Geodesic Profiles ArcGIS Tools

NAME: Geodesic Profiles ArcGIS Tools (BETA)

Install File: Geodesic_Profiles_9x.exe and Geodesic_Profiles_10x.exe

Last modified: June 13, 2017

TOPICS:

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Description: This extension includes three primary tools and one toolbar:

1.  *Elevation Profile of Polyline* tool, which intersects any linear feature with a DEM to show the change in elevation over the course of the line.
2.  *Cross Sections* tool, which includes all functions from the *Elevation Profile of Polyline* tool plus the ability to intersect the route with a polygon feature class of geologic types.
3.  *Cross Sections with Strike/Dip Lines* tool, which adds the ability to interpolate depth to strike/dip planes based on a point feature class of strike/dip locations.

Outputs for all tools include a variety of graphing options with flexible vertical exaggeration, statistical tables describing individual vertices and route-level data, and feature classes that can be used for graphing purposes.

Requires: ArcGIS 9.3 or better, at any license level. No ArcGIS extensions are required.

Revision History on p. 101.

About the Author

Jeff Jenness is an independent GIS consultant specializing in developing analytical applications for a wide variety of topics, although he most enjoys ecological and wildlife-related projects. He spent 16 years as a wildlife biologist with the USFS Rocky Mountain Research Station in Flagstaff, Arizona, mostly working on Mexican spotted owl research. Since starting his consulting business in 2000, he has worked with universities, businesses and governmental agencies around the world, including a long-term contract with the United Nations Food and Agriculture Organization (FAO) for which he relocated to Rome, Italy for 3 months. His free ArcView tools have been downloaded from his website and the ESRI ArcScripts site over 250,000 times.

Acknowledgements

These tools were suggested and funded by the US Geological Survey, Astrogeology Team (http://astrogeology.usgs.gov/).

Downloads

The latest version of this ArcGIS Extension, plus all code files, may be downloaded from:

- http://astrogeology.usgs.gov/facilities/mrctr/gis-tools
- http://www.jennessent.com/arcgis/arcgis_extensions.htm

Table of Contents

Installing the Geodesic Profiles ArcGIS Tools

For ArcGIS 9.x

First close ArcGIS if it is open. Tools do not install properly if ArcGIS is running during the installation.

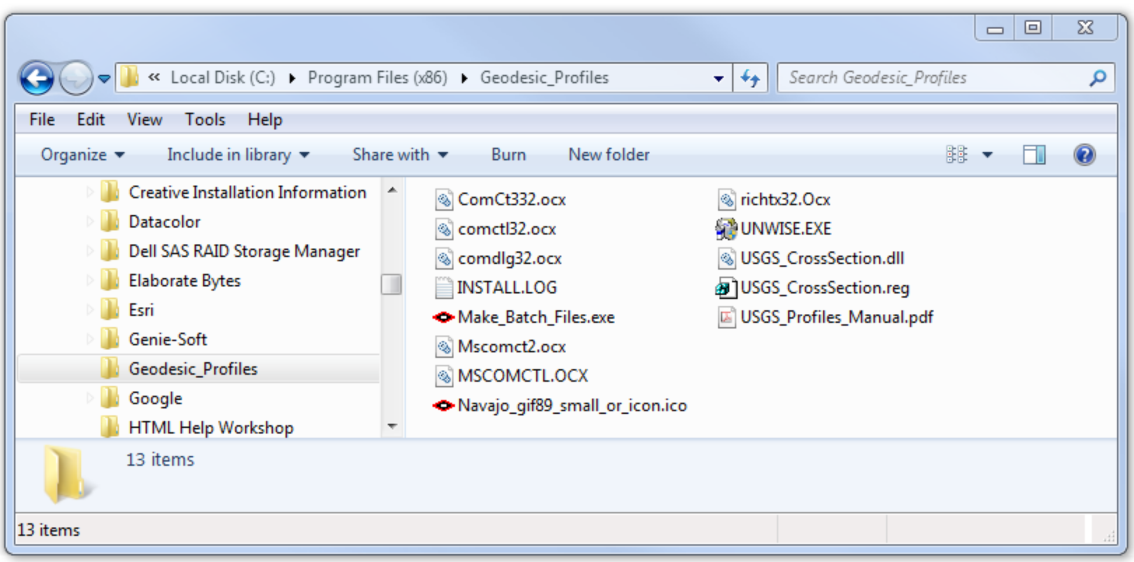
Install the *Geodesic Profiles ArcGIS Tools* extension by double-clicking on the file **Geodesic_Profiles_9x.exe** and following the instructions. The installation routine will register the USGS_CrossSection.dll with all the required ArcMap components.

The default install folder for the extension is named "Geodesic_Profiles" and is located at either "Program Files\Geodesic_Profiles\" (for 32-bit systems) or "Program Files (x86)\Geodesic_Profiles\" (for 64-bit systems). This folder will also include some additional files and this document.

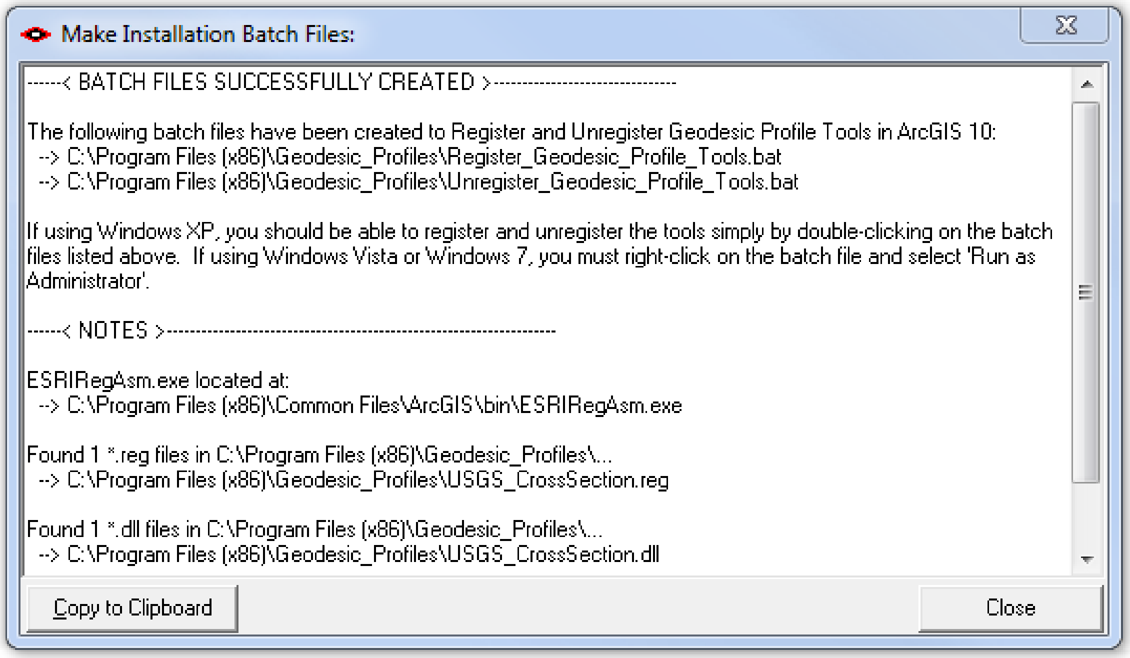
For ArcGIS 10.x

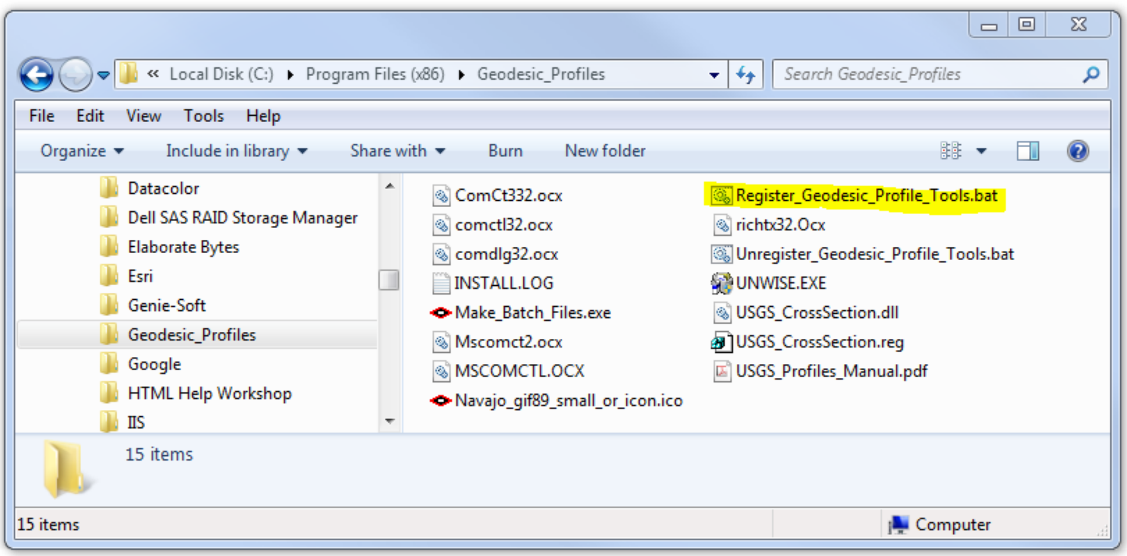
Note: This function will only work if you have ArcGIS 10 installed.

1. **First close ArcGIS if it is open.** The tools do not install properly if ArcGIS is running during the installation.
2. Install the *Geodesic Profiles ArcGIS Tools* files by double-clicking on the file **Geodesic_Profiles_10x.exe** and following the instructions. This installation routine will install the USGS_CrossSection.dll and several ancillary files on your hard drive, but will **not** register the tool with ArcGIS.
3. Use Windows Explorer to open your installation folder. If you used the default values, then this folder will be located at either "Program Files\Geodesic_Profiles\" (for 32-bit systems) or "Program Files (x86)\Geodesic_Profiles\" (for 64-bit systems). This folder will also include some additional files and this manual.



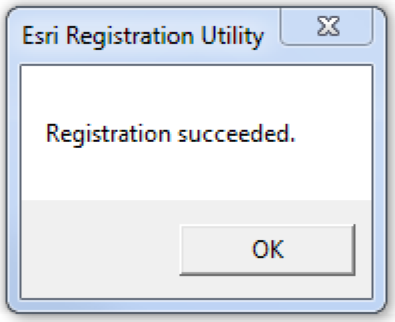
4. **For Windows XP:** Double-click the file "Make_Batch_Files.exe" to create registration and unregistration batch files that are properly formatted to your system.



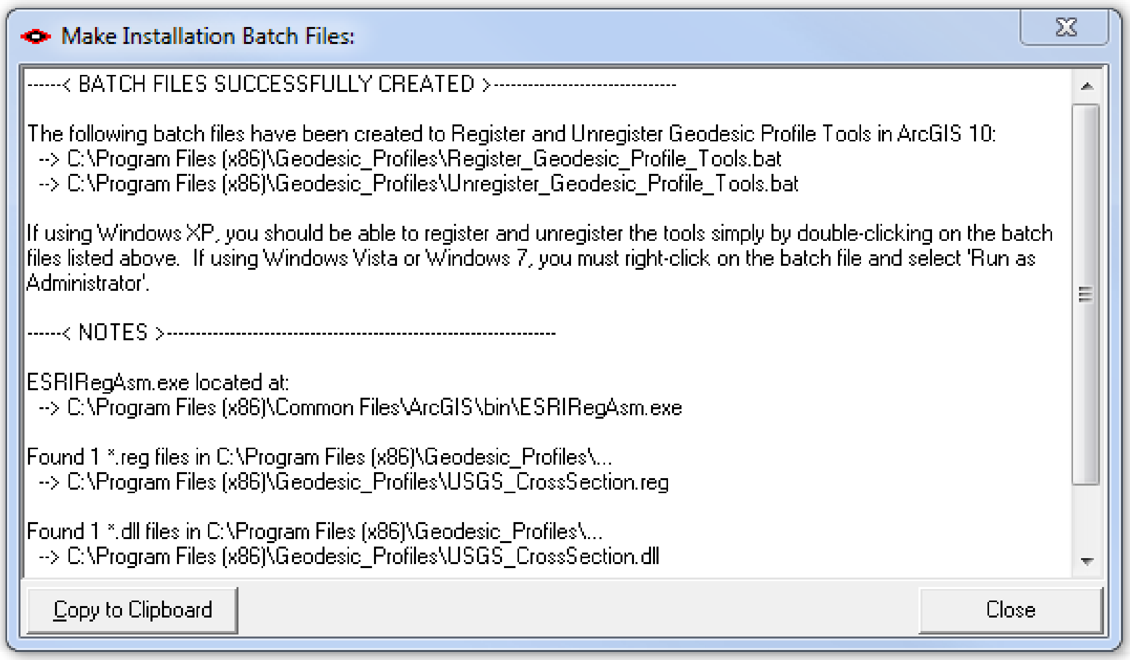


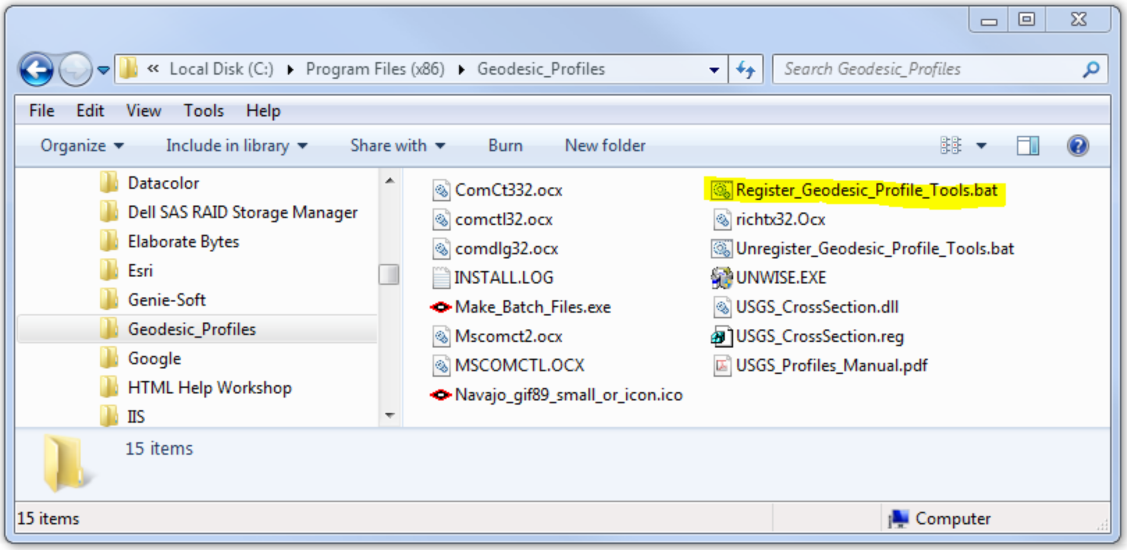
a. Double-click the new batch file "Register_Geodesic_Profile_Tools.bat" to register the tool with ArcGIS 10.x.

b. If the registration is successful, then you should see a "Registration Succeeded" notice.

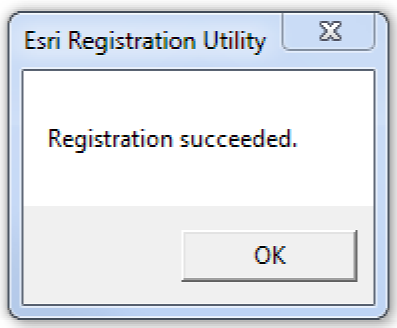


5. **For Windows Vista, Windows 7, 8 or 10:** Right-click the file “Make_Batch_Files.exe”, and then choose “Run as Administrator” to create registration and unregistration batch files that are properly formatted to your system.





6. Right-click the new batch file “Register_Geodesic_Profile_Tools bat”, and then choose “Run as Administrator” to register all the tools with ArcGIS 10.x.
7. If the registration is successful, then you should see a “Registration Succeeded” notice.



Note: For the concerned or curious, the batch file *Register_Geodesic_Profile_Tools.bat* contains a single line of text that looks similar to the following:

```
"C:\Program Files (x86)\Common Files\ArcGIS\bin\ESRIRegAsm.exe" /p:Desktop
"C:\Program Files (x86)\Geodesic_Profiles\USGS_CrossSection.dll" /f:"C:\Program
Files (x86)\Geodesic_Profiles\USGS_CrossSection.reg"
```

It directs the ESRI installer *ESRIRegAsm* to register the extension DLL *USGS_CrossSection.dll* within ArcGIS, using GUID and Class ID values from the registry file *USGS_CrossSection.reg* (also located in your installation directory). Both *Register_Geodesic_Profile_Tools.bat* and *USGS_CrossSection.reg* may be opened and viewed using standard text editors such as Notepad or WordPad.

Viewing the Tool

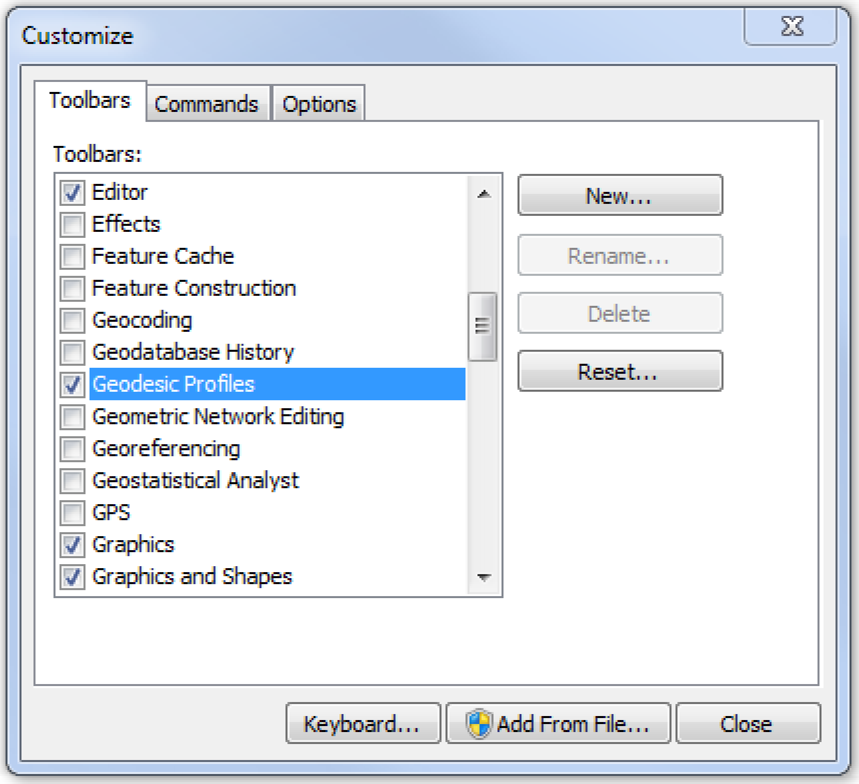
This tool is installed as an extension in ArcMap, but it is a type of extension that is automatically loaded. You will not see this extension in the “Extensions” dialog available in the ArcGIS “Tools” menu. It is not dependent on any other extensions or any ArcGIS license level.

After installing the extension, you should see the following new toolbar in your map (it may also be embedded in your standard ArcMap toolbars, rather than as a standalone object):

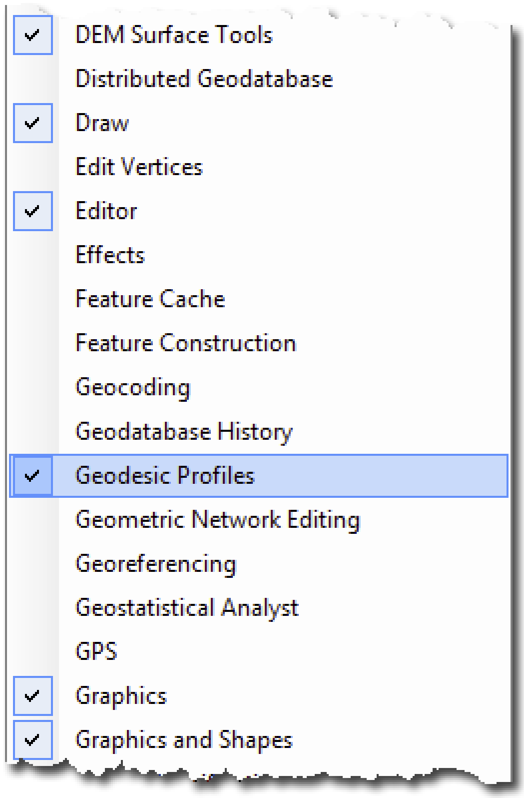
If you do not see this toolbar, then open your "Customize" tool by either:

1) Double-clicking on a blank part of the ArcMap toolbar, or
2) For ArcGIS 9, click the "Tools" menu, then "Customize", or
3) For ArcGIS 10, click the "Customize" menu, then "Customize Mode"

In the "Customize" dialog, click the "Toolbars" tab and check the box next to "Geodesic Profiles":



Alternatively, you can turn on ArcMap toolbars by right-clicking in a blank part of the ArcMap toolbar region and finding *Geodesic Profiles* in the dropdown list of available toolbars:



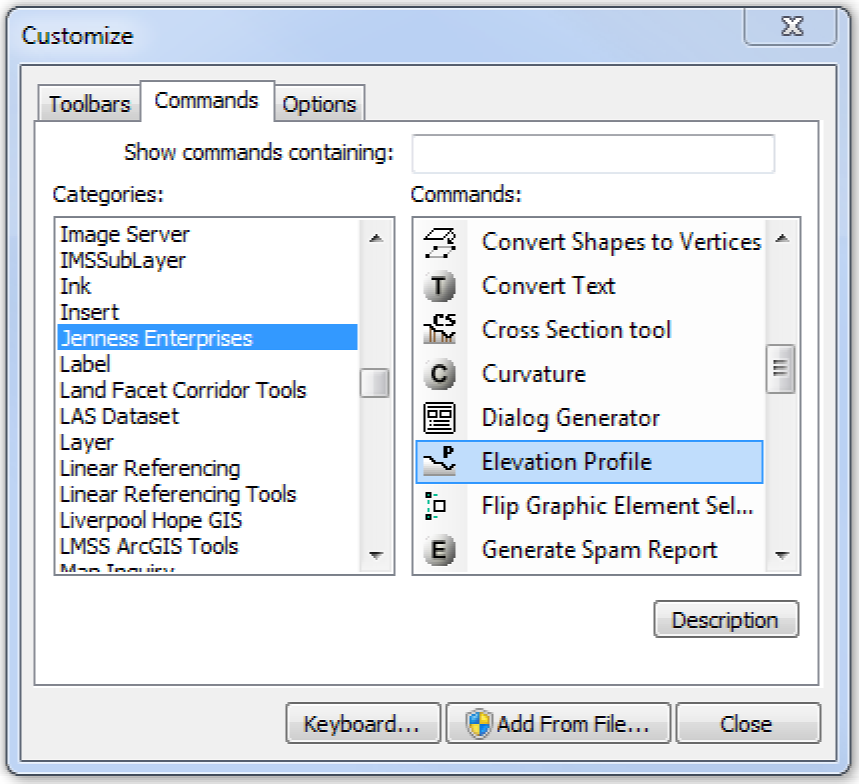
Copying and Adding Tools to Other Toolbars

Because of the way ArcGIS handles toolbars and command buttons, you may add any Geodesic Profiles Tools command buttons to any toolbar you wish. For example, if you would like to keep any of the tools available even when the Geodesic Tools toolbar is closed, you may easily add those tools to any of the existing ArcGIS toolbars.

