glass of water. The image seen through the glass is distorted by the change in refractive index from air, to glass, to water and back. There are many ways of explaining this phenomenon. They are all related by Maxwell's equations, and we know that Maxwell's equations apply equally well to radio waves and light waves.

Nevertheless, through what "non-uniform" media are these radio waves propagating? The non-uniformity is in the atmosphere. The refractive index of a medium is a function of its

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permittivity (dielectric constant) and its permeability. In all but the most bizarre circumstances, air contains the same amount of ferrous material as free space, so its permeability is pretty much that of free space. Its dielectric constant, however, is influenced by temperature, humidity and pressure. As altitude increases, the density of the atmosphere decreases. As such, its dielectric constant approaches that of free-space—it decreases relative to air at see level. The presence of water vapor increases the dielectric constant. Cold air has a higher dielectric constant than warm air. When all of these are accounted for, the general trend is that the dielectric constant decreases as altitude increases.

When a wave propagates through a medium whose refractive index is gradually but steadily changing, the wave bends. In extreme cases, where the refractive index changes abruptly, the wave is reflected. This is what makes "ducting" work. Since the refractive index of the atmosphere decreases with altitude, a wave pointed into the sky will encounter a gradually changing atmosphere and its path will be bent *toward the surface of the earth.*

This effect was explored rather thoroughly by the folks at the MIT Radiation Laboratory back in the 1940s. (Volume 13, *Propagation of Short Radio Waves,* has a very readable treatment of this material in Chapter 1.) They discovered that, while the amount of bending varies with atmospheric conditions, the path of a radio wave propagating in the atmosphere is fairly approximated by an arc of a radius 4/3 times that of the earth. The approximation holds reasonably well up through X band. The consequence of this can be seen in Fig 1, a plot of the "terrain" between two points separated by water.

The two points in the figure are separated by about 85 km. The left-hand station is at 120 meters elevation, and the right-hand station is at 115 meters. If the earth were flat, the two stations would clearly have a line-of-sight path. When we accurately represent the earth's curvature (labeled "true-earth") the visual path between the two points is obstructed. If we assume that the earth's apparent radius is 33% larger (to account for bending of the path), then the two points are on a line of sight.

Path curvature is, of course, not the entire story when it comes to "over the horizon" propagation. Tropospheric "ducting" in the presence of temperature/humidity inversions can substantially enhance a microwave path that is deemed "obstructed" by the simple approximation presented here. Scatter, diffraction and other phenomena can also improve an otherwise obstructed path. Similarly, paths that look good relative to a line-of-sight plot may well be obstructed by objects that are not shown on maps, such as buildings, trees or grain elevators. Nevertheless, an understanding of the topography between two points can give us an idea of whether a contact will be possible, or unlikely.

