1. Your mission

Imagine your group are scientists interested in siting a radar for an upcoming field campaign (i.e. the North American Monsoon Experiment this summer). Primary scientific objectives of this project will include mapping rainfall over the complex terrain in the region such that the radar rainfall estimates can be compared with surface rain gauge accumulations. It is highly desirable for the low level scans of the radar to be unblocked over as large an area as possible over the mountains. In addition, unblocked coverage is desired to estimate rainfall over the Gulf of California where there are no gauges. In order for the radar to be within the sounding network, the NCAR S-Pol polarimetric radar needs to be sited on the Mexican coastal plain: west of the Sierra Madre Occidental Mountains of Mexico in the region 50 to 150 km NNW of Mazatlan, Mexico. Your job is to place the radar at a site such that low level elevation angles of the radar (< 3°) are unblocked as much as possible.

2. How you can model the problem

You will adapt the equations shown in class to create a computer program which will model beam propagation given a latitude and longitude of a potential radar site, elevation angle of the radar sweep, and the vertical refractivity gradient \((dN/dh)\), which is proportional to the atmospheric stability. A 30-arc-second resolution (~1 km) digital elevation model (DEM) will provide terrain data, which along with your propagation calculations, will allow the calculation of a beam-blockage fraction (or the fraction of the circular geometric projection of the radar beam that will be blocked by the terrain at a given range). From this information, you will be able to evaluate the suitability of a given radar site.

3. Basis for the model

Atmospheric propagation of the radar beam with height is modeled as given by Battan (1973), where \(k_e\) (the ratio between \(R_e\), the earth’s radius, and \(R_e’\), the equivalent earth’s radius) is given by:

\[
k_e = \frac{1}{1 + R_e \left(\frac{dn}{dh}\right)}.
\]

You are given the value of vertical refractivity gradient \(dN/dh\), which can vary based on the atmospheric stability, the standard atmosphere value being 40 km\(^{-1}\). Note \(N=(n-1)10^6\), thus \(dN/dh=10^6*dn/dh\).
The height of the center of the radar beam is calculated with:

\[ h = \sqrt{r^2 + \left(k_c R_c \right)^2 + 2rk_c R_c \sin E - k_c R_c + H_0}, \]

where \( E \) is the elevation angle of the antenna. The effective “loss” of distance along the ground for each range gate (i.e. the difference between the slant range along the beam and the ground range) \( dr \) is then calculated for each range gate from the corresponding change in height \( dh \) (which is calculated incrementally from the \( h \) equation above along the ray) with the following:

\[ dr = \frac{dh}{\tan(90^\circ - E)}. \]

The cumulative distance to that range gate along the ground \( r_{gnd} \) can be calculated as the difference between the slant range and the sum of the array \( dr \) up to that point.

The radius of the half-power point of the radar beam at each gate \( a \) is calculated at each range gate using the antenna half-power beam width \( \phi_0 \):

\[ a = r \phi_0 / 2 \]

Once the propagation characteristics of the beam are calculated, the topography is then matched to the simulated range bins of the radar. In this problem, 30-arc-second topography is given by the USGS GTOPO-30 DEM (http://edcdaac.usgs.gov/gtopo30/gtopo30.html). The elevation of the radar system \( H_0 \) is given by the DEM interpolated to the input location, plus the height of the center of the radar antenna (10 m for S-Pol). The DEM is linearly interpolated to a polar coordinate system (the radar site constituting the origin) with 250 m radial spacing and 1° azimuth spacing, taking into account the effective loss of distance along the ground caused by the beam’s height gain along the radial.

The difference between the interpolated terrain \( t \) and the height of the radar beam \( h \) is then calculated:

\[ y = t - h. \]

If \( y \) is negative, then the beam is above the terrain; if \( y \) is positive then the beam is below the terrain (and some local beam blockage would be predicted to occur).

Bech et al. (2000) calculates a local beam-blockage fraction (BBF) at each azimuth and range gate as the ratio of the projected radar beam area that is blocked to the total beam area at that range. BBF is defined as the ratio of the area of blocked beam to the total area of the beam. Only the main lobe of the radar beam out to the half power point is considered here.

If the terrain is within the half-power beam width of the radar, BBF is then calculated as the following:
\[ \text{BBF} = \frac{y \sqrt{a^2 - y^2} + a^2 \arcsin \frac{y}{a} + \frac{\pi a^2}{2}}{\pi a^2}. \]

If the radar half-power beam width does not intercept the terrain, then BBF equals 0 locally, if it is completely blocked then \( \text{BBF} = 1 \). The cumulative beam-blocking function (CBF), which is proportional to the amount of power that would be returned at a particular location, is then calculated as the maximum value of BBF found as you proceed away from the radar on a radial.

This model is coded in the IDL programming language (beam_block.pro), and a template for the code and the DEM files are provided for you at the anonymous ftp site: ftp://radarmet.atmos.colostate.edu/pub/snesbitt/class/. Copy all of the files in that directory to a local directory and then edit and run the programs as displayed in class.

3. The assignment
You are asked to simulate the beam blockage patterns at the locations shown as (1) and (2) on the attached map.
At the appropriate places in the code, enter the correct initial values for the radar locations and elevation angles. You must also code up the equations for the beam propagation relationships in the proper spots. The equations are supplied in the lines above.

For the assignment, please do the following:

(1) Using a vertical refractivity gradient of 40 km\(^{-1}\), plot the height of the beam versus range for elevation angles of 0.5, 1, 2, and 3 degrees.

(2) Repeat for a refractivity gradient of 80 km\(^{-1}\) in the lowest 1 km above the radar site, with 40 km\(^{-1}\) above.

(3) Plot a map from sites 1 and 2 of the CBBF at 0.5 degree elevation angle for a refractivity gradient of 40 km\(^{-1}\). Repeat for the situation in (2). How do they differ?

(4) Imagine you have a developing cumulus cloud at a range of 20 km from the radar with a 0 dBZ echo top height at 2 km. With the atmospheric conditions in (1) and (2), calculate different estimates of echo top height considering that the radar software algorithm assumes the conditions in (1) to estimate echo top height. Why is this difference a problem?

5. References
Figure 1. Sites to be simulated for NAME S-Pol sighting.