To do this, open your "Customize" tool by either:

1) Double-clicking on a blank part of the ArcMap toolbar, or
2) For ArcGIS 9, click the "Tools" menu, then "Customize", or
3) For ArcGIS 10, click the "Customize" menu, then "Customize Mode"

In the "Customize" dialog, click the "Commands" tab and scroll down to select "Jenness Enterprises":

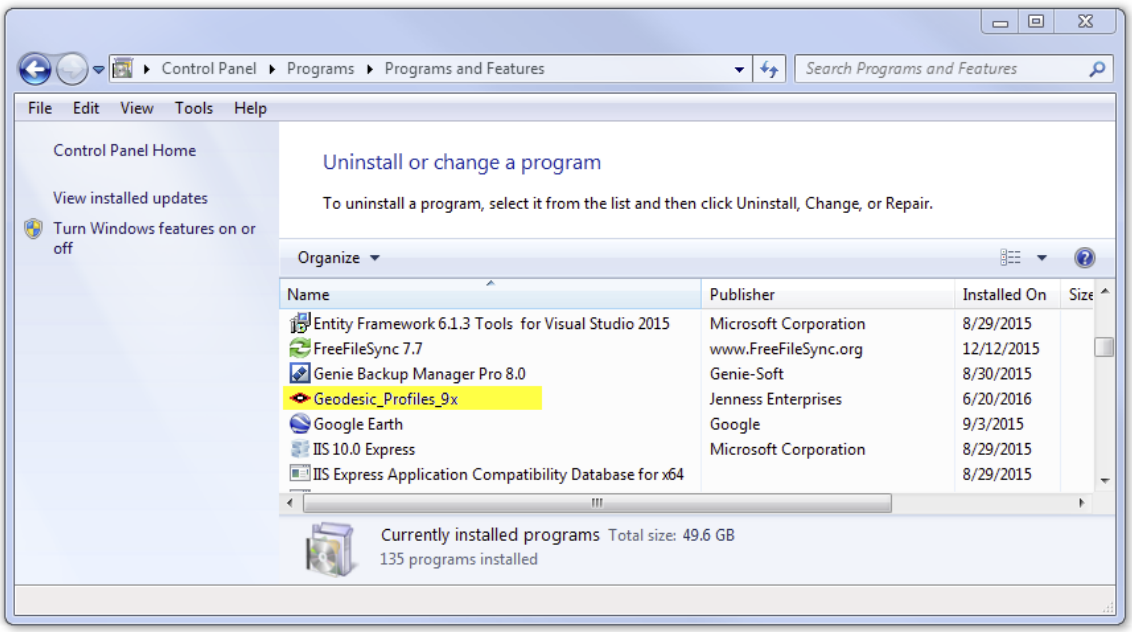


Finally, simply drag any of the commands out of the Customize dialog up into any of the existing ArcGIS toolbars.

Uninstalling the Geodesic Profiles ArcGIS Tools Extension

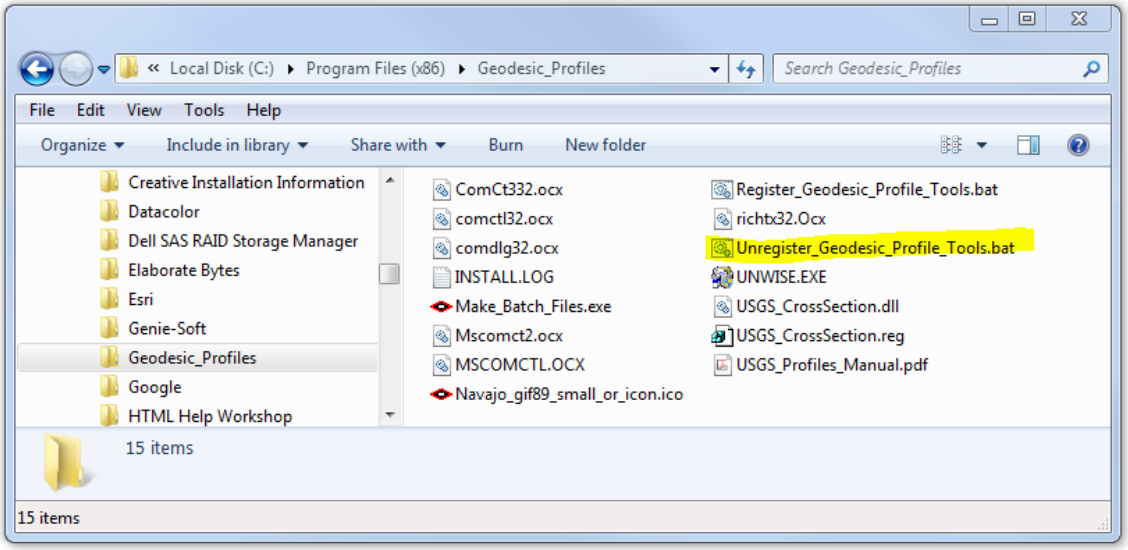
For ArcGIS 9.x.

1) Close ArcGIS if it is open.
2) Click the Start button.
3) Open your Control Panel.
4) Double-click "Add or Remove Programs".
5) Scroll down to find and select "Geodesic_Profiles_9x".
6) Click the "Remove" button and follow the directions.



For ArcGIS 10.x

1) Close ArcGIS if it is open.
2) Use Windows Explorer to open your installation folder. If you used the default values, then this folder will be located at either "Program Files\Geodesic_Profiles\" (for 32-bit systems) or "Program Files (x86)\Geodesic_Profiles\" (for 64-bit systems). This folder will also include some additional files and this manual.

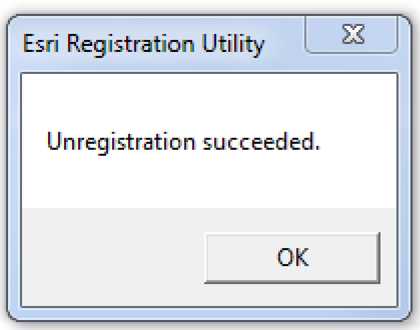


3) Find the file *Unregister_Geodesic_Profile_Tools.bat.* **IF YOU DO NOT SEE THIS FILE,** use the *Make_Batch_Files.exe* tool to create the batch file. Refer to Step 4 in "Installing the Geodesic Profiles ArcGIS Tools Extension" above for instructions on how to use this tool.

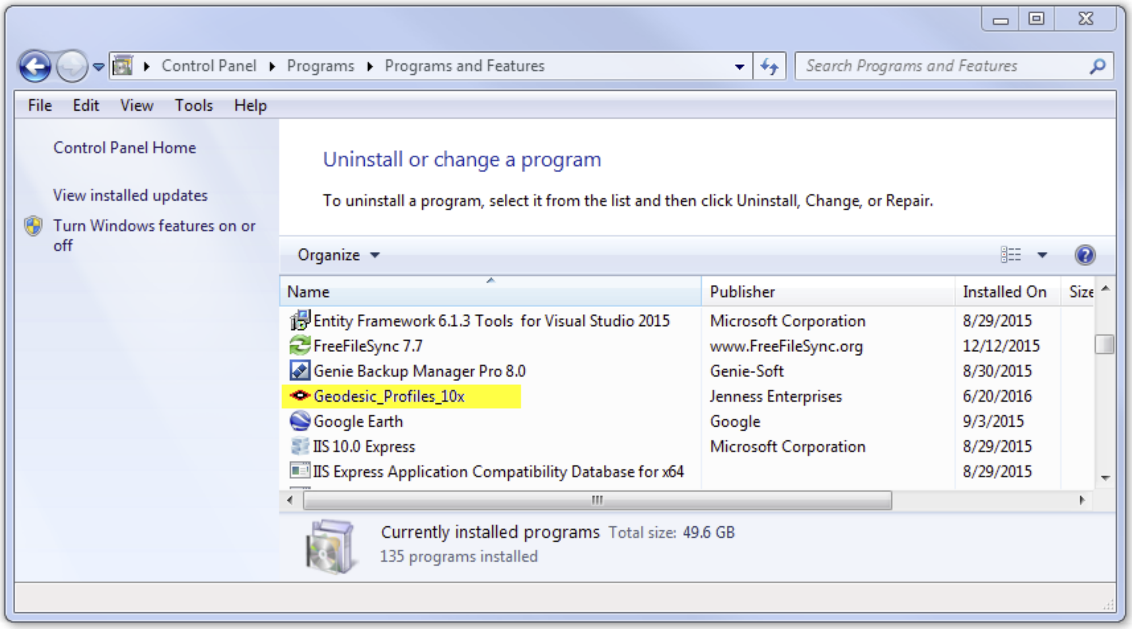
4) **For Windows XP:** Double-click the file *Unregister_Geodesic_Profile_Tools.bat* to unregister the tool with ArcGIS 10.x.

   For Windows Vista, Windows 7, 8 and 10: Right-click the file *Unregister_Geodesic_Profile_Tools.bat* and select "Run as Administrator" to unregister the tool with ArcGIS 10.x.

   If the unregistration is successful, then you should see an "Unregistration Succeeded" notice.



5) Click the Start button.
6) Open your Control Panel.
7) Double-click "Add or Remove Programs".
8) Scroll down to find and select "Geodesic_Profiles_10x".
9) Click the "Uninstall" button and follow the directions.



Note: For the concerned or curious, the batch file *Unregister_Geodesic_Profile_Tools.bat* contains something similar to the following single line of text:

```
"C:\Program Files (x86)\Common Files\ArcGIS\bin\ESRIRegAsm.exe" /p:Desktop /u
"C:\Program Files (x86)\Geodesic_Profiles\USGS_CrossSection.dll"
```

It directs the ESRI installer *ESRIRegAsm* to unregister the DLL *USGS_CrossSEction.dll* within ArcGIS. *Unregister_Geodesic_Profile_Tools.bat* may be opened and viewed using standard text editors such as Notepad or WordPad.

Troubleshooting

If Any of the Tools Crash

If a tool crashes, you should see a dialog that tells us what script crashed and where it crashed. I would appreciate it if you could copy the text in that dialog, or simply take screenshots of the dialog and email them to me at jeffj@jennessent.com. **Note:** Please make sure that the line numbers are visible in the screenshots! The line numbers are located on the far right side of the text. Use the scrollbar at the bottom of the dialog to make the line numbers visible.

Error Log

In most cases, a crash will cause an error log to be produced in the Installation folder, named "Geodesic_Profiles_Error_Log_[Year][Month][Day]_[Hour][Minute][Second].txt". For example, an error that occurred at exactly 5 seconds past 3:01pm, on October 1, 2015, would produce an error report named "Geodesic_Profiles_Error_Log_20151001_150105.txt". Please send this error log to me at jeffj@jennessent.com.

"Object variable or With block variable not set" Error:

If you open ArcMap and immediately see the error dialog appear with one or more error messages stating that "Object variable or With block variable not set", then 90% of the time it is because ArcGIS was running when you installed the extension. The "Object" variable being referred to is the "Extension" object, and ArcGIS only sets that variable when it is initially opened.

The solution is usually to simply close ArcGIS and restart it. If that does not work, then:

1) Close ArcGIS
2) Reinstall the extension
3) Turn ArcGIS back on.

RICHTX32.OCX Error (also comct332.ocx, comdlg32.ocx, mscomct2.ocx, mscomctl.ocx, msstdfmt.dll errors):

If you see a line in the error dialog stating:

```
Component 'RICHTX32.OCX' or one of its dependencies not correctly registered: a file is
missing or invalid
```

Or if you see a similar error stating that one or more of the files *comct332.ocx, comdlg32.ocx, mscomct2.ocx, mscomctl.ocx* or *msstdfmt.dll* are missing or invalid, then simply follow the instructions for *RICHTX32.OCX* below, but substitute the appropriate file for *RICHTX32.OCX*.

This error is almost always due to the fact that new installations of Windows 7 and Windows Vista do not include a file that the extension expects to find. For example, the file "richtx32.ocx" is actually the "Rich Text Box" control that appears on some of the extension dialogs. The other OCX files refer to other common controls that might appear on the various extension dialogs.

The solution is to manually install the missing file (richtx32.ocx) yourself. Here is how to do it:

1) Open Windows Explorer and locate the file *richtx32.ocx* in your extension installation file.

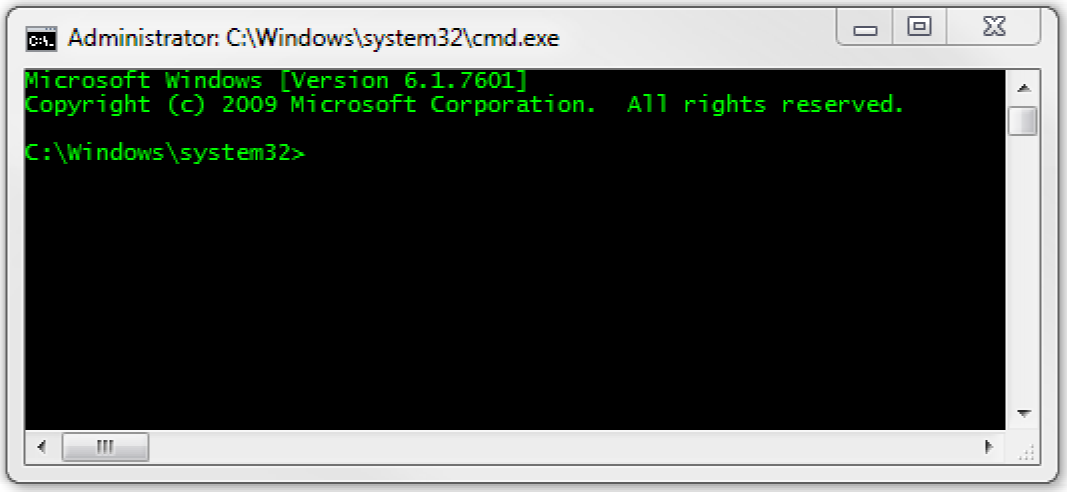
2) If you are running a **32-bit version of Windows**, then copy *richtx32.ocx* to the directory

   `C:\Windows\System32\`

   If you are running a **64-bit version of Windows**, then copy *richtx32.ocx* to the directory

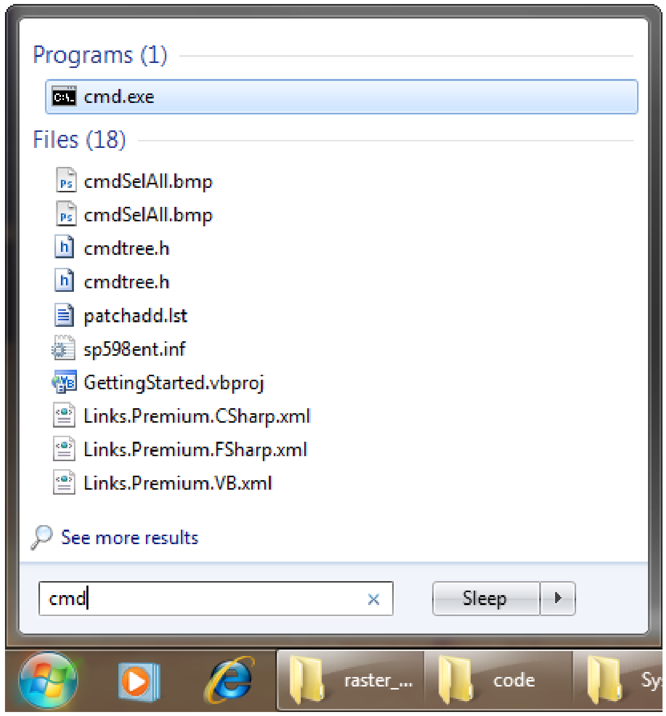
   `C:\Windows\SysWOW64\`

3) Open an "Elevated Command Prompt" window. This is the standard Windows Command Prompt window, but with administrative privileges enabled. You need these privileges enabled in order to register the OCX with Windows. **Note:** The Elevated Command Prompt opens up in the "..\windows\system32" directory, not the "..\Users\[User Name]" directory. The window title will also begin with the word "Administrator:"



   a. **Method 1:** Click the "Start" button, then "All Programs", then "Accessories" and then **right-click** on "Command Prompt" and select **Run as Administrator**.

   b. **Method 2:** Click the "Start" button, and then click on the "Search Programs and Files" box. Type "cmd" and then click CONTROL+SHIFT+ENTER to open the Command window with Administrator privileges.



For more help on opening an Elevated Command Prompt, please refer to:

http://www.sevenforums.com/tutorials/783-elevated-command-prompt.html

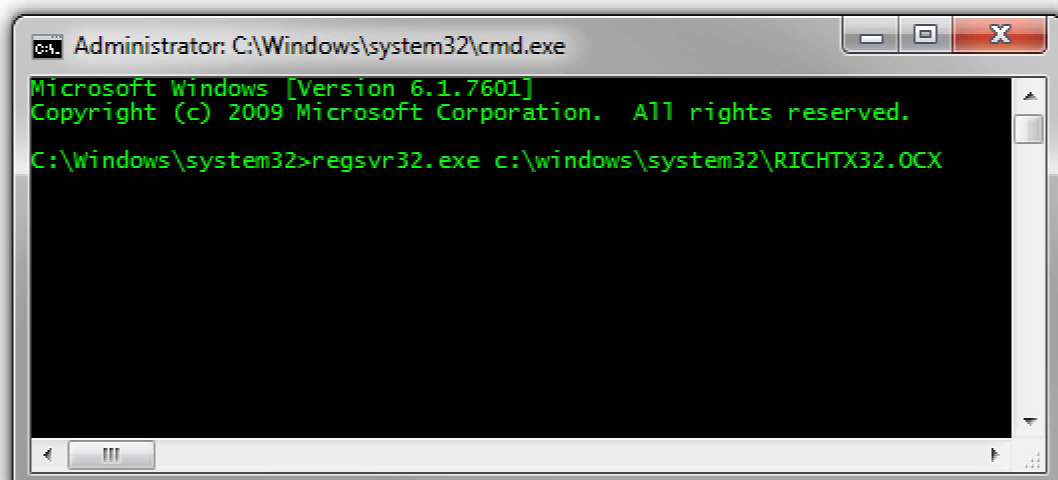
http://www.winhelponline.com/articles/158/1/How-to-open-an-elevated-Command-Prompt-in-Windows-Vista.html

Or simply do a search for "Elevated Command Prompt".

4) Register the file *richtx32.ocx* using the Windows RegSvr function:

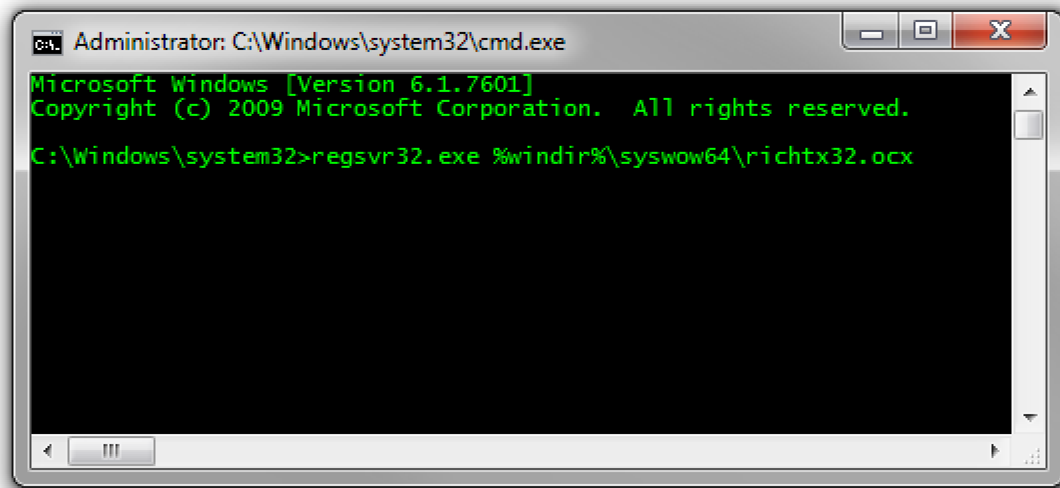
   a. If using a **32-bit version of Windows**, type the line

```
regsvr32.exe c:\windows\system32\richtx32.ocx
```

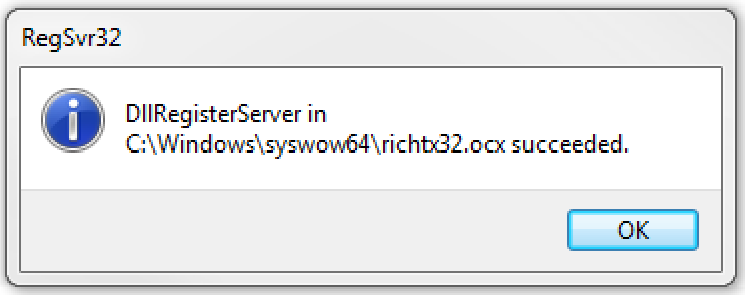


b. If using a **64-bit version of Windows**, type the line

```
regsvr32.exe %windir%\syswow64\richtx32.ocx
```



c. Click [ENTER] and you should see a message that the registration succeeded.



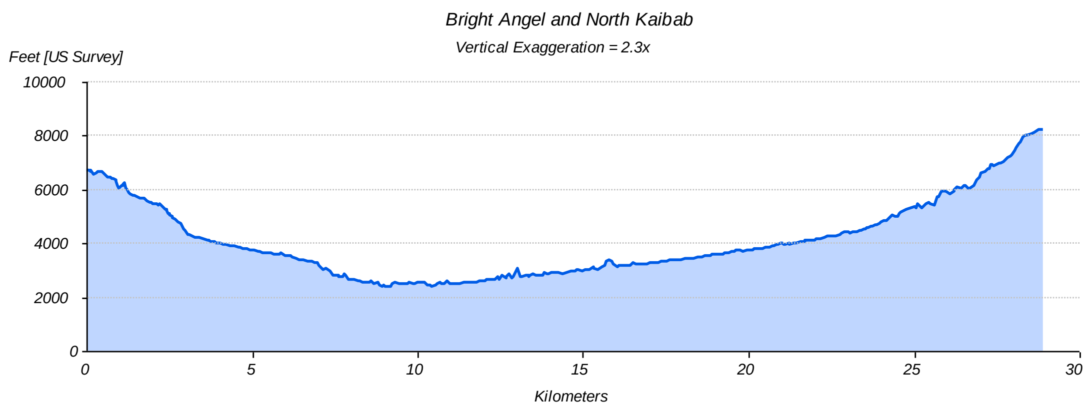
Using the Tools

Elevation Profile of Polyline Tool

The Elevation Profile tool creates a profile of a polyline by intersecting it with a digital elevation model, and provides several options for graphical and statistical outputs.

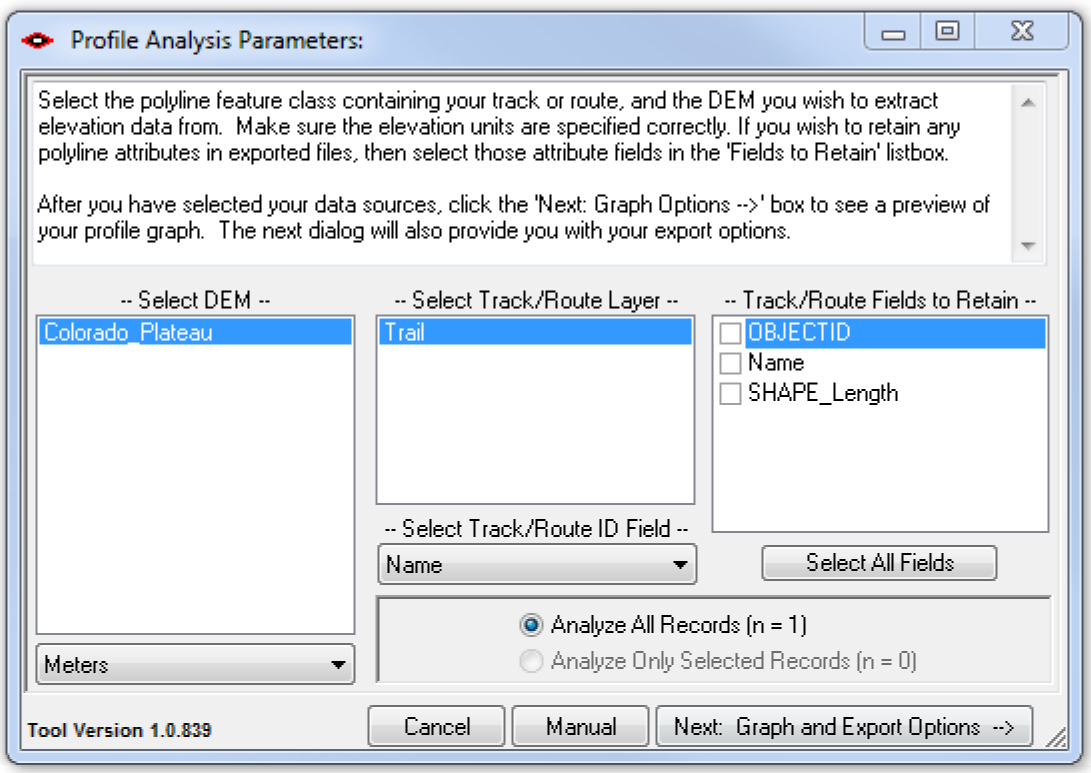
For example, we could create a profile of this trail (actually the Bright Angel and North Kaibab trails) across the Grand Canyon and analyze the elevation change, slope and direction across the entire route.