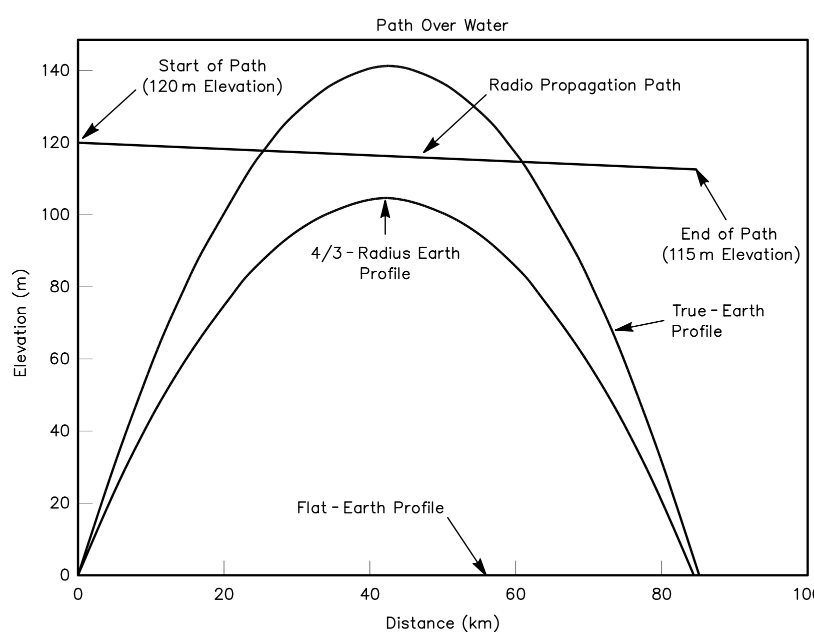

Fig 1—4/3-radius versus true-earth versus flat-earth profiles for two points separated by 85 km.

The Digital-Elevation Maps

The United States Geological Service provides Internet access to a set of digitized topographic maps that cover most of the continental US. Each map in the set represents a square of one degree in each direction. These are referred to as "Digital Elevation Maps" or the DEM database. Each map is stored in its own file. Each file contains 1200 lines of 1200 points each. This amounts to a point every three arc-seconds (about 90 meters, or so, in the Northeast). The maps are not without error or flaw, but they are nearly exhaustive—that is, they cover the entire "lower 48" and then some. The elevation at each of the 1,440,000 points in each map is in meters, with a resolution of approximately three meters.

There are 956 maps in the set. As stored at the USGS, they are quite large. The raw files are amenable to compression however. (The USGS Web site now has all the files stored in compressed format.) The compression technique used by the USGS is rather generic and doesn't account for the rather flat nature of most terrain. Applying additional loss-less compression to the data sets helps. Reformatted and recompressed, all 956 maps consume approximately 600 MB of disk space.

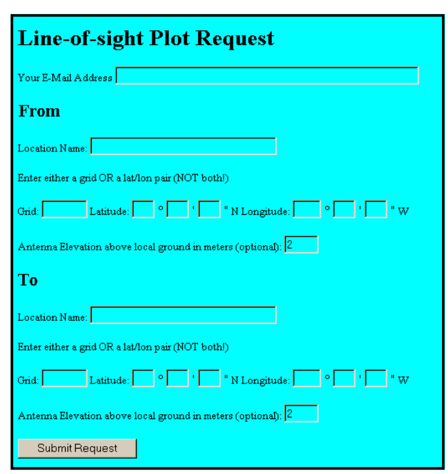

Fig 2—The request form.

The USGS also provides digitized topographic maps that are not in raster form. These are digital versions of the familiar topographic (topo) maps, showing contour lines of equal elevation at intervals of a few meters or so. When this work was started several years ago, these maps were not yet widely available. Their "vector" form makes their utility for plotting line-of-sight paths somewhat marginal, however they may promise better accuracy than the current DEM database. In the future, I'll try to translate these vector-form maps into raster form.

The Server

So, we have maps and we know how to warp the terrain slice to model radio propagation. The rest should be a mere matter of calculating—and so it is. I have set up a server to provide line-of-sight plots free of charge for amateur use only. You need only fill in a Web form with the required information and the server will provide a GIF-formatted plot of the terrain between any two points in the continental United States.

The computing task is, however, rather formidable. So, rather than calculating the path in real time, the user's information is stored for later retrieval by a "batch" server that satisfies all requests via e-mail. The server currently gathers all currently unfilled requests at 2:00 AM Eastern Time. Each response is e-mailed to an address supplied by the user as GIF encoded plot compatible with most network mail readers.

The Request Form

To request a plot, connect to **http://www.tiac.net/users/reilly/los_form.html**, which presents a summary of the service and some background information. At the bottom of the information page, click the "Plot Request" button to reach the actual request form shown in Fig 2.

Users must know a few things before making a request:

1. *A valid return e-mail address:* The Web form may not recognize badly formed addresses, so the user may not be notified if the address is incorrect.

2. *A name for the "starting" location:* This can be any name, but must be no longer than 40 characters.

3. *The six-character Maidenhead locator grid or the latitude and longitude of the starting location:* If the user enters a latitude/longitude (lat/lon) pair, the plot will start from that point. Otherwise, the user must enter a six-character grid location. The server will start the path from the highest point in that grid square.

4. *The elevation of the antenna at the starting location:* If the antenna at the starting point is 6 meters above the local terrain, the user should enter "6."

5. *A name for the "ending" location*

6. *The six-character grid or lat/lon pair for the ending location.*

7. *The elevation of the ending location.*

After filling out the form, click the "Submit Request" button. If any required entry has been omitted, you will be directed back to try again. If all is well, you will be asked to confirm the request. A confirmed request will be entered in the queue and serviced at a later time.

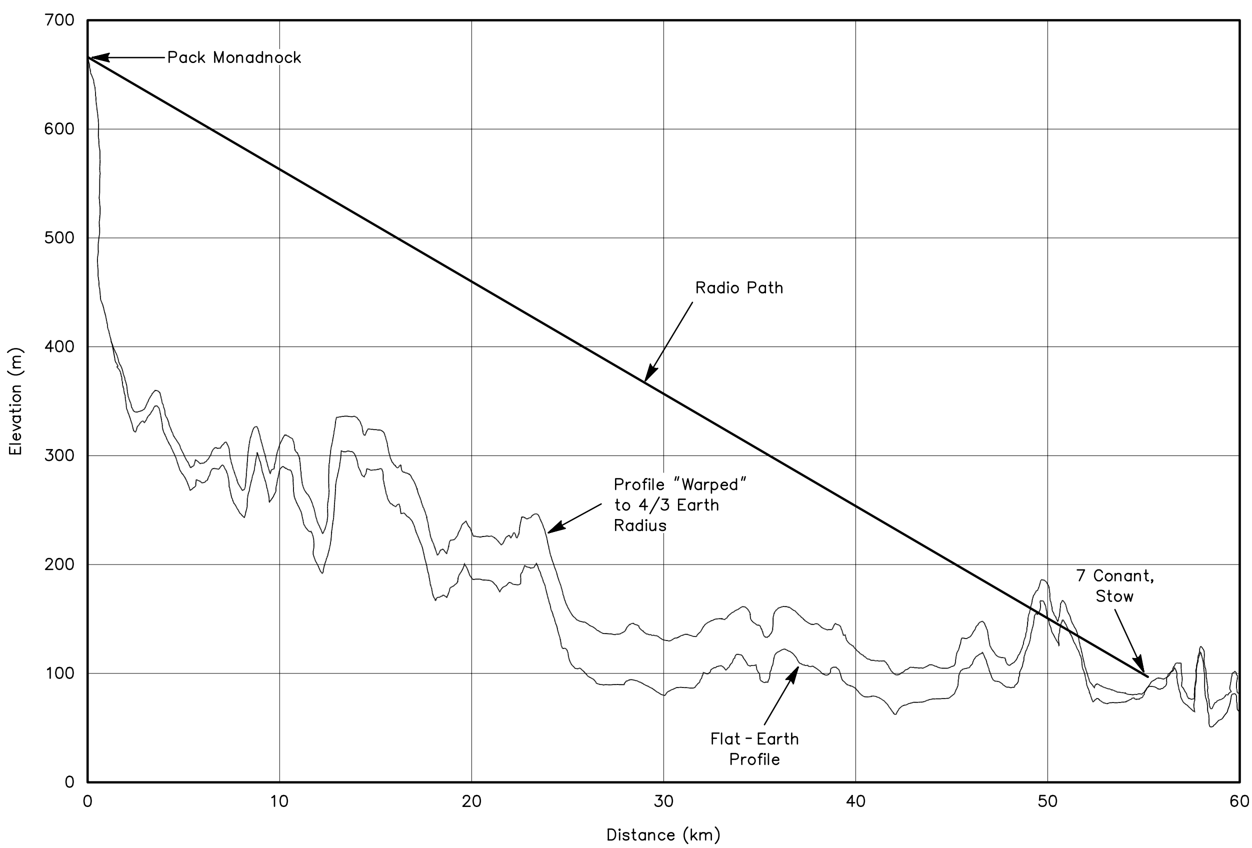

Fig 3—A sample line-of-sight plot from Pack Monadnock (42°53'10" N, 71° 51' 58" W), New Hampshire, to the author's home (42° 27' 18" N, 71° 32' 13" W). (The path is obstructed.)