Profile charts may be exported to EMF (Windows Enhanced Metafile) images, which may easily be loaded into many document types:



Using the Tool:

1) Make sure your Route polyline feature class and your DEM raster datasets are loaded into your ArcMap document.
2) Click the **Elevation Profile of Polyline** command to open the *Profile Analysis Parameters* dialog.



3) You must specify 6 parameters:
   a) DEM: This is the elevation raster that the polyline(s) will be intersected with.

b) Units: DEMs typically define elevation in meters or feet, but there is nothing in the dataset itself that explicitly defines the unit. Therefore you must specify the correct unit yourself. The tool defaults to **Meters**.

c) Track/Route Layer: This is the polyline feature class containing the route(s) to analyze.

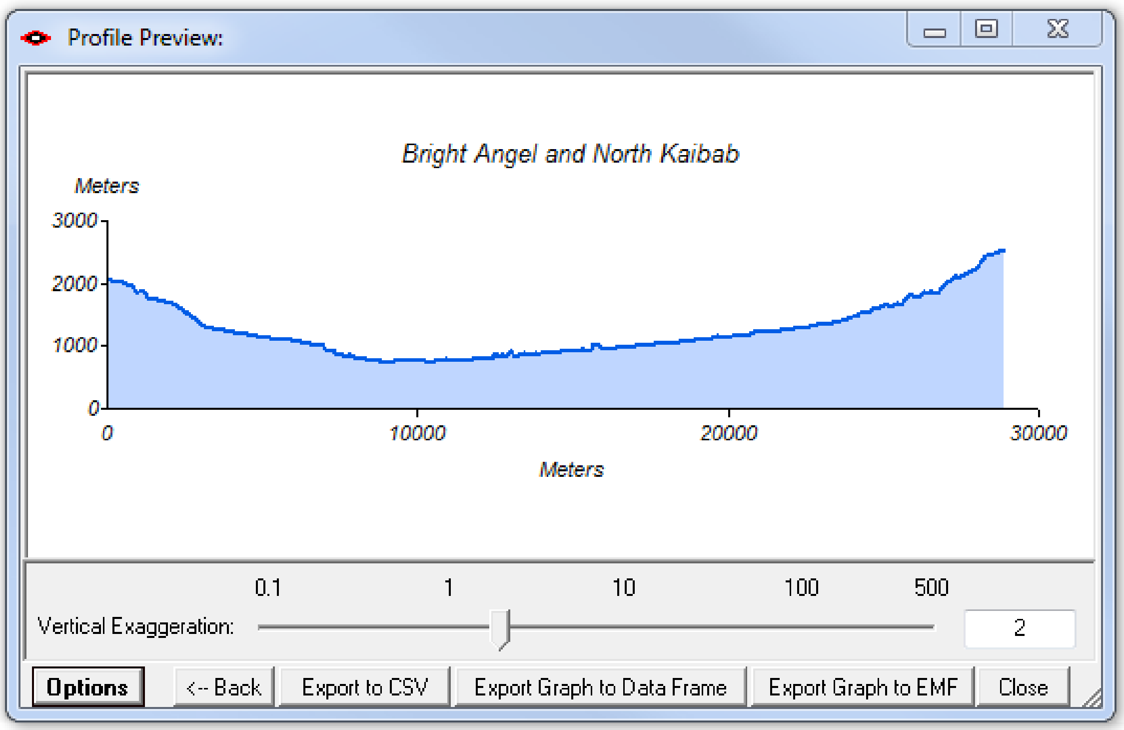
d) Track/Route ID Field: This is the attribute used by the tool to label the graphs.

e) Track/Route Fields to Retain: The tool offers several output options for graphs and statistical tables. If you would like any of the original Track/Route attributes to be included in those statistical tables, then select those fields here. **Note:** The "Track/Route ID Field" will automatically be retained in all output datasets.

f) Whether to analyze all polylines, or only selected subset: If you have any polylines selected, then you have the option to restrict your analysis to only the selected subset. If you choose to analyze multiple polylines simultaneously, then the tool will overlay the graphs on each other.

Note: There may be issues regarding the coordinate systems of your data. If your data are in different geographic datums, then you **may** need to specify a geographic transformation. Please see Appendix A (p. 102) for details.

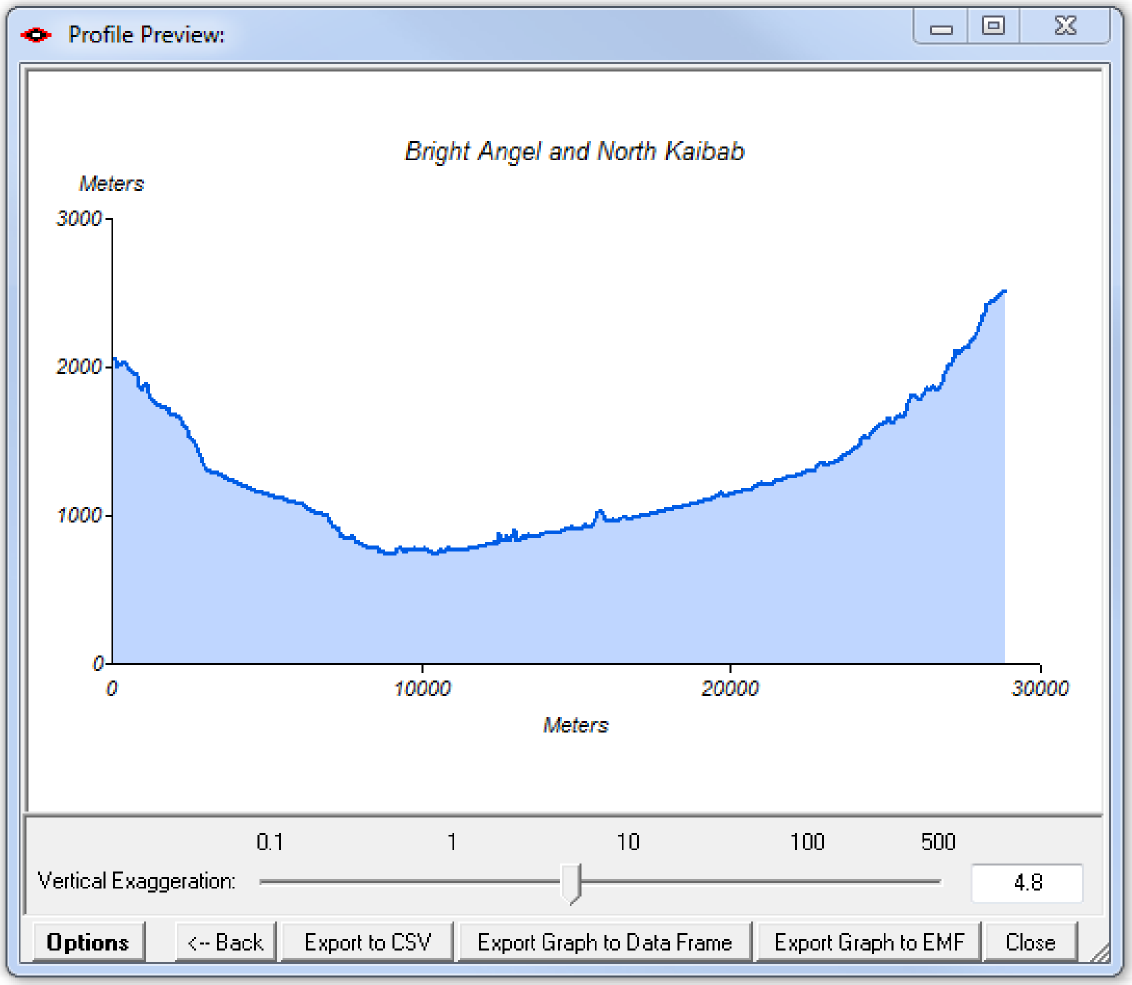
After selecting your initial parameters, click the *Next: Graph and Export Options* --> button to preview your profile graph.



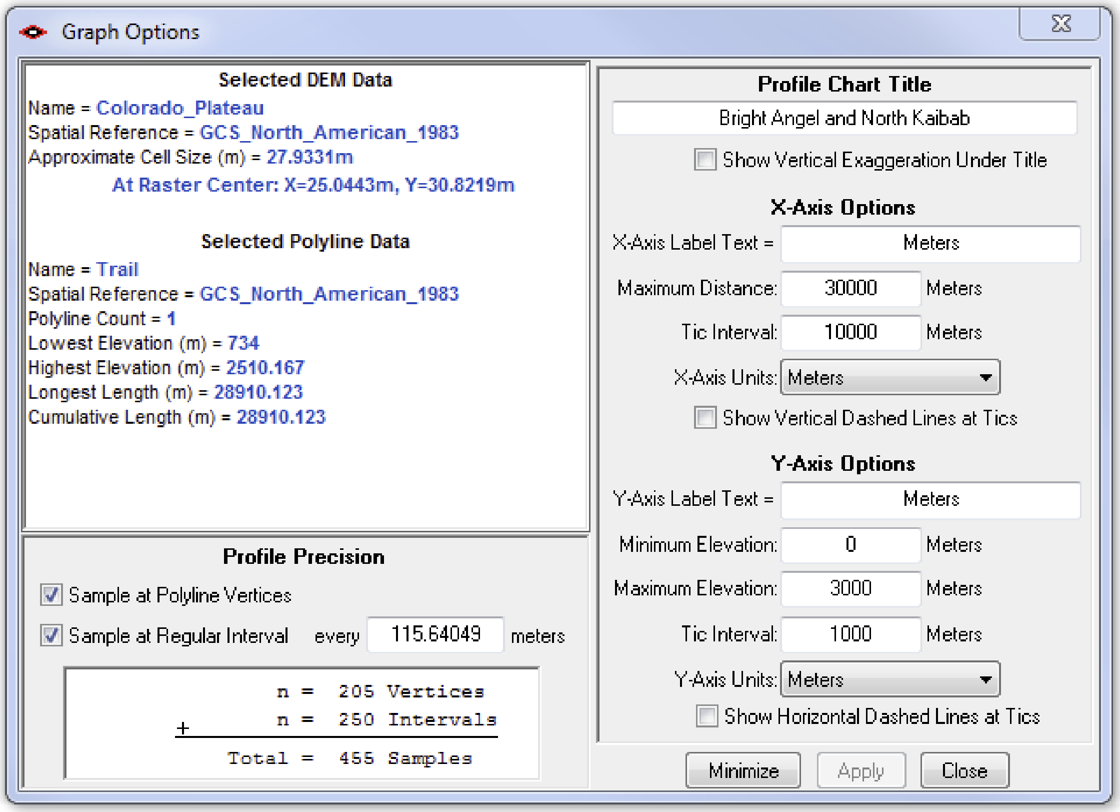
If you are graphing a single polyline, then the title will default to the ID value of that feature. If you are graphing multiple polylines, the title will default to the name of the feature layer. The color of the features in the graph are based on the colors of your features in your map.

Modifying the graph:

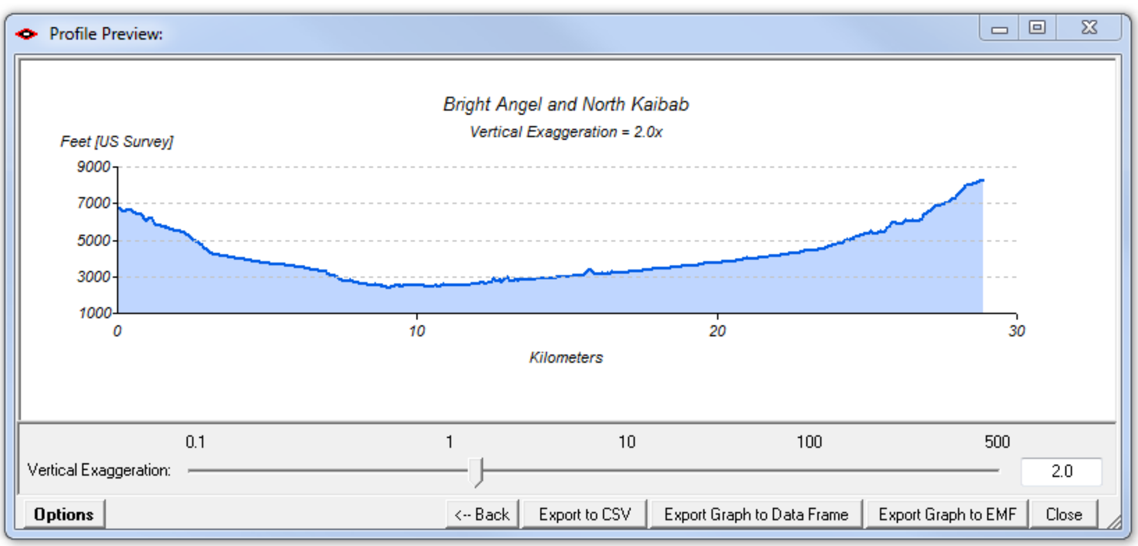
You have several options to modify the graph. Within the preview window itself, you may change the vertical exaggeration by dragging the slider beneath the graph. You may also change the size of the graph by resizing the window itself.



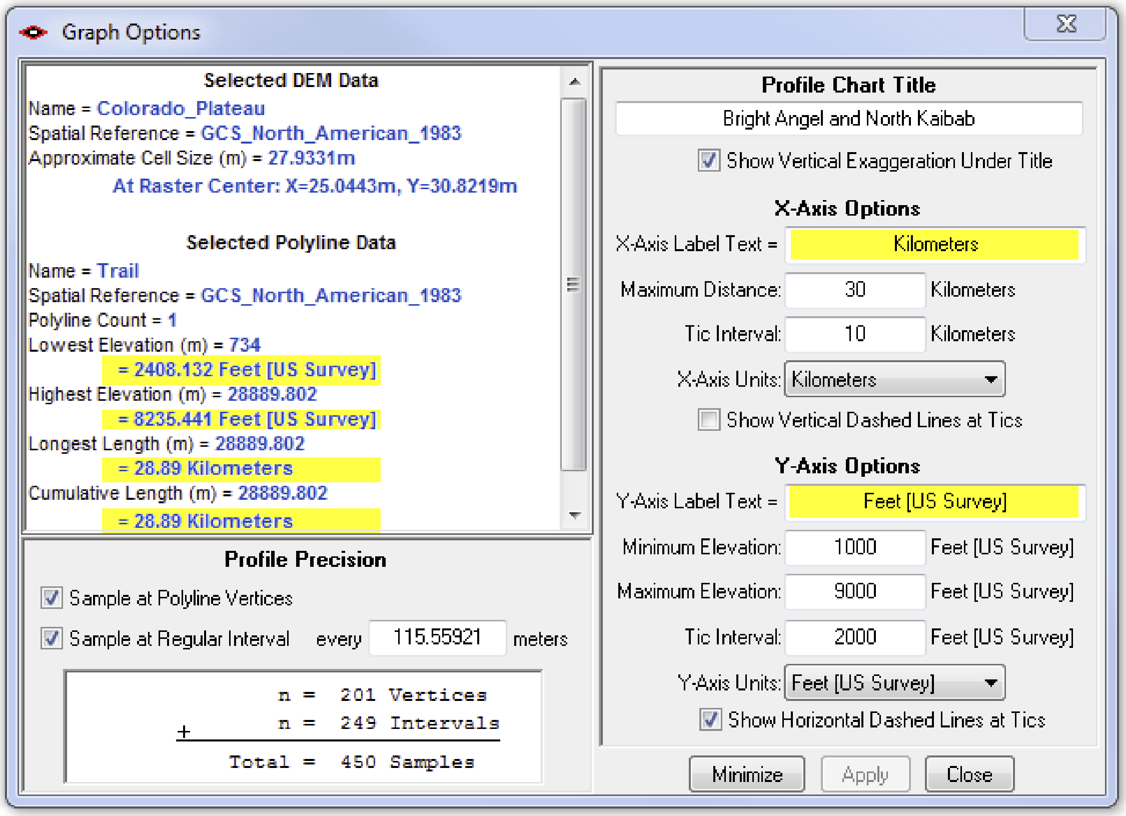
A few more options are available by clicking the *Options* button:



You may change the labels, units, extents and tic intervals of your distance and elevation axes, and whether or not you would like to add dashed lines to the tic marks. For example, we could change the elevation units of our Grand Canyon trail profile to *Feet*, reset the interval and add dashed lines. We could also add the exaggeration factor to the graph:



Notice that changing units in the *Options* dialog causes the descriptive information in the upper left corner to change. This descriptive information may be a helpful guide when deciding on appropriate minimum and maximum values to graph:



You may also reset the sampling level for your elevation values. By default, the tool will sample the DEM at every vertex along your route, and also at 250 evenly-distributed points along the route. You may increase or decrease that sampling density in this dialog.

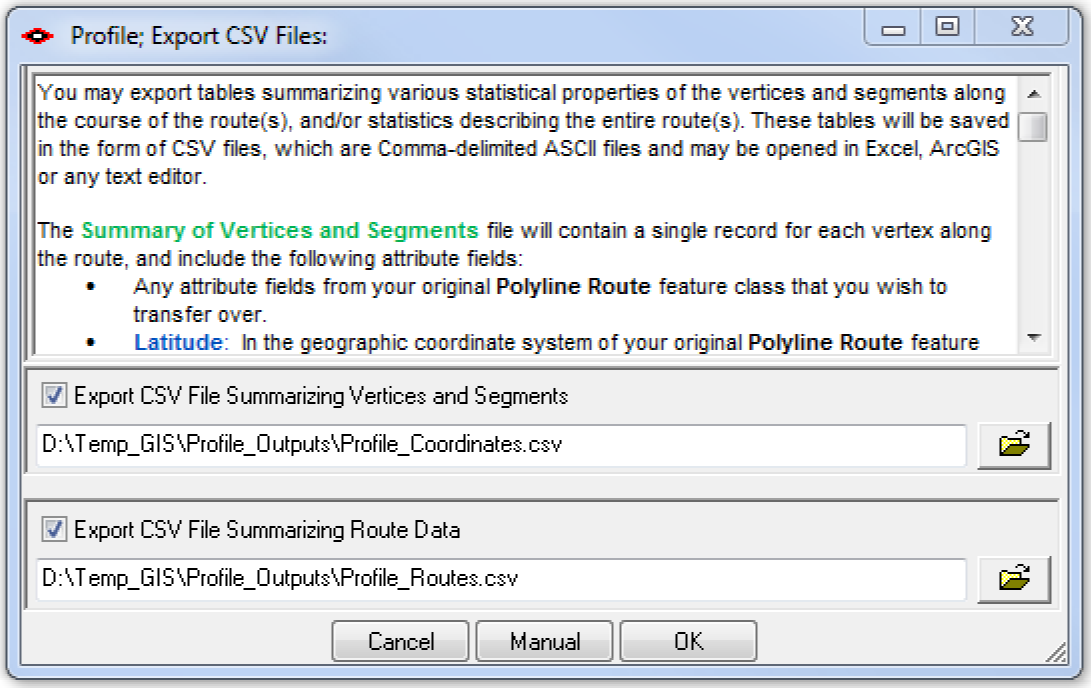
For example, our Grand Canyon trail polyline is almost 29,000m long (see upper left corner of Graph Options window above). By default the tool will sample at all vertices, and then split the trail into 250 sections and sample approximately every 116m (see *Profile Precision* of Graph Options window above).

However, the DEM has a resolution of roughly 28m, and therefore we are only sampling every 4 – 5 cells. If we wanted, we could increase our sampling interval to around 28m in order to take better advantage of the precision of the DEM.

The downside of increasing the sampling precision is that the tool takes longer to generate the data and graphs. You will need to balance your need for tool speed and responsiveness with your requirements for data precision.

Exporting CSV Tables:

You may export tables summarizing various statistical properties of the vertices and segments along the course of the route(s), and/or statistics describing the entire route(s). These tables will be saved in the form of CSV files, which are comma-delimited ASCII files and may be opened in Excel, ArcGIS or any text editor.



This function offers output options for 2 CSV files. One file summarizes statistics for individual vertices along the route and the other summarizes entire routes.

The **Summary of Vertices and Segments** file will contain a single record for each vertex along the route, and include the following attribute fields:

- Any attribute fields from your original **Polyline Route** feature class that you wish to transfer over.
- **Latitude**: In the geographic coordinate system of your original **Polyline Route** feature class.
- **Longitude**: In the geographic coordinate system of your original **Polyline Route** feature class.
- **Compass_Bearing:** The compass bearing from the previous vertex to this vertex. The first record will have a compass bearing = -999.
- **Slope_Degrees:** The absolute value of the slope between the previous vertex and this vertex. The first record will have a slope value = -999.
- **Elevation_Meters:** The elevation value of this vertex based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.

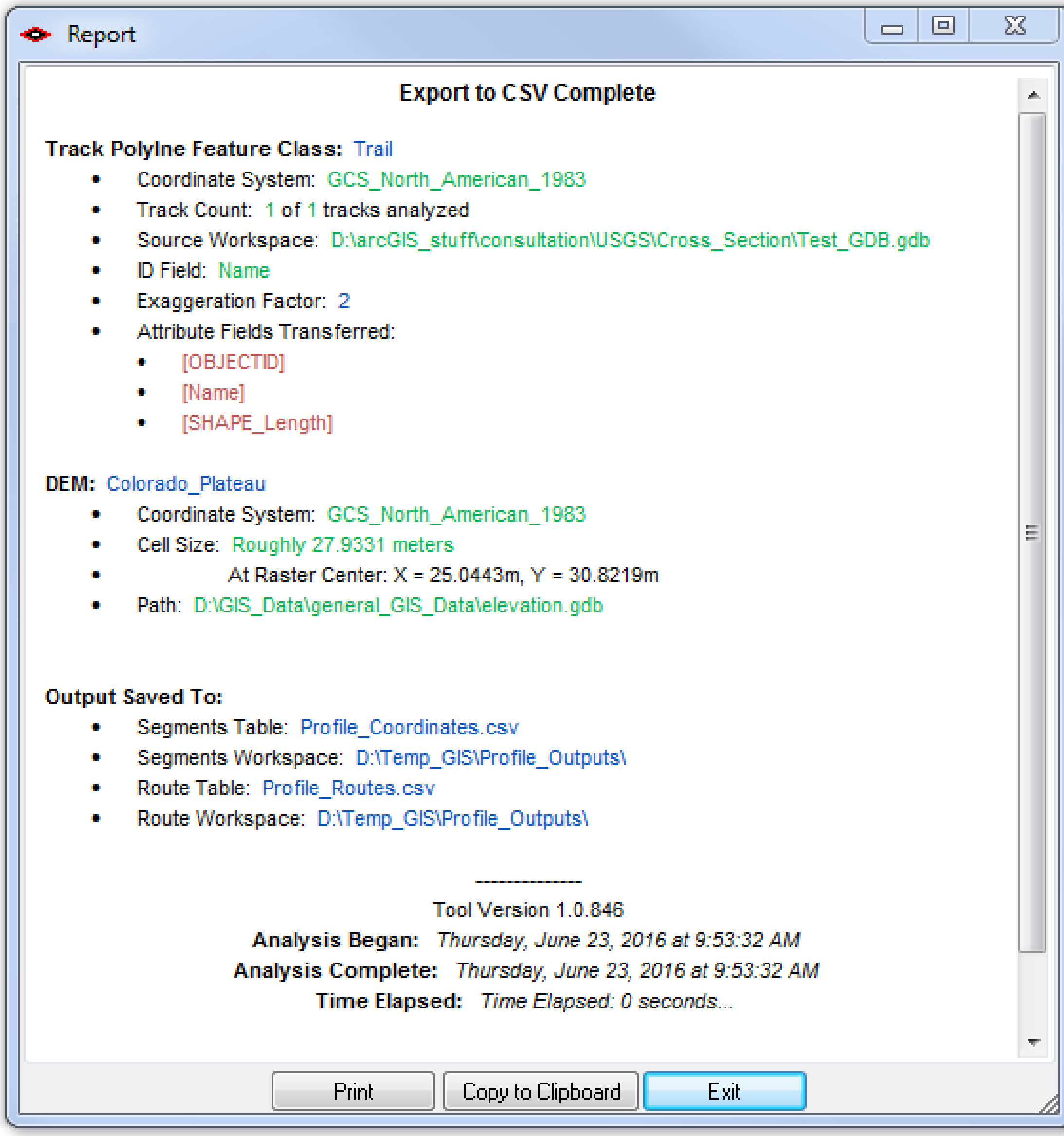
- **Segment_Geodesic_Distance_Meters:** The distance, in meters, between the previous vertex and this one, calculated using Vincenty's algorithms to estimate geodesic distances over the original Polygon Route feature class spheroid (see Vincenty 1975; also p. 124 of this manual).
- **Segment_Surface_Distance_Meters:** The surface distance, in meters, between the previous vertex and this one, calculated using the Pythagorean theorem to determine the hypotenuse of the triangle formed by the change in elevation and the geodesic distance.
- **Cumulative_Proportion:** The proportion of the original route at this vertex. This proportion is based on the surface distance of the line, not the geodesic distance.
- **Cumulative_Geodesic_Distance_Meters:** The total geodesic distance along the route up to this vertex.
- **Cumulative_Surface_Distance_Meters:** The total surface distance along the route up to this vertex.
- **X_Original_Units:** The X-coordinate in the original units of the source **Polyline Route** feature class. For example, if the source data were in UTM coordinates, then this value would be the vertex Easting value.
- **Y_Original_Units:** The Y-coordinate in the original units of the source **Polyline Route** feature class. For example, if the source data were in UTM coordinates, then this value would be the vertex Northing value.
- **Elevation_Original_Units:** The elevation value in the original units of the source DEM.
- **Exaggeration_Factor:** The exaggeration factor used to adjust the dimensions of the profile graph. This may be useful if you wish to generate a profile graph from these points in some other software package such as **R**.
- **Exaggerated_Elev:** The elevation of the vertex after being multiplied by the exaggeration factor. This is the value that is actually being plotted on the graph, and this value may also be useful if you wish to generate a profile graph from these points in some other software package.