The Response

Within a day or two after posting a request, you will get a response via e-mail. (The server batch job runs every morning, but Murphy works the night shift at the ISP that hosts the Web pages, so there are occasional delays.) The server gathers all unfilled requests, creates the plot files and sends each answer as a MIME encapsulated image that can be read by almost all modern PC-based mail readers. The plot is attached to the mail message: The service does not work for users with mail systems that do not allow such attachments. A plot sent in response to a Web request is shown in Fig 3. Note that the path is obstructed for both a "flat earth" assumption and the "warped" approximation. Because the plot shows the earth's surface in "warped space," we can draw a line from the peak of Pack Monadnock so as to clear the obstruction 50 km from the start. Thus determining that the path would be unobstructed if the tower at 7 Conant Dr were just 50 meters taller. Given local building codes, it would be more profitable to move the antenna or wait for anomalous propagation.

Ideally, the service would be provided in real time. As it turns out, however, the size of the map database, the magnitude of the computing task and the cost of ISP service all argue against real-time responses. During the initial trials of the service, the server has been very reliable, responding to each request within 24 hours. The server process is entirely automatic in that requests are satisfied without any human intervention. At the end of each night's run, the server sends the maintainer a log, which is reviewed as part of the continuing "bug search" activity. (The programs that generate the profile plots are laced with "consistency checkers" that report anomalous conditions to the maintainer.)

The plot may show that the path is obstructed, but remember that many obstructed paths, in fact, work almost all the time. WBlFKF and WA1MBA regularly communicate between their homes on a 10-GHz path that is obstructed by Mount Wachusett.

Nitty Gritty Details

Line-of-sight plots are produced from the starting and ending locations and the large set of digital-elevation maps. Between request and result, a number of operations take place.

First, the input coordinates are examined. If the location for the start or end point was supplied as a Maidenhead grid, the highest-point program scans the map database to find the highest point within the grid square. (It does this by scanning the region of the digital elevation map containing the Grid Square. If the region is perfectly flat, the resulting point will be in the northeast comer of the grid.) The result of the scan is a new start/end point specified in terms of lat/lon.

Given the start and end points, the next step is to make a list of all the map sections that contain some part of the path. Since there are over 900 map files, we don't want to scan each one. For example, if we know that the path is between two points in Texas, we will not need to scan the maps for New England or Oregon. This is actually a more-dicey proposition than it seems. As an example, take the path from EM99bx to FM29xx shown in Fig 4. A simple "flat earth" view of map intersections would allow us to draw a "bounding box" with EM99bx at the northwest corner and FM29xx at the southeast corner. Intersecting this bounding box with the known maps would yield a list of maps that cover EM99, FM09, FM19 and FM29. In fact, the actual great-circle route will very likely cross over into EN90, FN00, FN10 and FN20. For this reason, the map-intersections program uses the great-circle route between the start and end points to make a list of maps that fall along the path.

The *dirprof* or directional-profile program scans each map for points that fall under the great circle path. First, it makes a vector of points along the path spaced at 100-meter intervals. Each point (P) is specified as a lat/lon pair and the highest elevation found so far in the database along with the point at which it was found. This allows the program to find the elevation of the grid point nearest to each point (P) along the path. The maps are scanned in raster format, one line at a time. Each line represents a scan along a constant longitude. When a raster line is found to intersect the path, the program finds the closest point (P) on the path. If the point on the raster line is closer to (P) than any previously encountered raster point, then the elevation for (P) is updated. (Interpolation would be a better choice, and this may be incorporated in a later version.) After scanning all appropriate maps, the *dirprof* program writes a table to its output. Column one is the distance along the propagation path, and column two contains the respective elevation at that point.