The **Summary of Routes** file will contain a single record for each route analyzed, and will include the following attribute fields:

- Any attribute fields from your original **Polyline Route** feature class that you wish to transfer over.
- **Sample_Points:** The number of DEM values sampled to generate the statistics for this polyline.
- **Start_Latitude:** In the geographic coordinate system of your original **Polyline Route** feature class.
- **Start_Longitude:** In the geographic coordinate system of your original **Polyline Route** feature class.

- **End_Latitude:** In the geographic coordinate system of your original **Polyline Route** feature class.
- **End_Longitude:** In the geographic coordinate system of your original **Polyline Route** feature class.
- **Start_Elevation:** The elevation value of starting point based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
- **End_Elevation:** The elevation of the ending point based on the selected DEM.
- **Min_Elevation:** The elevation of the lowest point based on the selected DEM.
- **Max_Elevation:** The elevation of the highest point based on the selected DEM.
- **Avg_Slope:** The average slope over the course of the route, calculated as the weighted mean of the segment slopes, weighted by the segment surface distances.
- **Slope_StDev:** The standard deviation of slope over the course of the route.
- **Avg_Bearing:** The mean direction of the route, equal to the bearing from the starting point to the ending point of the route (see p. 137 for details).
- **BearingMRL:** The Mean Resultant Length of the route, calculated as the ratio of the geodesic length of the complete route divided by the geodesic distance of the straight line between the starting and ending points (see p. 137 for details). The MRL is the basis of several circular measures of dispersion (see Batschelet 1981, Fisher 1995, Mardia and Jupp 2000). MRL values near 1 indicate little direction variation over the line.
- **Length_Geodesic:** The geodesic length of the route.
- **Length_Surface:** The surface length of the route.
- **Surface Ratio:** The ratio of [Surface Length] / [Geodesic Length]. Values near 1 indicate a flat line, while values > 1 indicate increasing elevational variation.

Upon completion, the tool will display a report window showing where the files were saved.

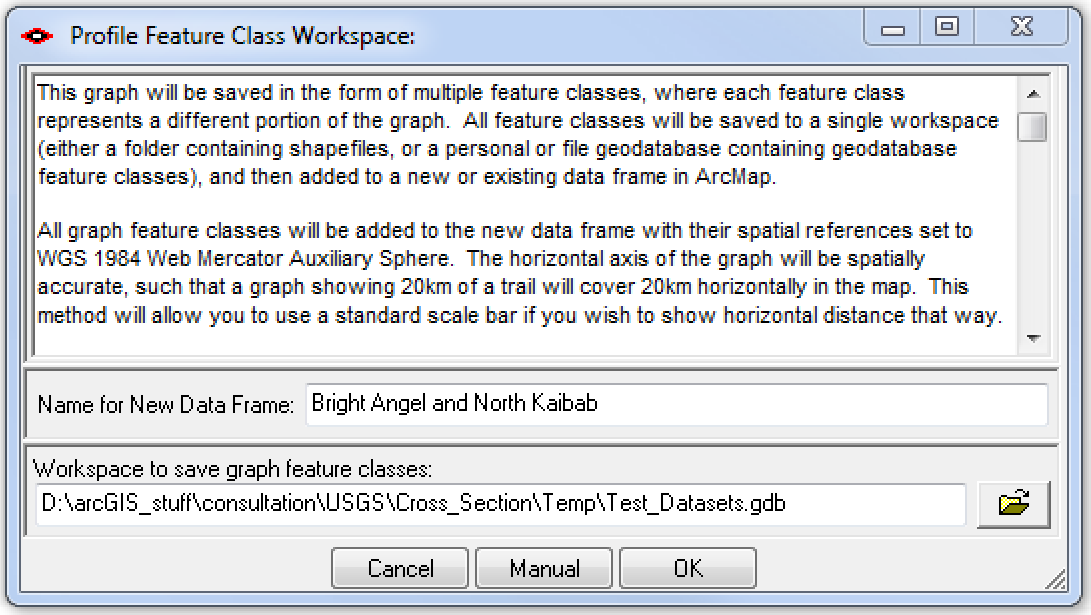

Report
Export to CSV Complete
Track Polylne Feature Class: Trail
Coordinate System: GCS_North_American_1983
Track Count: 1 of 1 tracks analyzed
Source Workspace: D:\arcGIS_stuff\consultation\USGS\Cross_Section\Test_GDB.gdb
ID Field: Name
Exaggeration Factor: 2
Attribute Fields Transferred:
[OBJECTID]
[Name]
[SHAPE_Length]
DEM: Colorado_Plateau
Coordinate System: GCS_North_American_1983
Cell Size: Roughly 27.9331 meters
At Raster Center: X = 25.0443m, Y = 30.8219m
Path: D:\GIS_Data\general_GIS_Data\elevation.gdb
Output Saved To:
Segments Table: Profile_Coordinates.csv
Segments Workspace: D:\Temp_GIS\Profile_Outputs\
Route Table: Profile_Routes.csv
Route Workspace: D:\Temp_GIS\Profile_Outputs\
Tool Version 1.0.846
Analysis Began: Thursday, June 23, 2016 at 9:53:32 AM
Analysis Complete: Thursday, June 23, 2016 at 9:53:32 AM
Time Elapsed: Time Elapsed: 0 seconds...
Print
Copy to Clipboard
Exit

Exporting Graph to Data Frame as Feature Classes:

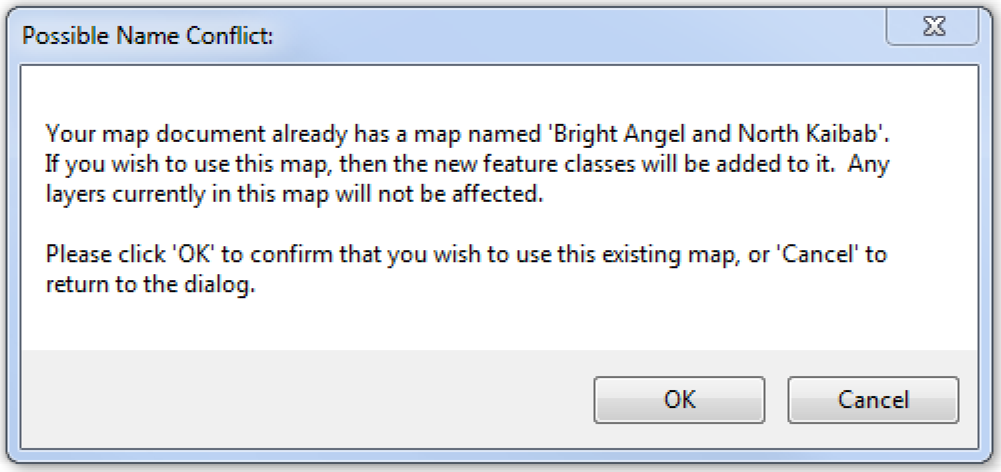
This graph will be saved in the form of multiple feature classes, where each feature class represents a different portion of the graph. All feature classes will be saved to a single workspace (either a folder containing shapefiles, or a personal or file geodatabase containing geodatabase feature classes), and then added to a new or existing data frame in ArcMap.

All graph feature classes will be added to the new data frame with their spatial references set to WGS 1984 Web Mercator Auxiliary Sphere. The horizontal axis of the graph will be spatially accurate, such that a graph showing 20km of a trail will cover 20km horizontally in the map. This method will allow you to use a standard scale bar if you wish to show horizontal distance that way.

You must specify the workspace you wish to use and the name of the new data frame.



This tool will create your new data frame automatically and assign it the name you specify in the dialog. If you specify a data frame name that already exists in your map document, this tool will alert you to the fact and ask you to confirm your choice:



All datasets will be named automatically, based on the name of your Track/Route layer.

Details: This tool will create 4 new feature classes representing different aspects of the graph.

1) **Segments Feature Class:** Contains a separate record for each vertex-to-vertex segment along a route. When initially added to the map, it will be symbolized by slope in a blue-to-red color ramp. In addition to any attribute fields from the original route feature class you may choose to transfer, this feature class will also include the following calculated attributes:

- **Start_Latitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **Start_Longitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **End_Latitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **End_Longitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **Geodesic_Length:** The segment length, in meters, calculated using Vincenty's algorithms to estimate geodesic distances over the original Polygon Route feature class spheroid (see Vincenty 1975; also p. 124 of this manual).
- **Surface_Length:** The segment surface length, in meters, calculated using the Pythagorean theorem to determine the hypotenuse of the triangle formed by the change in elevation and the geodesic distance.
- **Slope_Degrees:** The absolute value of the segment slope.
- **Bearing:** The compass bearing of the segment.
- **Start_Elevation:** The elevation value at the beginning of the segment based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this attribute field.

- **Mid_Elevation:** The elevation value at the centerpoint of the segment.
- **End_Elevation:** The elevation value at the end of the segment.
- **End_Proportion:** The proportion of the original route at the segment endpoint. This proportion is based on the surface distance of the line, not the geodesic distance. Values will range from 0 to 1.
- **Total_Geodesic_Distance:** The total geodesic distance, in meters, along the route up to the end of this segment.
- **Total_Surface_Distance:** The total surface distance, in meters, along the route up to the end of this segment.

2) **Polyline Feature Class:** Contains a separate record for each route showing the profile of the route over the DEM. When initially added to the map, it will be symbolized by ID value based on the ID field you select. If you do not select an ID field, it will be symbolized by the Feature Object ID of the original route. In addition to any attribute fields from the original route feature class you may choose to transfer, this feature class will also include the following calculated attributes:

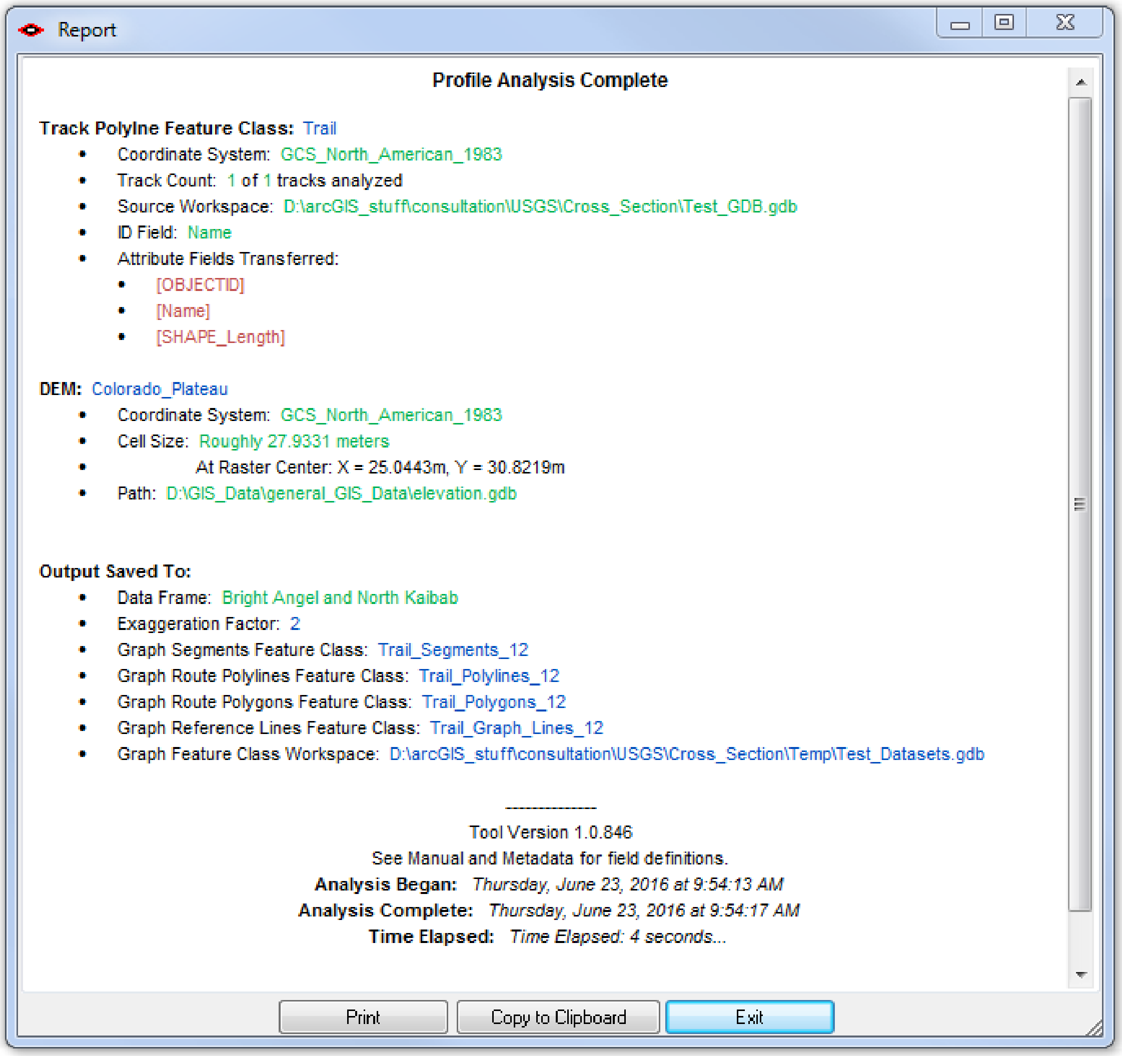
   - **Sample_Points:** The number of DEM values sampled to generate the statistics for this polyline.
   - **Start_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Start_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **End_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **End_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Start_Elevation:** The elevation value of starting point based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
   - **End_Elevation:** The elevation of the ending point based on the selected DEM.
   - **Min_Elevation:** The elevation of the lowest point based on the selected DEM.
   - **Max_Elevation:** The elevation of the highest point based on the selected DEM.
   - **Avg_Slope:** The average slope over the course of the route, calculated as the weighted mean of the segment slopes, weighted by the segment surface distances.
   - **Slope_StDev:** The standard deviation of slope over the course of the route.
   - **Avg_Bearing:** The mean direction of the route, equal to the bearing from the starting point to the ending point of the route (see p. 137 for details).

- **BearingMRL:** The Mean Resultant Length of the route, calculated as the ratio of the geodesic length of the complete route divided by the geodesic distance of the straight line between the starting and ending points (see p. 137 for details). The MRL is the basis of several circular measures of dispersion (see Batschelet 1981, Fisher 1995, Mardia and Jupp 2000). MRL values near 1 indicate little direction variation over the line.
- **Length_Geodesic:** The geodesic length of the route.
- **Length_Surface:** The surface length of the route.
- **Surface Ratio:** The ratio of [Surface Length] / [Geodesic Length]. Values near 1 indicate a flat line, while values > 1 indicate increasing elevational variation.

3) **Polygon Feature Class:** Similar to the Polyline Feature Class, except that it symbolizes the route using a polygon to symbolize the portion of the graph underneath the route profile. Contains a separate record for each route. When initially added to the map, it will be symbolized by ID value based on the ID field you select. If you do not select an ID field, it will be symbolized by the Feature Object ID of the original route. This feature class will contain exactly the same attribute fields and values as the Polyline Feature Class described above.
4) **Graph_Lines:** Simply shows the reference lines of the graph, including axes, tick marks and horizontal/vertical references. Attribute values include the name of the line (X-Axis, Y-Axis, X-Tic, Y-Tic, X-Reference and Y-Reference), and a label value for that line.

This tool will also add graphic text boxes for label values, axis names and the chart title. **Note:** These graphics can be converted to annotation by right-clicking data frame name and choosing "Convert Labels to Annotation". This option helps the labels look better if you add the graph to a layout. See also a known issue with exported graphic text on p. 96.

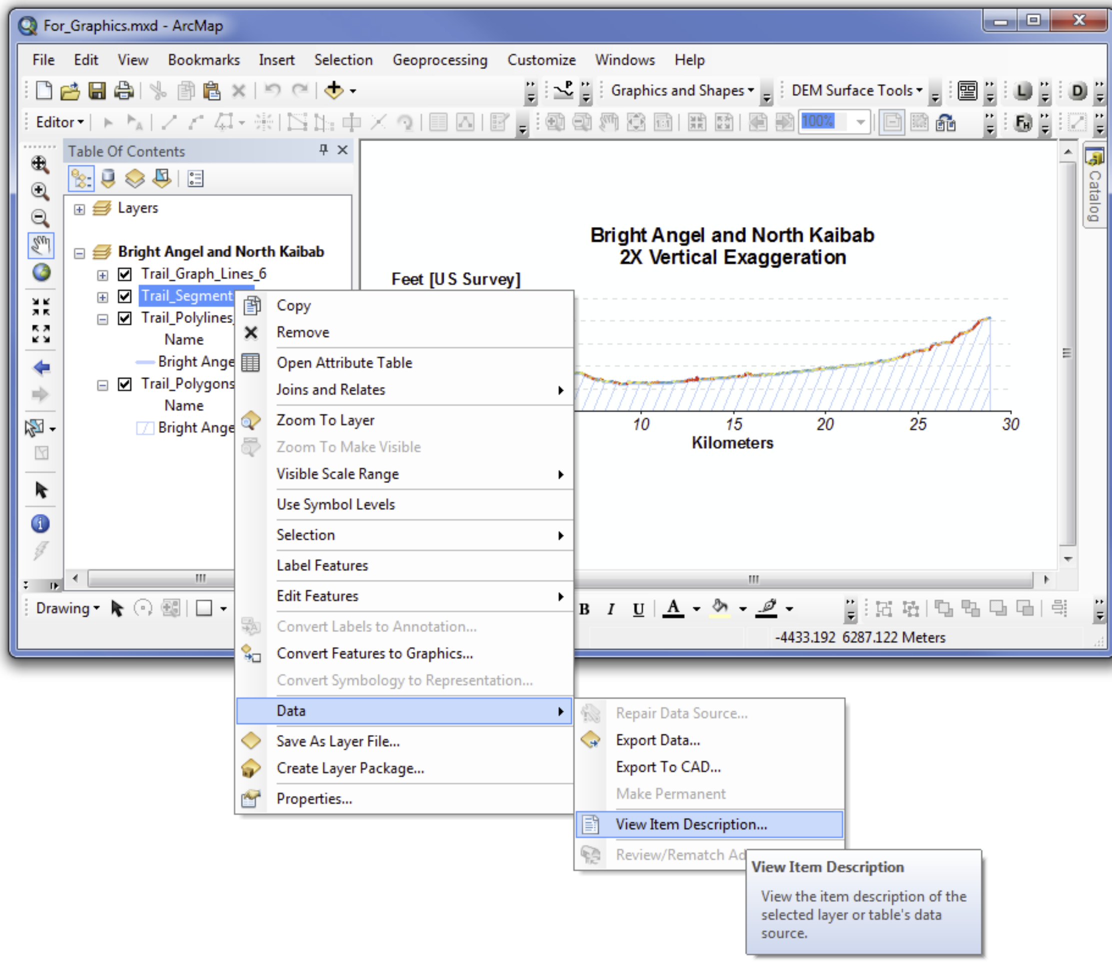
Upon completion, the tool will show you a report detailing what it did:

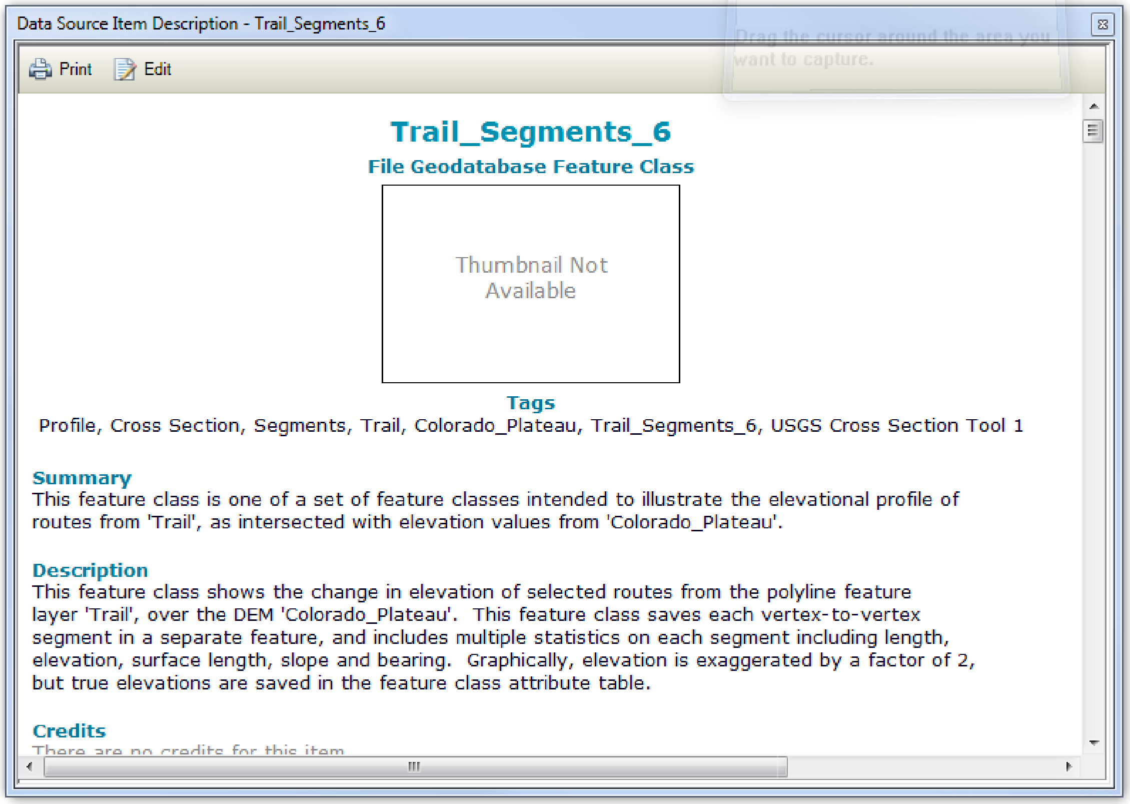


Your new data frame will open automatically, displaying all the elements of the graph. Initially the route profile line is symbolized by slope, so that steeper areas are red and gentler areas are blue. As with any feature layer in ArcMap, you can turn individual layers off and on, add labels, or resymbolize them to fit your preferences.