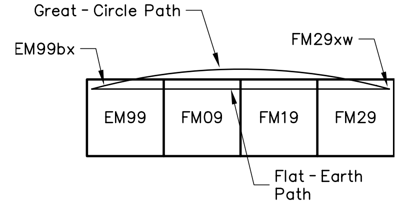

Fig 4—The great-circle path between EM99bx and FM29xw intersects maps outside the "flat-earth" path.

This table is a flat-earth view of the earth. To correct this view, the *rotwarp* or rotational-warp program reads the output of *dirprof* and transforms it into the 4/3-earth view that is more useful. This transformation however, can often cause the graph to look rather odd, as the starting location is plotted at the "correct" elevation, but the end location may be depressed below 0-meter elevation if it is "over the horizon." This is merely an artificial rotation of the view that was caused by the algorithm that corrects for earth curvature. This is corrected by rotating the plot so that elevations at the start and end points can be read directly from the graph.

The output of the *rotwarp* program is then sent to the *gnuplot* plotting program to produce the GIF output. The final plot contains a flat-earth profile as well as the 4/3-earth profile. The flat-earth profile can act as an aid to identifying any obstruction, as the elevation axis provides a true measure of elevation for the flat-earth view. On the 4/3-earth path, the elevation axis is only accurate at the start and end points.

Conclusions, Cautions and Tedious Stuff

The programs that produce the plots were written over a period of three years or so. The result comes from what could charitably called an "organic" approach that some have called "tinker-toy" engineering. The analogy is apt, as the plots are produced by a series of programs, each feeding its output to the next program's input. The bearing and distance calculation code is based on the *BD* program by Michael Gwen (W9IP) and Paul Wade (WlGHZ). Much of the format-translation code (to translate between grids and various lat/lon formats) was originally written for a laptop/notebook interface to a GPS that I developed in 1996. The plots themselves are drawn by *gnuplot* a widely used freeware plotting program. The actual profile scanner was written and modified over a period of two years as I found and fixed various "behavioral anomalies." The whole collection is tied together with about 500 lines of Perl. The Perl code is used to coordinate the half-dozen programs that participate in building a plot.

At the start, the code was written with an eye to optimizing *every* calculation to reduce the runtime of the map-scanning program. Though this offered an interesting set of problems and puzzles to solve, the effort was largely unnecessary. Most paths can be calculated within a second or two on a high performance Compaq Alpha workstation. (Though the runtime is much, much longer on Intel-based computers due to their relatively poor floating-point performance.) The bulk of the time that is required to service a request is consumed in actually mailing the response back to the user. (The server connects to the network via a 28-kbps dialup link.) It takes about 10 seconds to push a request through the relatively low-bandwidth channel from the server to the rest of the network.

As with any programs, there are still bugs waiting to be discovered. Some plots will have "gaps" that show up as very deep holes in the ground. These are manifestations of a bug of unknown cause. For this, and many other reasons, the copyright to these plots is owned by Matthew Reilly. Under the terms of the copyright, commercial use of any sort is prohibited. Subject to this restriction, the plots may be reprinted, distributed, used and re-published in any Amateur Radio related forum. Users of the service must agree that the author, his associates, employers past and present, neighbors and future issue assume no liability for any use, abuse, errors, disappointment, injury, damage, discomfort, sadness or indigestion resulting from the use or existence of the plot server, its programs, constituent parts or input data sets.

No effort was made to make the code portable to Windows or Windows/NT environments. All the code was developed under Linux, and it makes heavy use of the multiprogramming facilities provided by Unix operating systems. The source-code pool for the plotting routines is available from the author upon request.

For those with high bandwidth connections, or a lot of time on their hands, the digital elevation maps are available from the USGS at **ftp://edcftp.cr.usgs.gov/pub/data/DEM/250/**. I have no doubt that we can do many interesting things with this information: The effort described here has just brushed the surface. □□