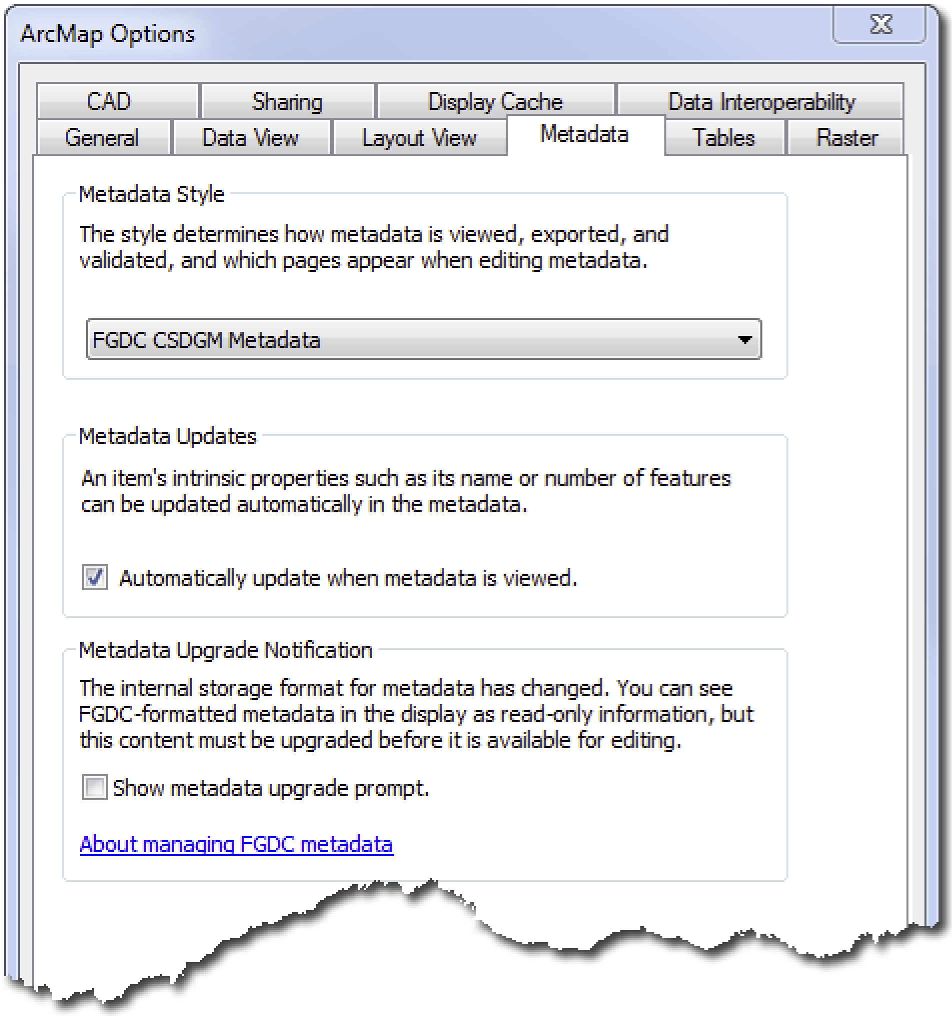
Another advantage to the feature class format is that you can edit the graph elements using the standard ArcMap Editor tools.

Finally, all graph element feature classes include metadata detailing the analysis options you specified and defining all the attribute fields. Simply right-click on the feature class, click on "Data", and then click "Show Item Description":


For_Graphics.mxd - ArcMap
File Edit View Bookmarks Insert Selection Geoprocessing Customize Windows Help
Graphics and Shapes
DEM Surface Tools
Editor
Table Of Contents
Layers
Bright Angel and North Kaibab
Trail_Graph_Lines_6
Trail_Segment
Trail_Polylines
Name
Trail_Polygons
Bright Angel and North Kaibab
2X Vertical Exaggeration
Feet [US Survey]
10
15
20
25
30
Kilometers
Copy
Remove
Open Attribute Table
Joins and Relates
Zoom To Layer
Zoom To Make Visible
Visible Scale Range
Use Symbol Levels
Selection
Label Features
Edit Features
Convert Labels to Annotation...
Convert Features to Graphics...
Convert Symbology to Representation...
Data
Save As Layer File...
Create Layer Package...
Properties...
Repair Data Source...
Export Data...
Export To CAD...
Make Permanent
View Item Description...
View Item Description
View the item description of the selected layer or table's data source.
Drawing
-4433.192 6287.122 Meters
Catalog



Note: If you do not see the field definitions in the metadata, then you may have ArcMap set to only show you the simplest "Item Description" form of metadata. This is easy to change if you want. Simply click the "Customize" menu, then ArcMap Options. Then click the "Metadata" tab and choose a different metadata style.

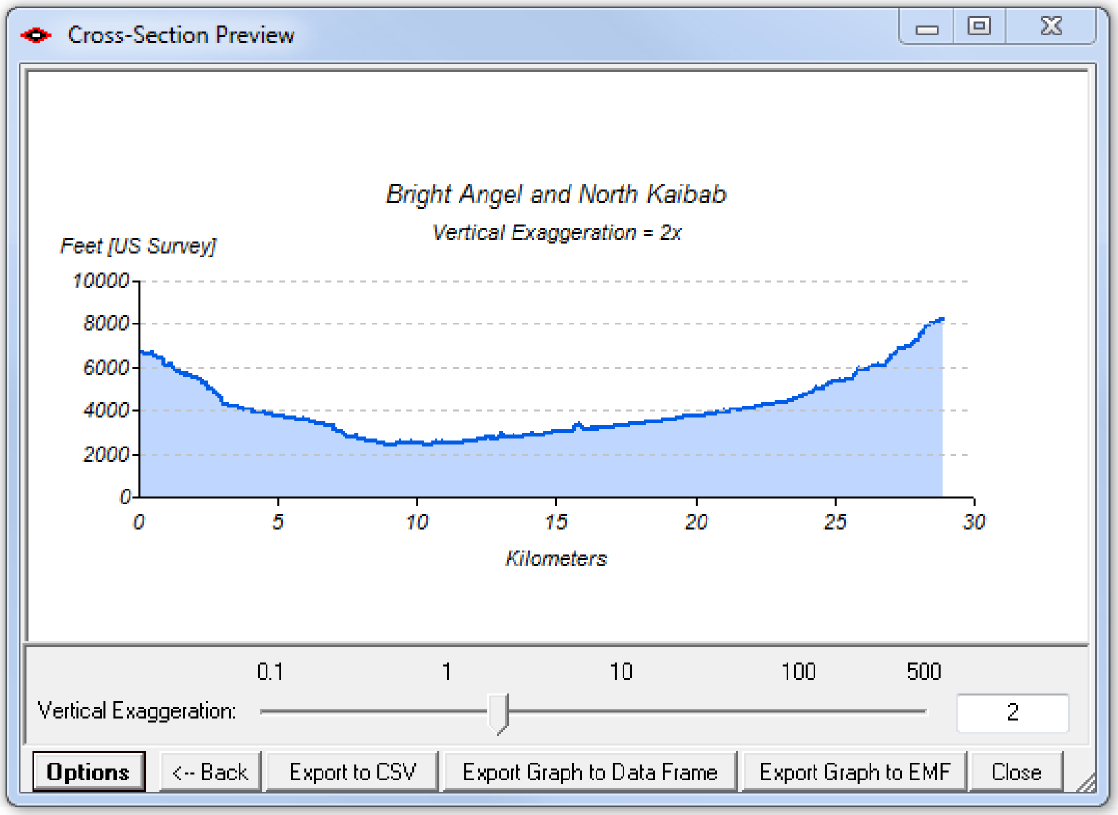

ArcMap Options
CAD
Sharing
Display Cache
Data Interoperability
General
Data View
Layout View
Metadata
Tables
Raster
Metadata Style
The style determines how metadata is viewed, exported, and validated, and which pages appear when editing metadata.
FGDC CSDGM Metadata
Metadata Updates
An item's intrinsic properties such as its name or number of features can be updated automatically in the metadata.
Automatically update when metadata is viewed.
Metadata Upgrade Notification
The internal storage format for metadata has changed. You can see FGDC-formatted metadata in the display as read-only information, but this content must be upgraded before it is available for editing.
Show metadata upgrade prompt.
About managing FGDC metadata

Export the Graph as an EMF file:

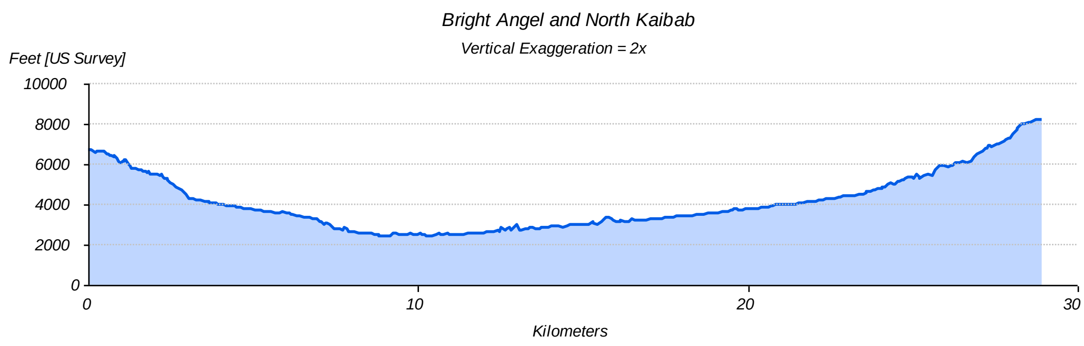
This option simply redraws the graph in the dialog onto an EMF (Windows Enhanced Metafile) surface and saves it to your hard drive. It also adds the EMF file as a graphic to your layout.

Click the *Export Graph to EMF* button and the tool will do everything automatically. The new EMF file will be named according to your graph title and saved in the same folder alongside your current ArcMap document (*.mxd file).

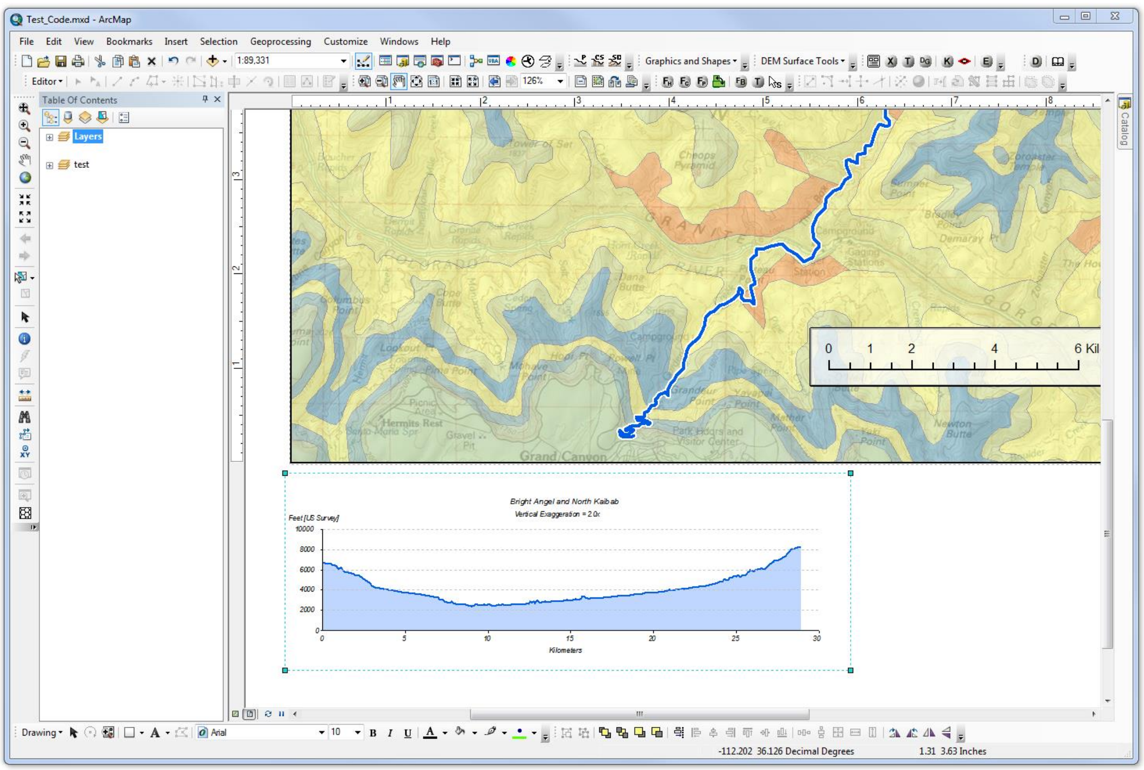
The EMF file can be opened and imported into several files, including Microsoft Word. For example, given the graph below,



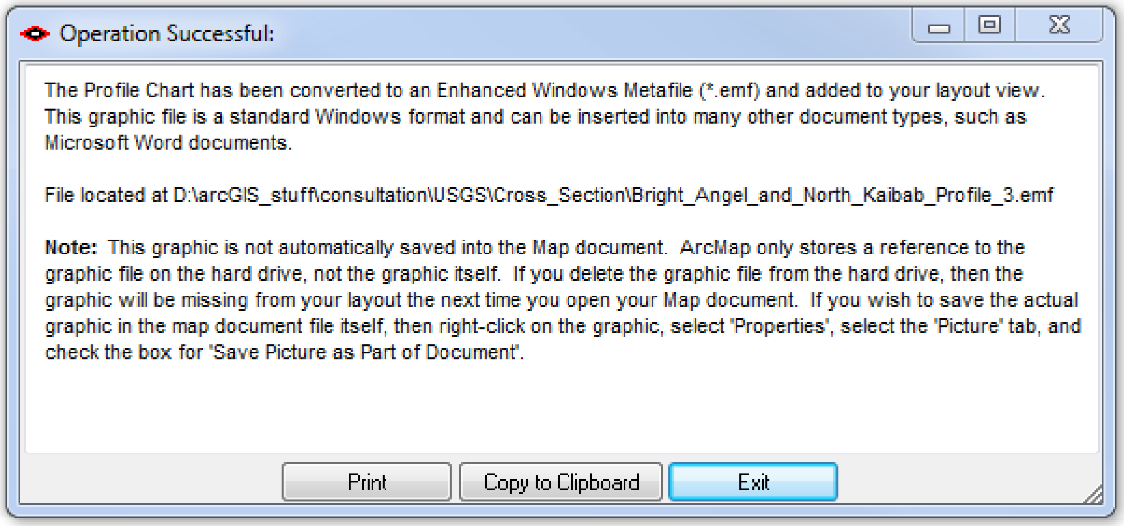
I have exported the graph to an EMF file and loaded it into this document below:



Upon completion, the tool will add the EMF file as a new graphic in your layout.



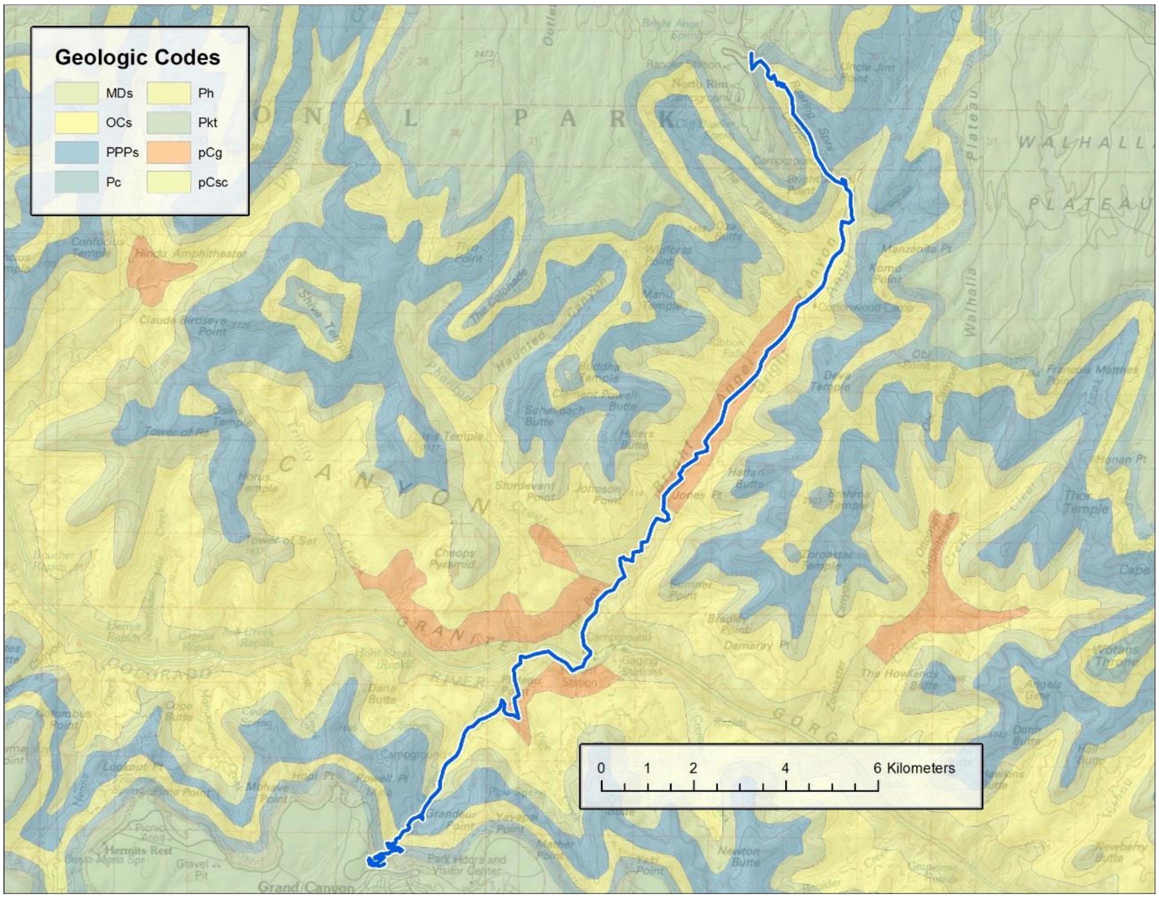
The tool will also give you a report detailing where it saved the EMF file and what the file is named:


Operation Successful:
The Profile Chart has been converted to an Enhanced Windows Metafile (*.emf) and added to your layout view. This graphic file is a standard Windows format and can be inserted into many other document types, such as Microsoft Word documents.
File located at D:\arcGIS_stuff\consultation\USGS\Cross_Section\Bright_Angel_and_North_Kaibab_Profile_3.emf
Note: This graphic is not automatically saved into the Map document. ArcMap only stores a reference to the graphic file on the hard drive, not the graphic itself. If you delete the graphic file from the hard drive, then the graphic will be missing from your layout the next time you open your Map document. If you wish to save the actual graphic in the map document file itself, then right-click on the graphic, select 'Properties', select the 'Picture' tab, and check the box for 'Save Picture as Part of Document'.
Print
Copy to Clipboard
Exit

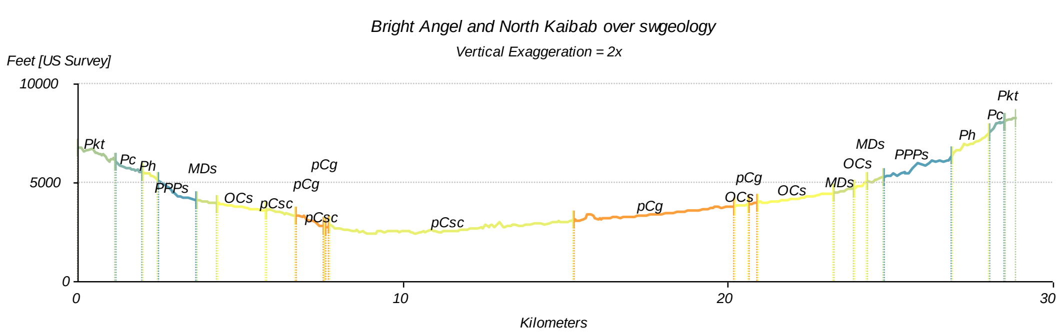
Cross Sections Tool

The Cross Sections tool is similar to the Elevation Profile tool, but adds the ability to intersect the track/route with a polygon feature class of geologic types. Output options include all those available for the Elevation Profile tool, plus additional statistics describing the portions of the route within each geologic polygon.

For example, our trail across the Grand Canyon also crosses several geologic regions:

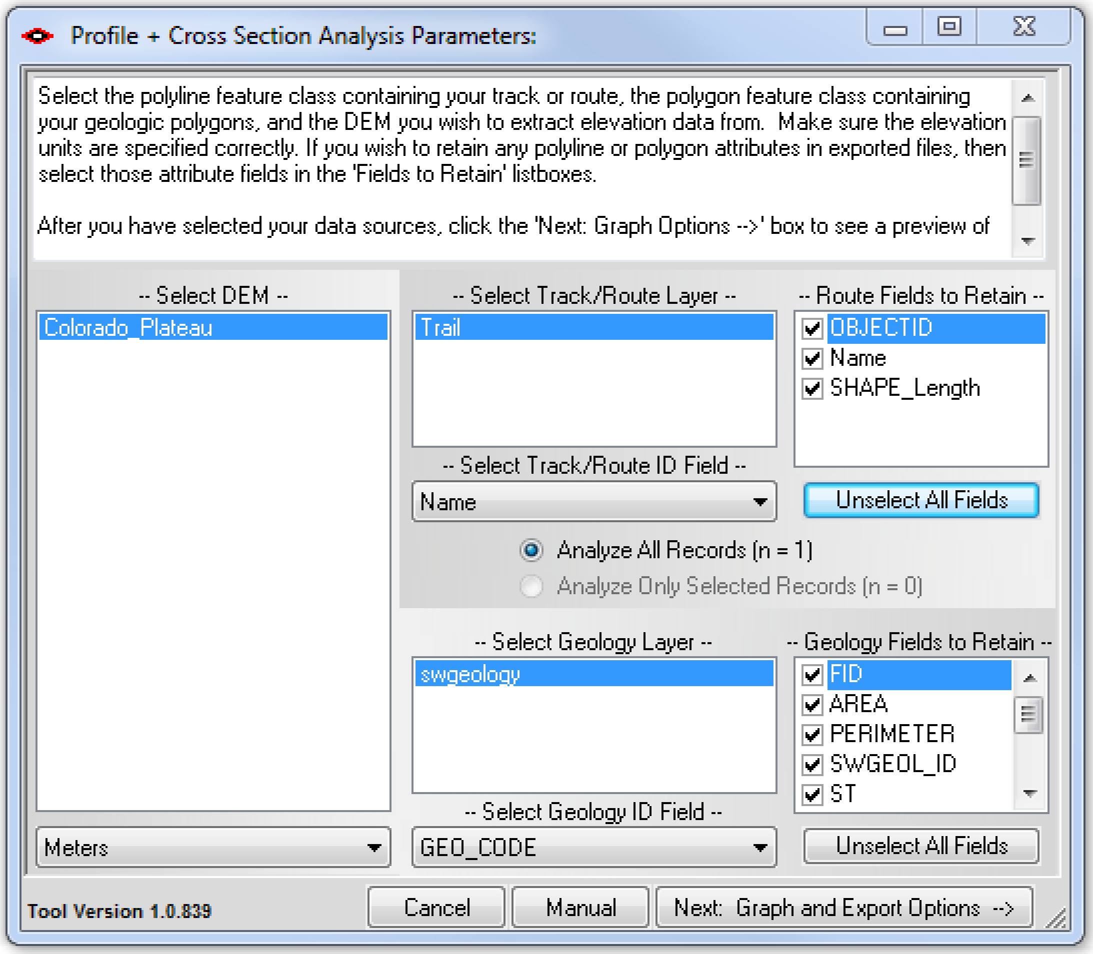


The Cross Sections tool allows us to generate the elevational profile divided by geologic types:



Using the Tool:

1) Make sure your Route polyline and Geology polygon feature classes, and your DEM raster dataset are loaded into your ArcMap document.
2) Click the **Cross Sections** command to open the *Profile + Cross Section Analysis Parameters* dialog.



3) You must specify 9 parameters:
   a) DEM: This is the elevation raster that the polyline(s) will be intersected with.
   b) Units: DEMs typically define elevation in meters or feet, but there is nothing in the dataset itself that explicitly defines the unit. Therefore you must specify the correct unit yourself. The tool defaults to **Meters**.
   c) Track/Route Layer: This is the polyline feature class containing the route(s) to analyze.
   d) Track/Route ID Field: This is the attribute used by the tool to label the graphs.
   e) Track/Route Fields to Retain: The tool offers several output options for graphs and statistical tables. If you would like any of the original Track/Route attributes to be included in those statistical tables, then select those fields here. **Note:** The "Track/Route ID Field" will automatically be retained in all output datasets.

f) Whether to analyze all polylines, or only selected subset: If you have any polylines selected, then you have the option to restrict your analysis to only the selected subset. If you choose to analyze multiple polylines simultaneously, then the tool will overlay the graphs on each other.

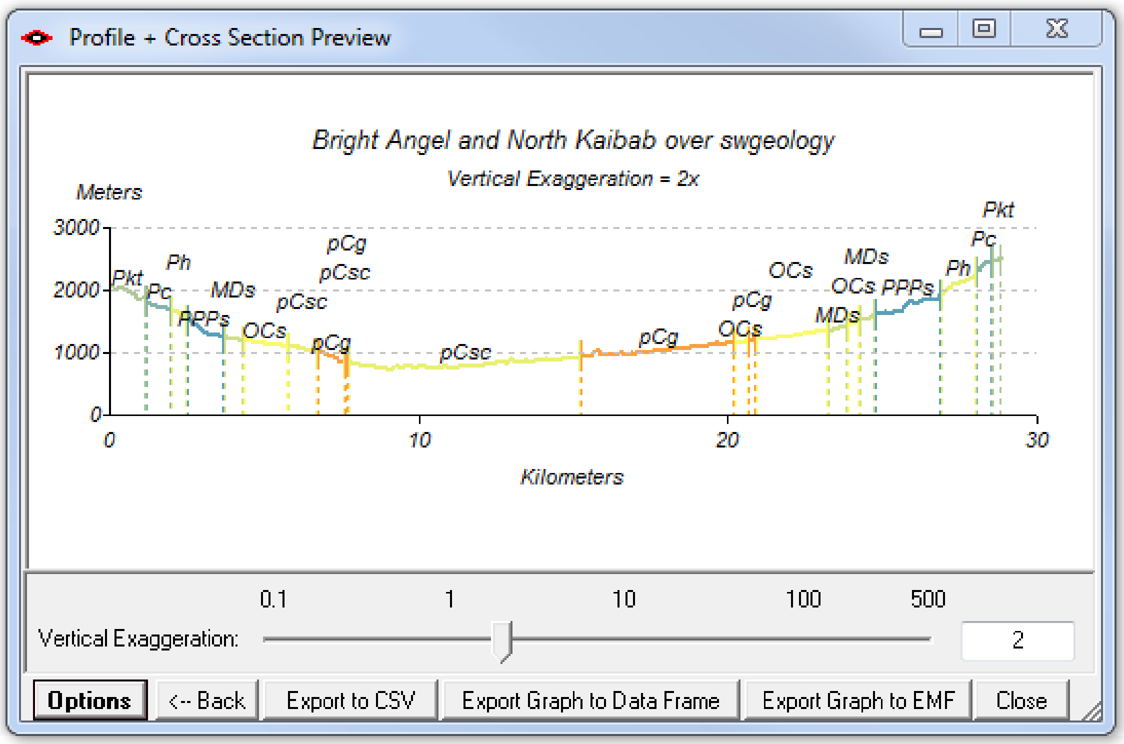
g) Geology polygon feature layer. **Note:** This tool was originally designed to intersect routes specifically with geologic polygon feature classes, but it will work just fine with any polygon feature class.

h) Geology ID Field: This is the attribute used by the tool to label the graphs.

i) Geology Fields to Retain: The tool will add these geology attributes to all output tables and feature classes.

Note: There may be issues regarding the coordinate systems of your data. If your data are in different geographic datums, then you **may** need to specify a geographic transformation. Please see Appendix A (p. 102) for details.

After selecting your initial parameters, click the *Next: Graph and Export Options -->* button to preview your profile graph.



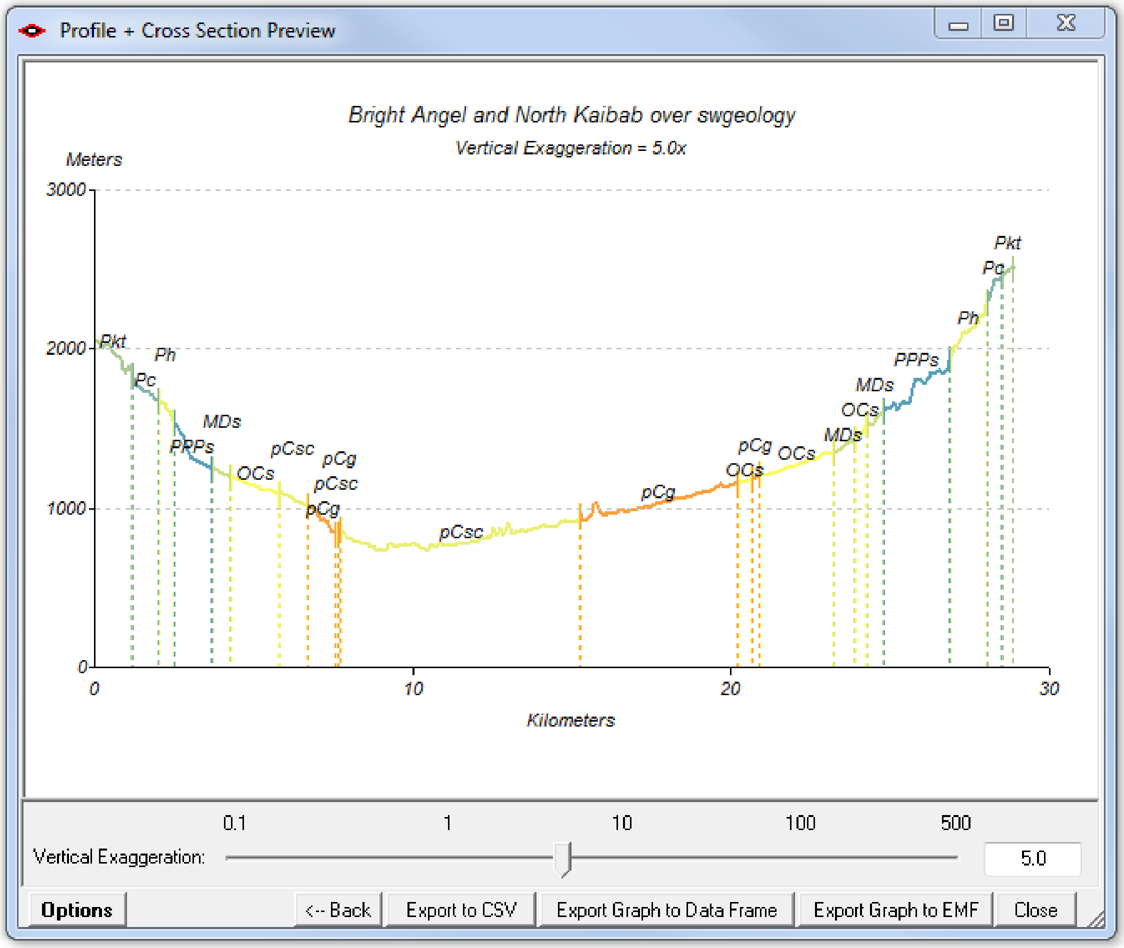
If you are graphing a single polyline, then the title will default to the ID value of that feature appended with “over [Your Geology Layer Name]”. If you are graphing multiple polylines, the title will default to the name of the feature layer appended with “over [Your Geology Layer Name]”.

The color of the profile features in the graph are based on the colors of your geologic polygons in your map. If your geologic polygons are transparent or hollow, then the tool assigns random Earth Tone colors adapted from Varian (2004).

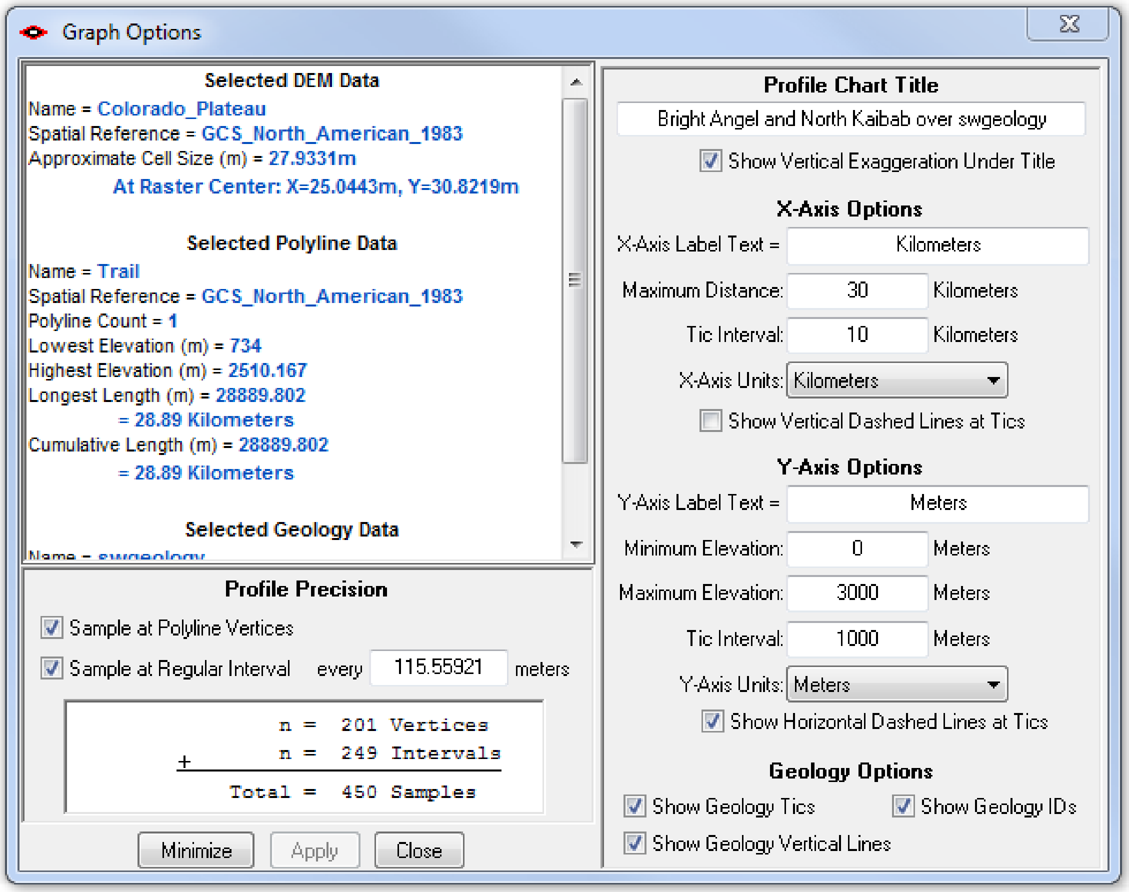
The color under the profile line is based on the color of your route feature in the map. In the example above, I have the route polyline colored white, so the graph region underneath the profile line is also white.

Modifying the graph:

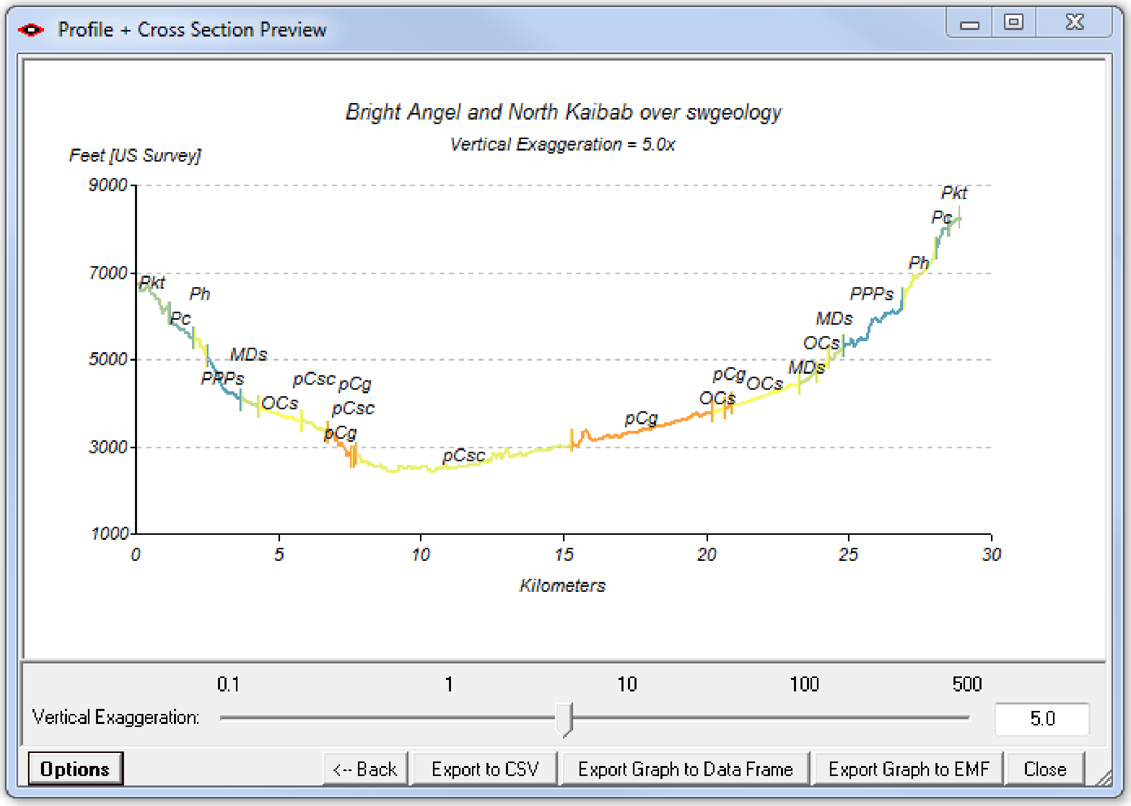
You have several options to modify the graph. Within the preview window itself, you may change the vertical exaggeration by dragging the slider beneath the graph. You may also change the size of the graph by resizing the window itself.



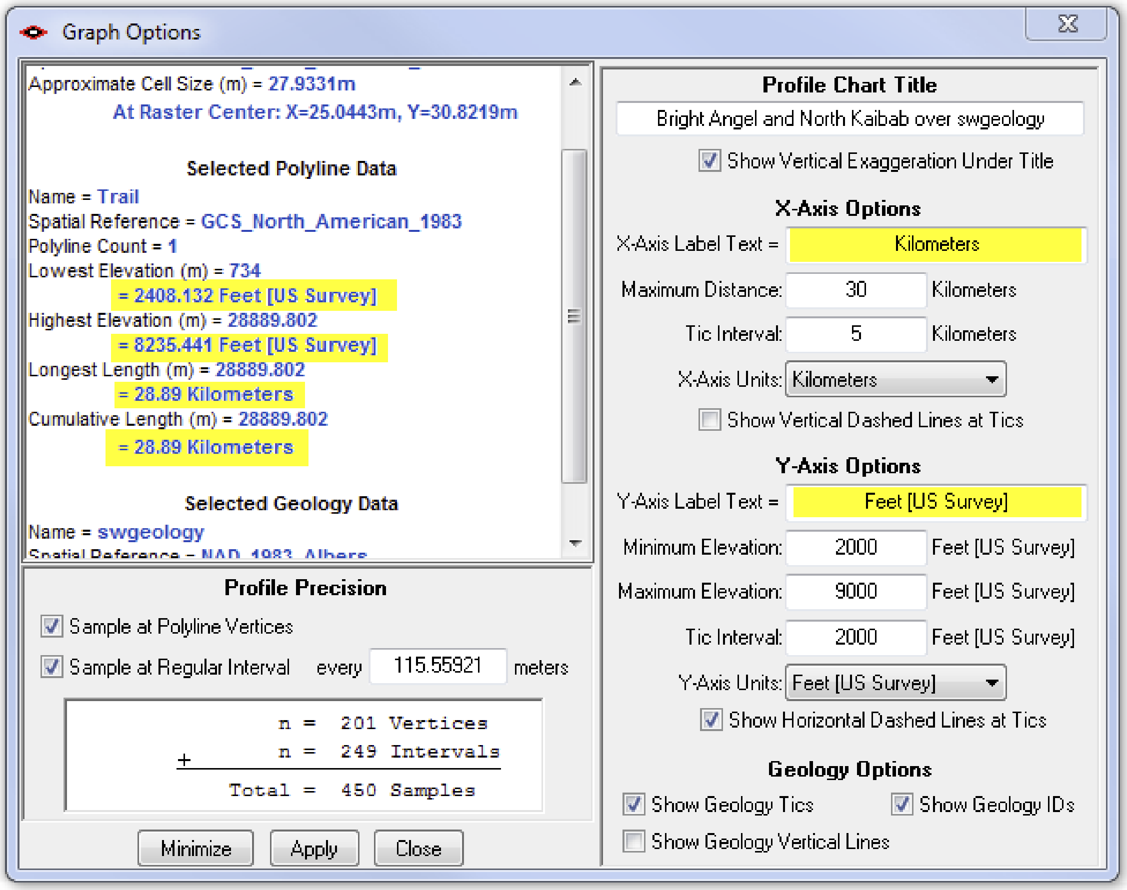
A few more options are available by clicking the *Options* button:



You may change the labels, units, extents and tic intervals of your distance and elevation axes, and whether or not you would like to add dashed lines to the tic marks. You may also specify whether or not you would like to see geologic labels, tick marcs or vertical lines in the graph. For example, we could change the elevation units of our Grand Canyon trail profile to *Feet*, reset the interval and remove the Geology vertical dashed lines.



Notice that changing units in the *Options* dialog causes the descriptive information in the upper left corner to change. This descriptive information may be a helpful guide when deciding on appropriate minimum and maximum values to graph:



You may also reset the sampling level for your elevation values. By default, the tool will sample the DEM at every vertex along your route, and also at 250 evenly-distributed points along the route. You may increase or decrease that sampling density in this dialog.

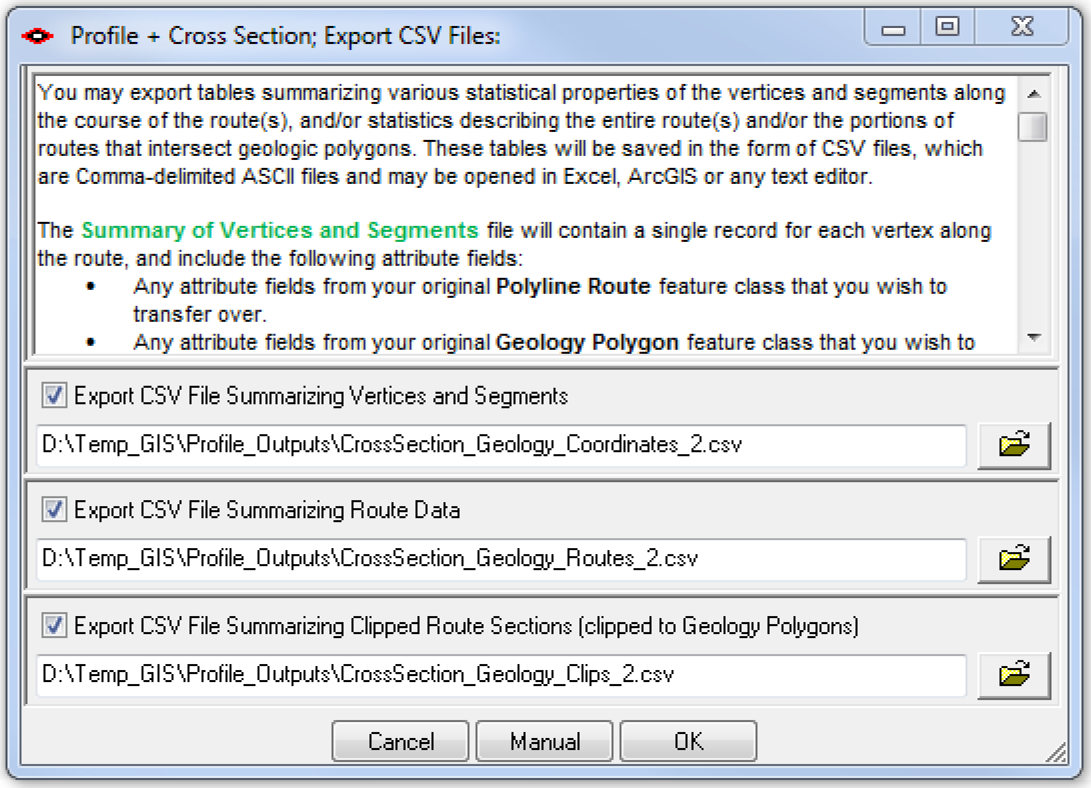
For example, our Grand Canyon trail polyline is almost 29,000m long (see upper left corner of Graph Options window above). By default the tool will sample at all vertices, and then split the trail into 250 sections and sample approximately every 116m (see *Profile Precision* of Graph Options window above).

However, the DEM has a resolution of roughly 28m, and therefore we are only sampling every 4 – 5 cells. If we wanted, we could increase our sampling interval to around 28m in order to take better advantage of the precision of the DEM.

The downside of increasing the sampling precision is that the tool takes longer to generate the data and graphs. You will need to balance your need for tool speed and responsiveness with your requirements for data precision.

Exporting CSV Tables:

You may export tables summarizing various statistical properties of the vertices and segments along the course of the route(s), and/or statistics describing the entire route(s). These tables will be saved in the form of CSV files, which are comma-delimited ASCII files and may be opened in Excel, ArcGIS or any text editor.



This function offers output options for 3 CSV files. One file summarizes statistics for individual vertices along the route, another summarizes entire routes and a third summarizes route segments that intersect geologic polygons.

The **Summary of Vertices and Segments** file will contain a single record for each vertex along the route, and include the following attribute fields:

- Any attribute fields from your original **Polyline Route** feature class that you wish to transfer over.
- **Latitude**: In the geographic coordinate system of your original **Polyline Route** feature class.
- **Longitude**: In the geographic coordinate system of your original **Polyline Route** feature class.
- **Compass_Bearing:** The compass bearing from the previous vertex to this vertex. The first record will have a compass bearing = -999.
- **Slope_Degrees:** The absolute value of the slope between the previous vertex and this vertex. The first record will have a slope value = -999.
- **Elevation_Meters:** The elevation value of this vertex based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.

- **Segment_Geodesic_Distance_Meters:** The distance, in meters, between the previous vertex and this one, calculated using Vincenty's algorithms to estimate geodesic distances over the original Polygon Route feature class spheroid (see Vincenty 1975; also p. 124 of this manual).
- **Segment_Surface_Distance_Meters:** The surface distance, in meters, between the previous vertex and this one, calculated using the Pythagorean theorem to determine the hypotenuse of the triangle formed by the change in elevation and the geodesic distance.
- **Cumulative_Proportion:** The proportion of the original route at this vertex. This proportion is based on the surface distance of the line, not the geodesic distance.
- **Cumulative_Geodesic_Distance_Meters:** The total geodesic distance along the route up to this vertex.
- **Cumulative_Surface_Distance_Meters:** The total surface distance along the route up to this vertex.
- **X_Original_Units:** The X-coordinate in the original units of the source **Polyline Route** feature class. For example, if the source data were in UTM coordinates, then this value would be the vertex Easting value.
- **Y_Original_Units:** The Y-coordinate in the original units of the source **Polyline Route** feature class. For example, if the source data were in UTM coordinates, then this value would be the vertex Northing value.
- **Elevation_Original_Units:** The elevation value in the original units of the source DEM.
- **Exaggeration_Factor:** The exaggeration factor used to adjust the dimensions of the profile graph. This may be useful if you wish to generate a profile graph from these points in some other software package such as **R**.
- **Exaggerated_Elev:** The elevation of the vertex after being multiplied by the exaggeration factor. This is the value that is actually being plotted on the graph, and this value may also be useful if you wish to generate a profile graph from these points in some other software package.

The **Summary of Routes** file will contain a single record for each route analyzed, and will include the following attribute fields:

- Any attribute fields from your original **Polyline Route** feature class that you wish to transfer over.
- **Sample_Points:** The number of DEM values sampled to generate the statistics for this polyline.
- **Start_Latitude:** In the geographic coordinate system of your original **Polyline Route** feature class.
- **Start_Longitude:** In the geographic coordinate system of your original **Polyline Route** feature class.

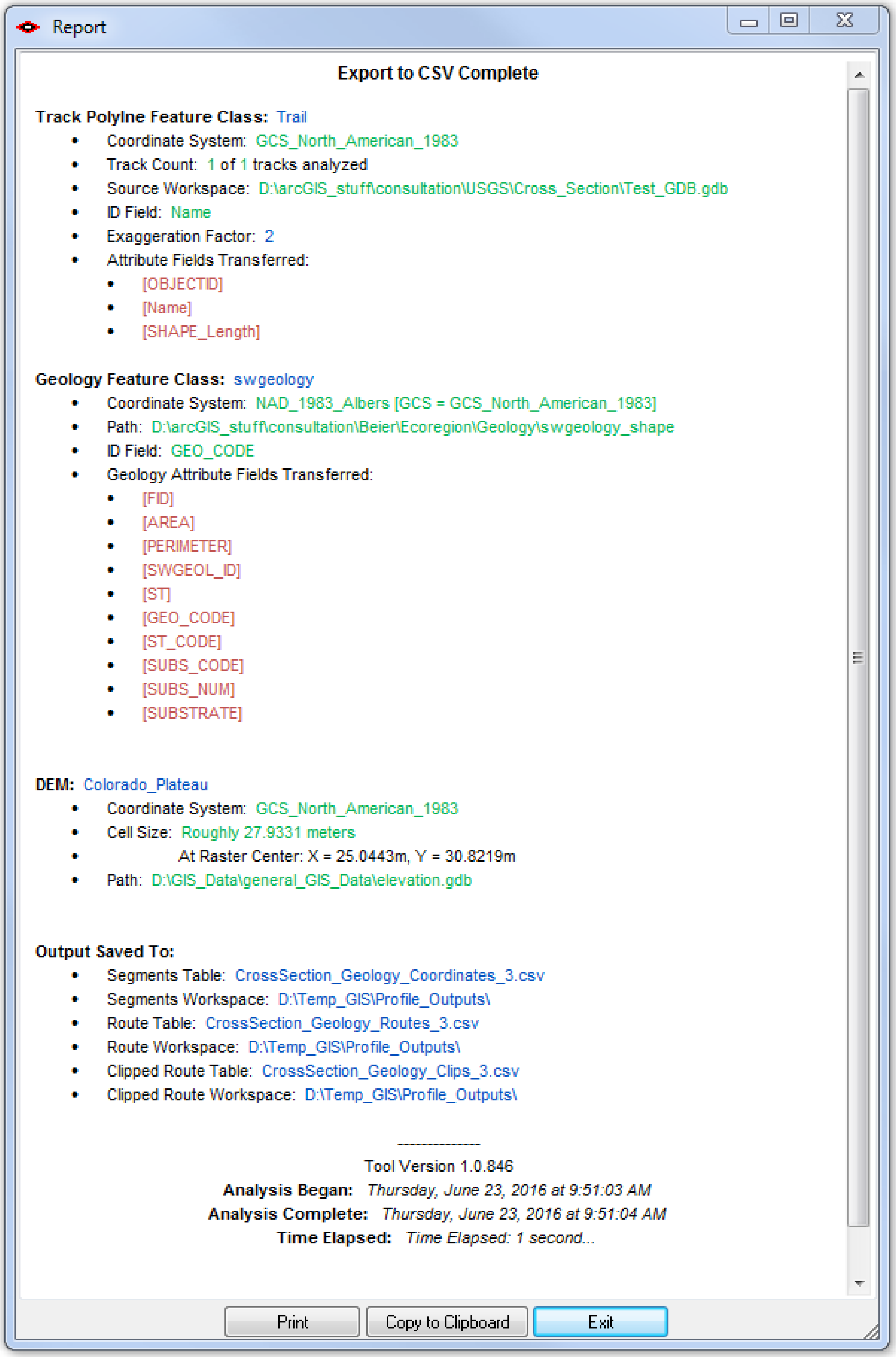
- **End_Latitude:** In the geographic coordinate system of your original **Polyline Route** feature class.
- **End_Longitude:** In the geographic coordinate system of your original **Polyline Route** feature class.
- **Start_Elevation:** The elevation value of starting point based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
- **End_Elevation:** The elevation of the ending point based on the selected DEM.
- **Min_Elevation:** The elevation of the lowest point based on the selected DEM.
- **Max_Elevation:** The elevation of the highest point based on the selected DEM.
- **Avg_Slope:** The average slope over the course of the route, calculated as the weighted mean of the segment slopes, weighted by the segment surface distances.
- **Slope_StDev:** The standard deviation of slope over the course of the route.
- **Avg_Bearing:** The mean direction of the route, equal to the bearing from the starting point to the ending point of the route (see p. 137 for details).
- **BearingMRL:** The Mean Resultant Length of the route, calculated as the ratio of the geodesic length of the complete route divided by the geodesic distance of the straight line between the starting and ending points (see p. 137 for details). The MRL is the basis of several circular measures of dispersion (see Batschelet 1981, Fisher 1995, Mardia and Jupp 2000). MRL values near 1 indicate little direction variation over the line.
- **Length_Geodesic:** The geodesic length of the route.
- **Length_Surface:** The surface length of the route.
- **Surface Ratio:** The ratio of [Surface Length] / [Geodesic Length]. Values near 1 indicate a flat line, while values > 1 indicate increasing elevational variation.

The **Summary of Clips** file will contain a single record for each section of the route polyline clipped within each intersecting geology polygon, and will include the following attribute fields:

- Any attribute fields from your original **Polyline Route** feature class that you wish to transfer over.
- Any attribute fields from your original **Geology Polygon** feature class that you wish to transfer over.
- **Sample_Points:** The number of DEM values sampled to generate the statistics for this polyline section.
- **Start_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.

- **Start_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
- **End_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
- **End_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
- **Start_Elevation:** The elevation value of starting point based on the selected DEM, calculated using Bilinear Interpolation. The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
- **End_Elevation:** The elevation of the ending point based on the selected DEM.
- **Min_Elevation:** The elevation of the lowest point based on the selected DEM.
- **Max_Elevation:** The elevation of the highest point based on the selected DEM.
- **Avg_Slope:** The average slope over the course of the route, calculated as the weighted mean of the segment slopes, weighted by the segment surface distances.
- **Slope_StDev:** The standard deviation of slope over the course of the route section.
- **Avg_Bearing:** The mean direction of the route section, equal to the bearing from the starting point to the ending point of the route (see p. 137 for details).
- **BearingMRL:** The Mean Resultant Length of the route section, calculated as the ratio of the geodesic length of the complete route divided by the geodesic distance of the straight line between the starting and ending points (see p. 137 for details). The MRL is the basis of several circular measures of dispersion (see Batschelet 1981, Fisher 1995, Mardia and Jupp 2000). MRL values near 1 indicate little direction variation over the line.
- **Length_Geodesic:** The geodesic length of the route section.
- **Length_Surface:** The surface length of the route section.
- **Surface_Ratio:** The ratio of [Surface Length] / [Geodesic Length]. Values near 1 indicate a flat line, while values > 1 indicate increasing elevational variation.
- **Start_Position_Geodesic:** The geodesic distance of the beginning of this clipped section, as located on the original route feature.
- **End_Position_Geodesic:** The geodesic distance of the end of this clipped section, as located on the original route feature.

Upon completion, the tool will display a report window showing where the files were saved.


Report
Export to CSV Complete
Track Polylne Feature Class: Trail
Coordinate System: GCS_North_American_1983
Track Count: 1 of 1 tracks analyzed
Source Workspace: D:\arcGIS_stuff\consultation\USGS\Cross_Section\Test_GDB.gdb
ID Field: Name
Exaggeration Factor: 2
Attribute Fields Transferred:
[OBJECTID]
[Name]
[SHAPE_Length]
Geology Feature Class: swgeology
Coordinate System: NAD_1983_Albers [GCS = GCS_North_American_1983]
Path: D:\arcGIS_stuff\consultation\Beier\Ecoregion\Geology\swgeology_shape
ID Field: GEO_CODE
Geology Attribute Fields Transferred:
[FID]
[AREA]
[PERIMETER]
[SWGEOL_ID]
[ST]
[GEO_CODE]
[ST_CODE]
[SUBS_CODE]
[SUBS_NUM]
[SUBSTRATE]
DEM: Colorado_Plateau
Coordinate System: GCS_North_American_1983
Cell Size: Roughly 27.9331 meters
At Raster Center: X = 25.0443m, Y = 30.8219m
Path: D:\GIS_Data\general_GIS_Data\elevation.gdb
Output Saved To:
Segments Table: CrossSection_Geology_Coordinates_3.csv
Segments Workspace: D:\Temp_GIS\Profile_Outputs\
Route Table: CrossSection_Geology_Routes_3.csv
Route Workspace: D:\Temp_GIS\Profile_Outputs\
Clipped Route Table: CrossSection_Geology_Clips_3.csv
Clipped Route Workspace: D:\Temp_GIS\Profile_Outputs\

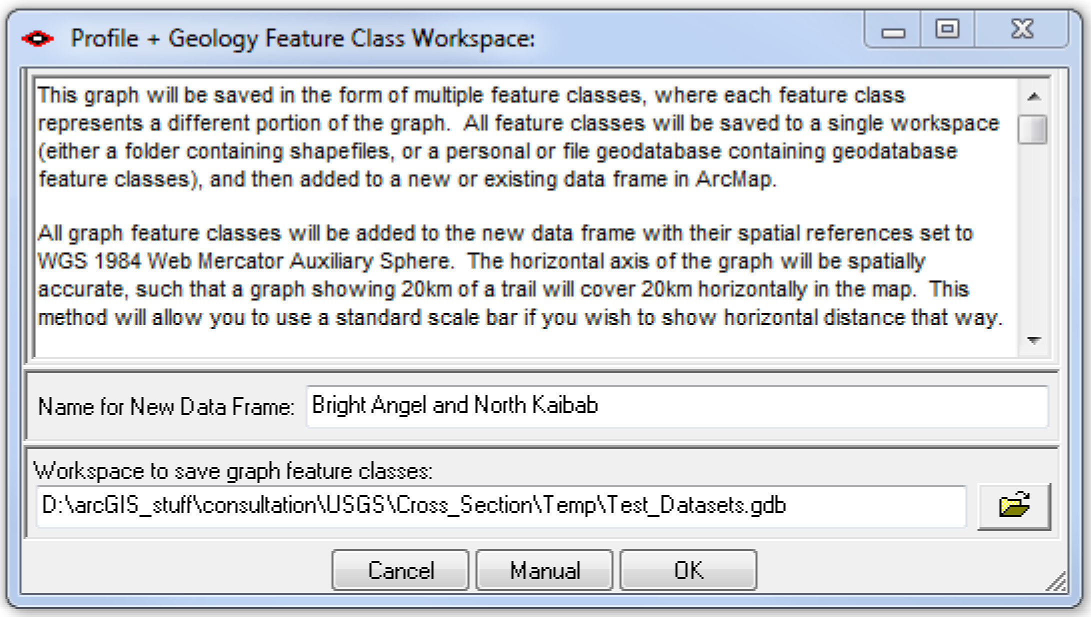
Tool Version 1.0.846
Analysis Began: Thursday, June 23, 2016 at 9:51:03 AM
Analysis Complete: Thursday, June 23, 2016 at 9:51:04 AM
Time Elapsed: Time Elapsed: 1 second...
Print
Copy to Clipboard
Exit

Exporting Graph to Data Frame as Feature Classes:

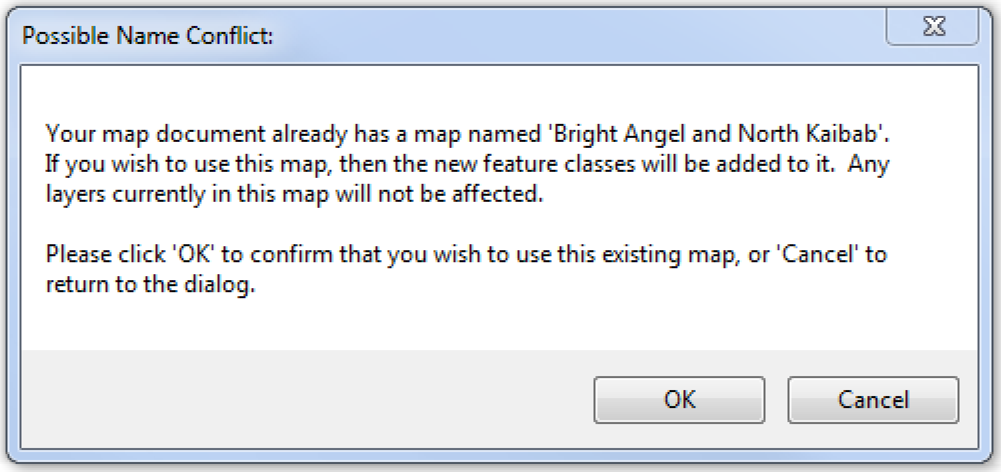
This graph will be saved in the form of multiple feature classes, where each feature class represents a different portion of the graph. All feature classes will be saved to a single workspace (either a folder containing shapefiles, or a personal or file geodatabase containing geodatabase feature classes), and then added to a new or existing data frame in ArcMap.

All graph feature classes will be added to the new data frame with their spatial references set to WGS 1984 Web Mercator Auxiliary Sphere. The horizontal axis of the graph will be spatially accurate, such that a graph showing 20km of a trail will cover 20km horizontally in the map. This method will allow you to use a standard scale bar if you wish to show horizontal distance that way.

You must specify the workspace you wish to use and the name of the new data frame.



This tool will create your new data frame automatically and assign it the name you specify in the dialog. If you specify a data frame name that already exists in your map document, this tool will alert you to the fact and ask you to confirm your choice:



All datasets will be named automatically, based on the name of your Track/Route layer.

Details: This tool will create 7 new feature classes representing different aspects of the graph.

1) **Segments Feature Class:** Contains a separate record for each vertex-to-vertex segment along a route. When initially added to the map, it will be symbolized by slope in a blue-to-red color ramp. In addition to any attribute fields from the original route feature class you may choose to transfer, this feature class will also include the following calculated attributes:

- **Start_Latitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **Start_Longitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **End_Latitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **End_Longitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **Geodesic_Length:** The segment length, in meters, calculated using Vincenty's algorithms to estimate geodesic distances over the original Polygon Route feature class spheroid (see Vincenty 1975; also p. 124 of this manual).
- **Surface_Length:** The segment surface length, in meters, calculated using the Pythagorean theorem to determine the hypotenuse of the triangle formed by the change in elevation and the geodesic distance.
- **Slope_Degrees:** The absolute value of the segment slope.
- **Bearing:** The compass bearing of the segment.
- **Start_Elevation:** The elevation value at the beginning of the segment based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this attribute field.

- **Mid_Elevation:** The elevation value at the centerpoint of the segment.
- **End_Elevation:** The elevation value at the end of the segment.
- **End_Proportion:** The proportion of the original route at the segment endpoint. This proportion is based on the surface distance of the line, not the geodesic distance. Values will range from 0 to 1.
- **Total_Geodesic_Distance:** The total geodesic distance, in meters, along the route up to the end of this segment.
- **Total_Surface_Distance:** The total surface distance, in meters, along the route up to the end of this segment.

2) **Polyline Feature Class:** Contains a separate record for each route showing the profile of the route over the DEM. When initially added to the map, it will be symbolized by ID value based on the ID field you select. If you do not select an ID field, it will be symbolized by the Feature Object ID of the original route. In addition to any attribute fields from the original route feature class you may choose to transfer, this feature class will also include the following calculated attributes:

   - **Sample_Points:** The number of DEM values sampled to generate the statistics for this polyline.
   - **Start_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Start_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **End_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **End_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Start_Elevation:** The elevation value of starting point based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
   - **End_Elevation:** The elevation of the ending point based on the selected DEM.
   - **Min_Elevation:** The elevation of the lowest point based on the selected DEM.
   - **Max_Elevation:** The elevation of the highest point based on the selected DEM.
   - **Avg_Slope:** The average slope over the course of the route, calculated as the weighted mean of the segment slopes, weighted by the segment surface distances.
   - **Slope_StDev:** The standard deviation of slope over the course of the route.
   - **Avg_Bearing:** The mean direction of the route, equal to the bearing from the starting point to the ending point of the route.

- **BearingMRL:** The Mean Resultant Length of the route, calculated as the ratio of the geodesic length of the complete route divided by the geodesic distance of the straight line between the starting and ending points. The MRL is the basis of several circular measures of dispersion (see Batschelet 1981, Fisher 1995, Mardia and Jupp 2000). MRL values near 1 indicate little direction variation over the line.
- **Length_Geodesic:** The geodesic length of the route.
- **Length_Surface:** The surface length of the route.
- **Surface Ratio:** The ratio of [Surface Length] / [Geodesic Length]. Values near 1 indicate a flat line, while values > 1 indicate increasing elevational variation.

3) **Polygon Feature Class:** Similar to the Polyline Feature Class, except that it symbolizes the route using a polygon to symbolize the portion of the graph underneath the route profile. Contains a separate record for each route. When initially added to the map, it will be symbolized by ID value based on the ID field you select. If you do not select an ID field, it will be symbolized by the Feature Object ID of the original route. This feature class will contain exactly the same attribute fields and values as the Polyline Feature Class described above.
4) **Clipped Polyline Feature Class:** Contains a separate record for each intersection between the route and a geology polygon, showing the profile of the route over the DEM. When initially added to the map, it will be symbolized by the color of the Geology polygons. In addition to any attribute fields from the original route and geology feature classes you may choose to transfer, this feature class will also include the following calculated attributes:
   - **Sample_Points:** The number of DEM values sampled to generate the statistics for this clipped portion of the route polyline.
   - **Start_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Start_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **End_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **End_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Start_Elevation:** The elevation value of starting point based on the selected DEM, calculated using Bilinear Interpolation. The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
   - **End_Elevation:** The elevation of the ending point based on the selected DEM.
   - **Min_Elevation:** The elevation of the lowest point based on the selected DEM.
   - **Max_Elevation:** The elevation of the highest point based on the selected DEM.
   - **Avg_Slope:** The average slope over the course of the route, calculated as the weighted mean of the segment slopes, weighted by the segment surface distances.

- **Slope_StDev:** The standard deviation of slope over the course of the route.
- **Avg_Bearing:** The mean direction of the route, equal to the bearing from the starting point to the ending point of the route.
- **BearingMRL:** The Mean Resultant Length of the route, calculated as the ratio of the geodesic length of the complete route divided by the geodesic distance of the straight line between the starting and ending points. The MRL is the basis of several circular measures of dispersion (see Batschelet 1981, Fisher 1995, Mardia and Jupp 2000). MRL values near 1 indicate little direction variation over the line.
- **Length_Geodesic:** The geodesic length of the route.
- **Length_Surface:** The surface length of the route.
- **Surface_Ratio:** The ratio of [Surface Length] / [Geodesic Length]. Values near 1 indicate a flat line, while values > 1 indicate increasing elevational variation.
- **Start_Position_Geodesic:** The geodesic distance of the beginning of this clipped section, as located on the original route feature.
- **End_Position_Geodesic:** The geodesic distance of the end of this clipped section, as located on the original route feature.

5) **Clipped Polyline Tic Mark Feature Class:** Contains a separate record for the intersection points between the route and geology polygons, showing a short vertical line that intersects the profile line. This feature class is intended primarily to add aesthetic qualities to the profile graph. When initially added to the map, it will be symbolized by the color of the Geology polygons. This feature class will only include the following calculated attributes:
   - **Left_GeoID:** The geology polygon ID value on the left side of the tick mark.
   - **Right_GeoID:** The geology polygon ID value on the right side of the tick mark.
   - **Label_Value**: A string value composed of [Left_GeoID] + a vertical line ("|") + [Right_GeoID]. This might be useful for labeling purposes in the graph.
   - **Position_Geodesic:** The geodesic distance of this point, as located on the original route feature.
   - **Elevation:** The elevation, in meters, at this point.
   - **Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Longitude:** In the geographic coordinate system of your original Polyline Route feature class.

6) **Clipped Polyline Vertical Line Feature Class:** Contains a separate record for the intersection points between the route and geology polygons, showing a vertical line that extends from the bottom of the graph up to the profile line. This feature class is intended primarily to add aesthetic qualities to the profile graph. When initially added to the map, it will be symbolized

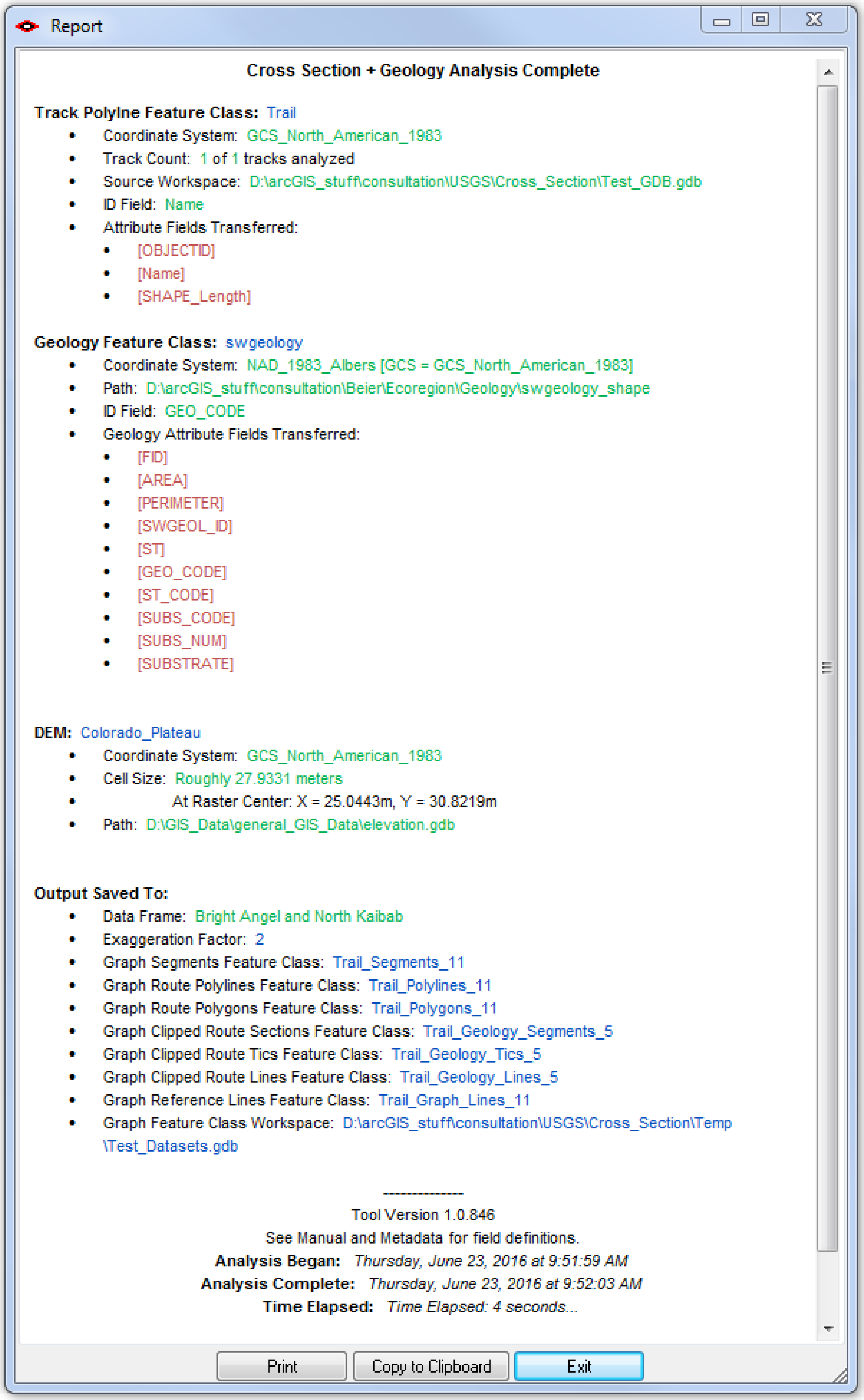
by the color of the Geology polygons. This feature class will only include the following calculated attributes:

- **Left_GeoID:** The geology polygon ID value on the left side of the line.
- **Right_GeoID:** The geology polygon ID value on the right side of the line.
- **Label_Value**: A string value composed of [Left_GeoID] + a vertical line ("|") + [Right_GeoID]. This might be useful for labeling purposes in the graph.
- **Position_Geodesic:** The geodesic distance of this point, as located on the original route feature.
- **Elevation:** The elevation, in meters, at this point.
- **Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
- **Longitude:** In the geographic coordinate system of your original Polyline Route feature class.

7) **Graph_Lines:** Simply shows the reference lines of the graph, including axes, tick marks and horizontal/vertical references. Attribute values include the name of the line (X-Axis, Y-Axis, X-Tic, Y-Tic, X-Reference and Y-Reference), and a label value for that line.

This tool will also add graphic text boxes for label values, axis names and the chart title. **Note:** These graphics can be converted to annotation by right-clicking data frame name and choosing "Convert Labels to Annotation". This option helps the labels look better if you add the graph to a layout. See also a known issue with exported graphic text on p. 96.

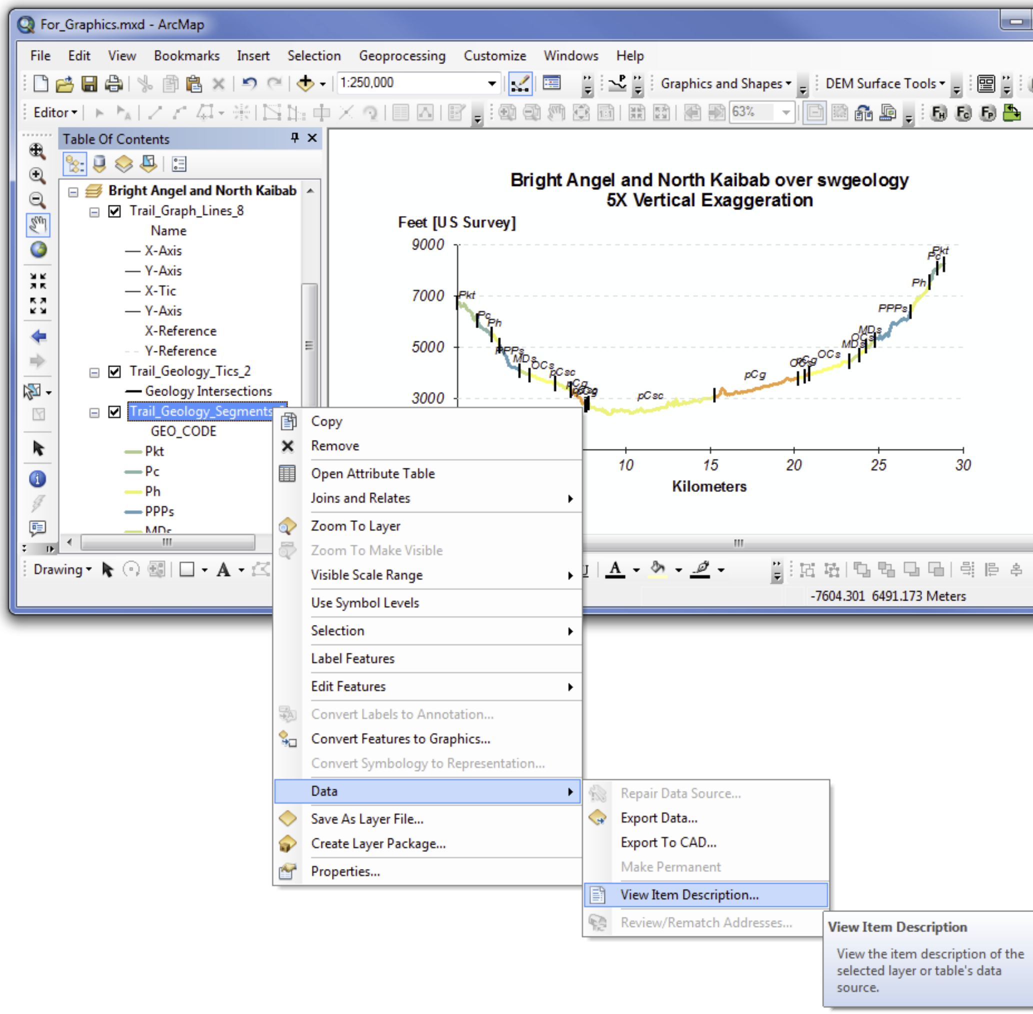
Upon completion, the tool will show you a report detailing what it did:

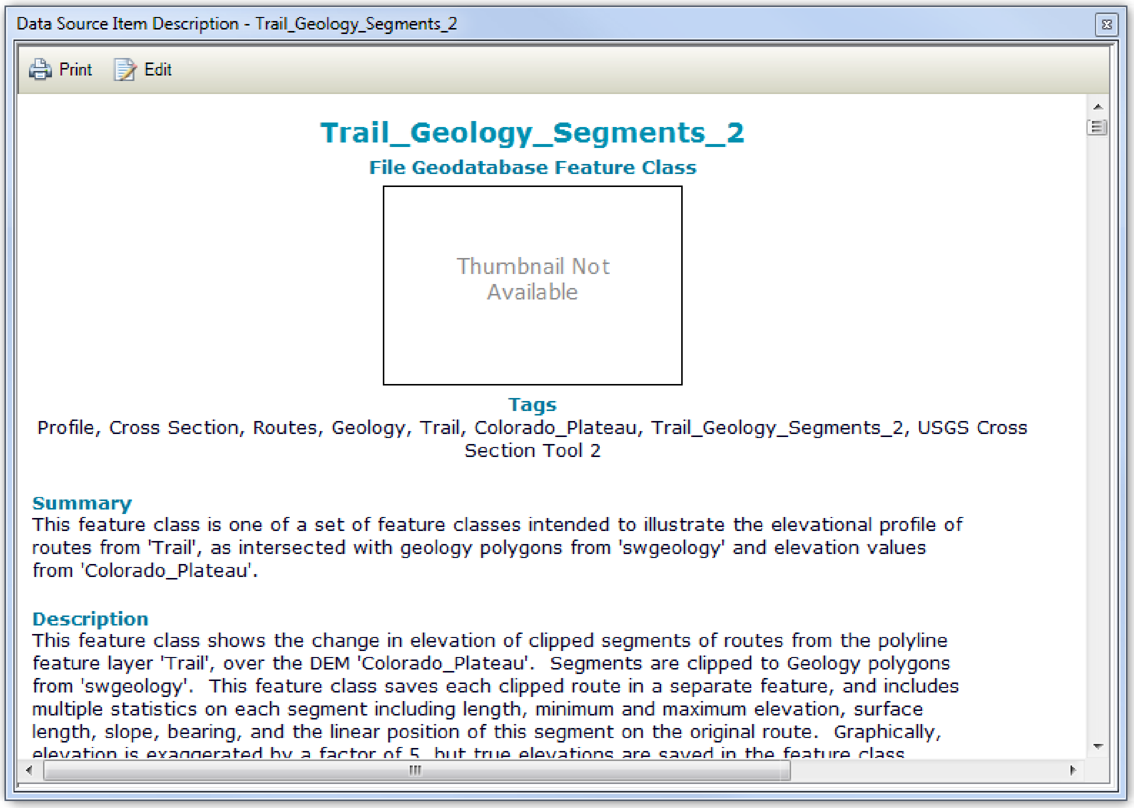

Report
Cross Section + Geology Analysis Complete
Track Polyne Feature Class: Trail
Coordinate System: GCS_North_American_1983
Track Count: 1 of 1 tracks analyzed
Source Workspace: D:\arcGIS_stuff\consultation\USGS\Cross_Section\Test_GDB.gdb
ID Field: Name
Attribute Fields Transferred:
[OBJECTID]
[Name]
[SHAPE_Length]
Geology Feature Class: swgeology
Coordinate System: NAD_1983_Albers [GCS = GCS_North_American_1983]
Path: D:\arcGIS_stuff\consultation\Beier\Ecoregion\Geology\swgeology_shape
ID Field: GEO_CODE
Geology Attribute Fields Transferred:
[FID]
[AREA]
[PERIMETER]
[SWGEOL_ID]
[ST]
[GEO_CODE]
[ST_CODE]
[SUBS_CODE]
[SUBS_NUM]
[SUBSTRATE]
DEM: Colorado_Plateau
Coordinate System: GCS_North_American_1983
Cell Size: Roughly 27.9331 meters
At Raster Center: X = 25.0443m, Y = 30.8219m
Path: D:\GIS_Data\general_GIS_Data\elevation.gdb
Output Saved To:
Data Frame: Bright Angel and North Kaibab
Exaggeration Factor: 2
Graph Segments Feature Class: Trail_Segments_11
Graph Route Polylines Feature Class: Trail_Polylines_11
Graph Route Polygons Feature Class: Trail_Polygons_11
Graph Clipped Route Sections Feature Class: Trail_Geology_Segments_5
Graph Clipped Route Tics Feature Class: Trail_Geology_Tics_5
Graph Clipped Route Lines Feature Class: Trail_Geology_Lines_5
Graph Reference Lines Feature Class: Trail_Graph_Lines_11
Graph Feature Class Workspace: D:\arcGIS_stuff\consultation\USGS\Cross_Section\Temp\Test_Datasets.gdb
----
Tool Version 1.0.846
See Manual and Metadata for field definitions.
Analysis Began: Thursday, June 23, 2016 at 9:51:59 AM
Analysis Complete: Thursday, June 23, 2016 at 9:52:03 AM
Time Elapsed: Time Elapsed: 4 seconds...
Print
Copy to Clipboard
Exit

Your new data frame will open automatically, displaying all the elements of the graph. By default, the Geology Segments feature class will be set to visible and will be the primary way the route profile will be symbolized. However, like any feature class, this layer can be turned off and the "Trail Segments" layer can be turned on. (which by default symbolizes the route profile by steepness of slope). Or, you may resymbolize any feature layer by any attribute to fit your preferences.

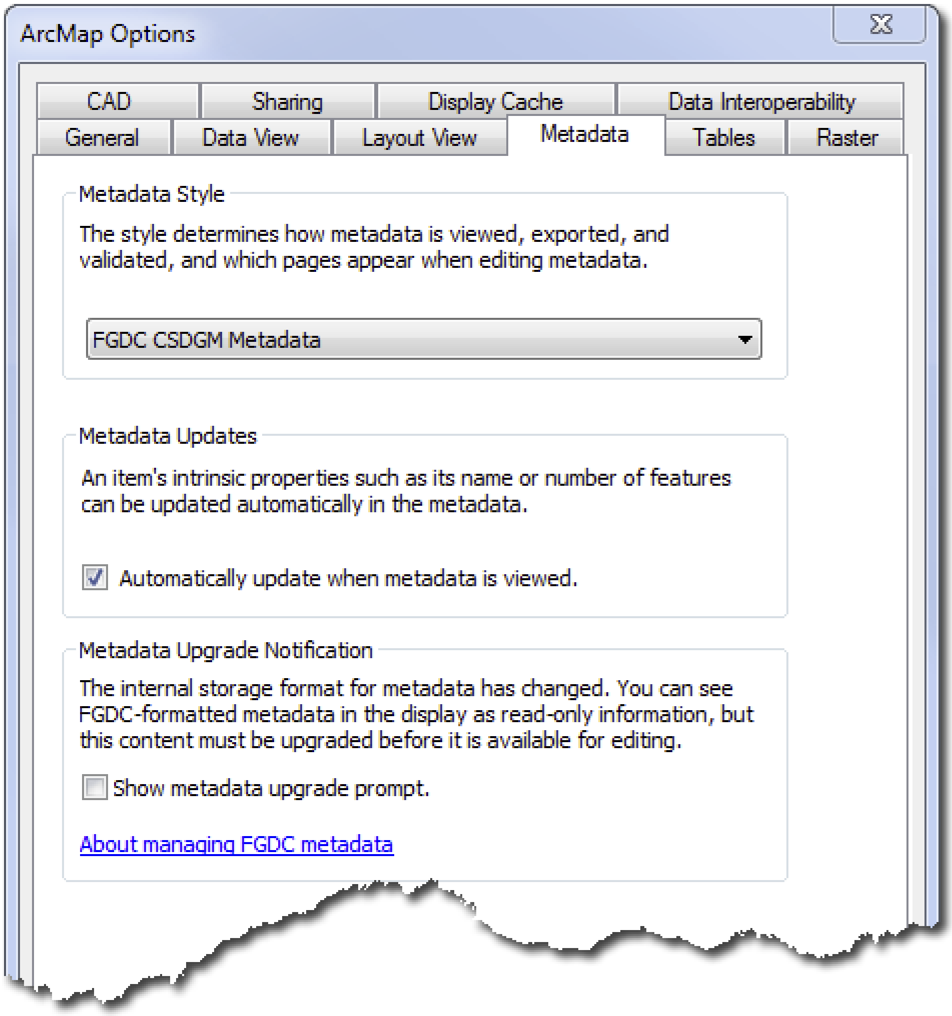
Another advantage to the feature class format is that you can edit the graph elements using the standard ArcMap Editor tools.

Finally, all graph element feature classes include metadata detailing the analysis options you specified and defining all the attribute fields. Simply right-click on the feature class, click on "Data", and then click "Show Item Description":





Note: If you do not see the field definitions in the metadata, then you may have ArcMap set to only show you the simplest “Item Description” form of metadata. This is easy to change if you want. Simply click the “Customize” menu, then ArcMap Options. Then click the “Metadata” tab and choose a different metadata style.

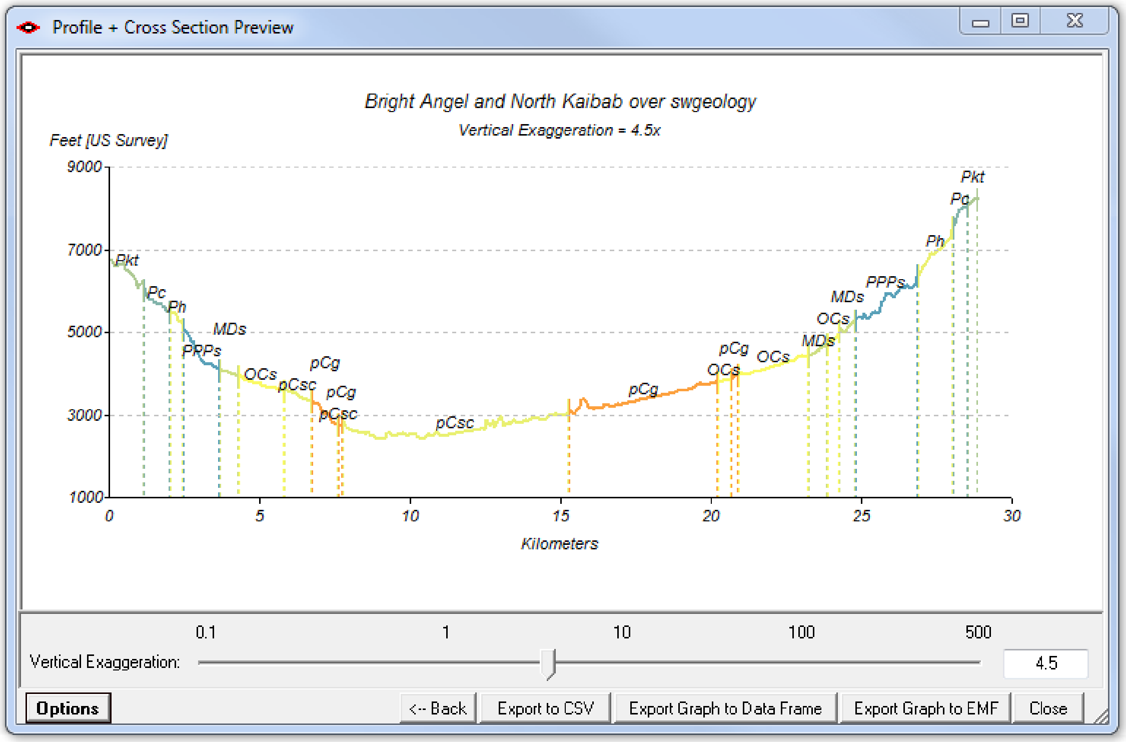


Export the Graph as an EMF file:

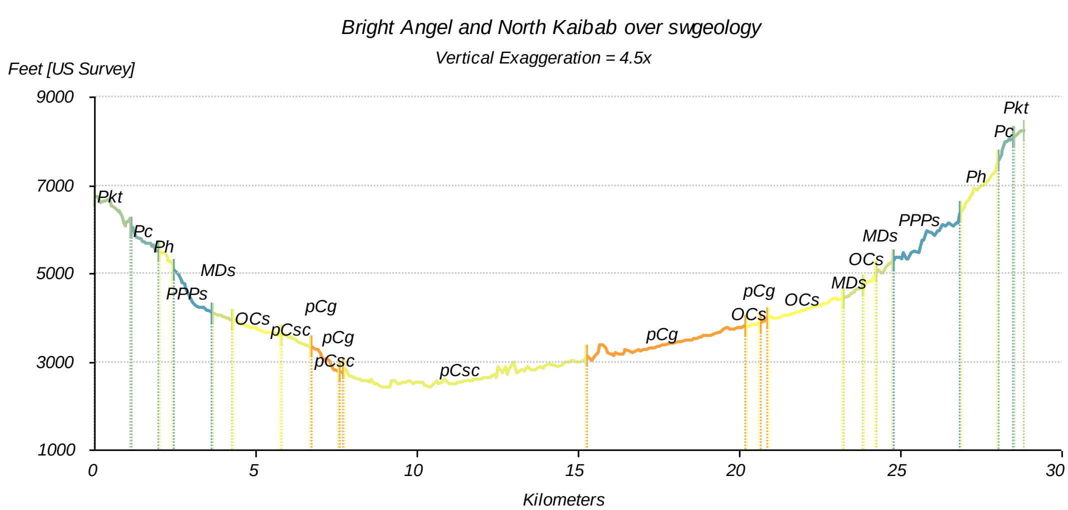
This option simply redraws the graph in the dialog onto an EMF (Windows Enhanced Metafile) surface and saves it to your hard drive. It also adds the EMF file as a graphic to your layout.

Click the *Export Graph to EMF* button and the tool will do everything automatically. The new EMF file will be named according to your graph title and saved in the same folder alongside your current ArcMap document (*.mxd file).

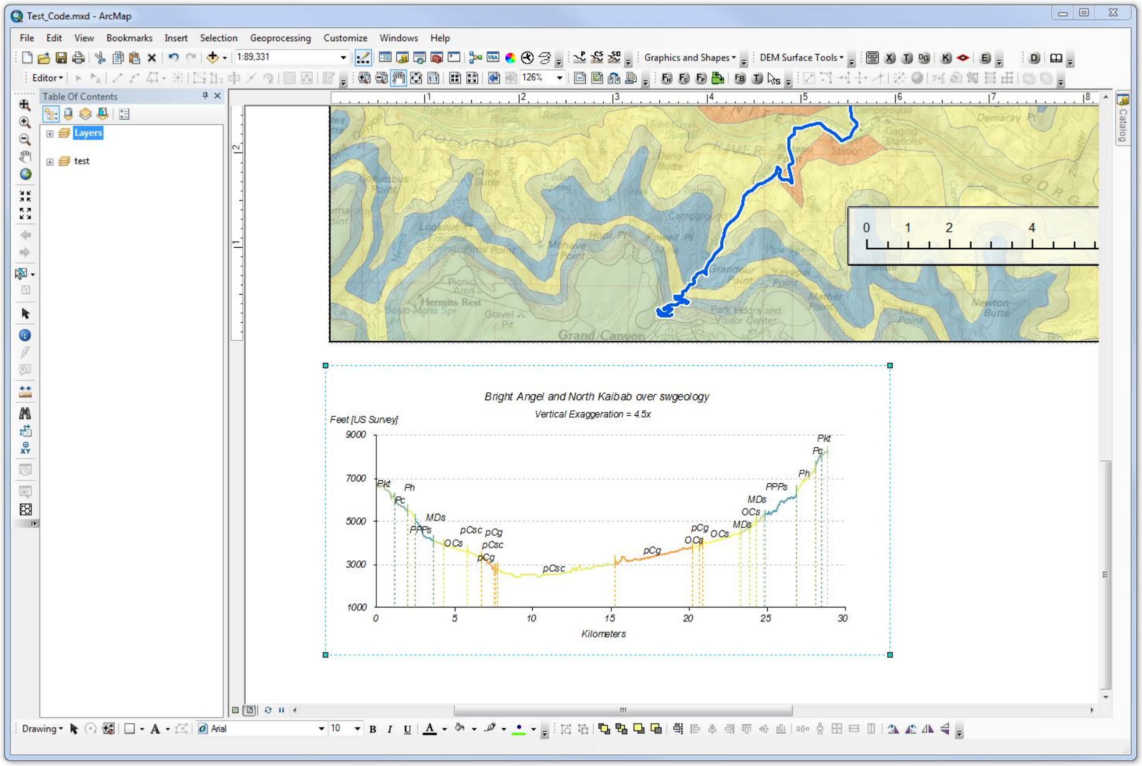
The EMF file can be opened and imported into several files, including Microsoft Word. For example, given the graph below,



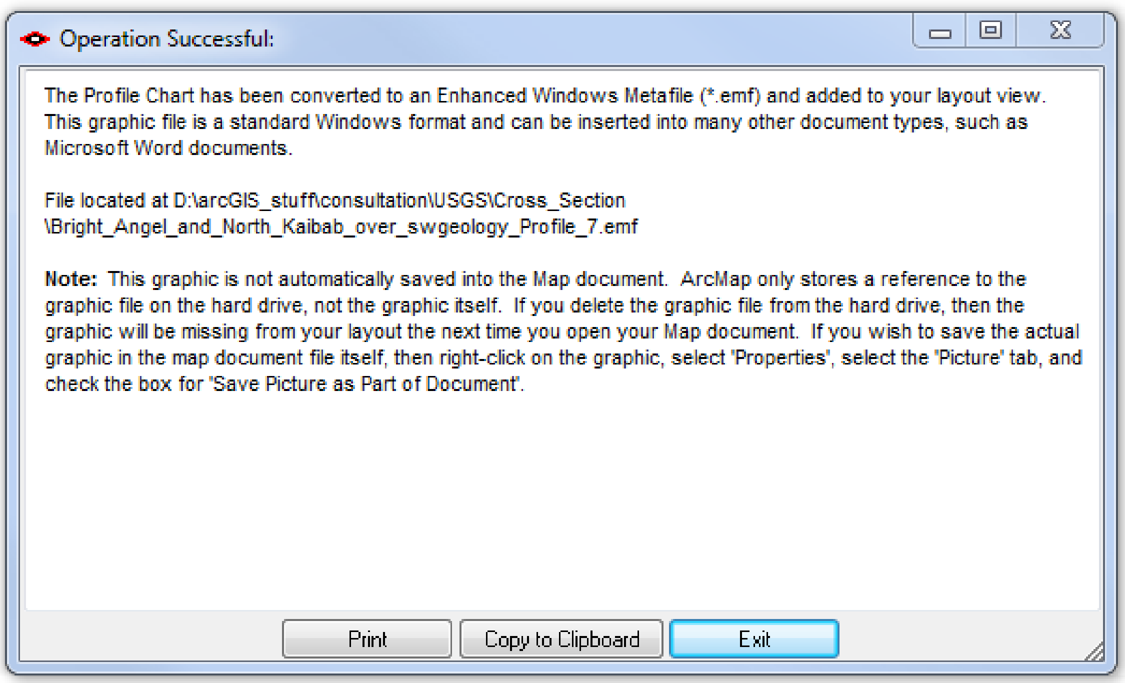
I have exported the graph to an EMF file and loaded it into this document below:



Upon completion, the tool will add the EMF file as a new graphic in your layout.



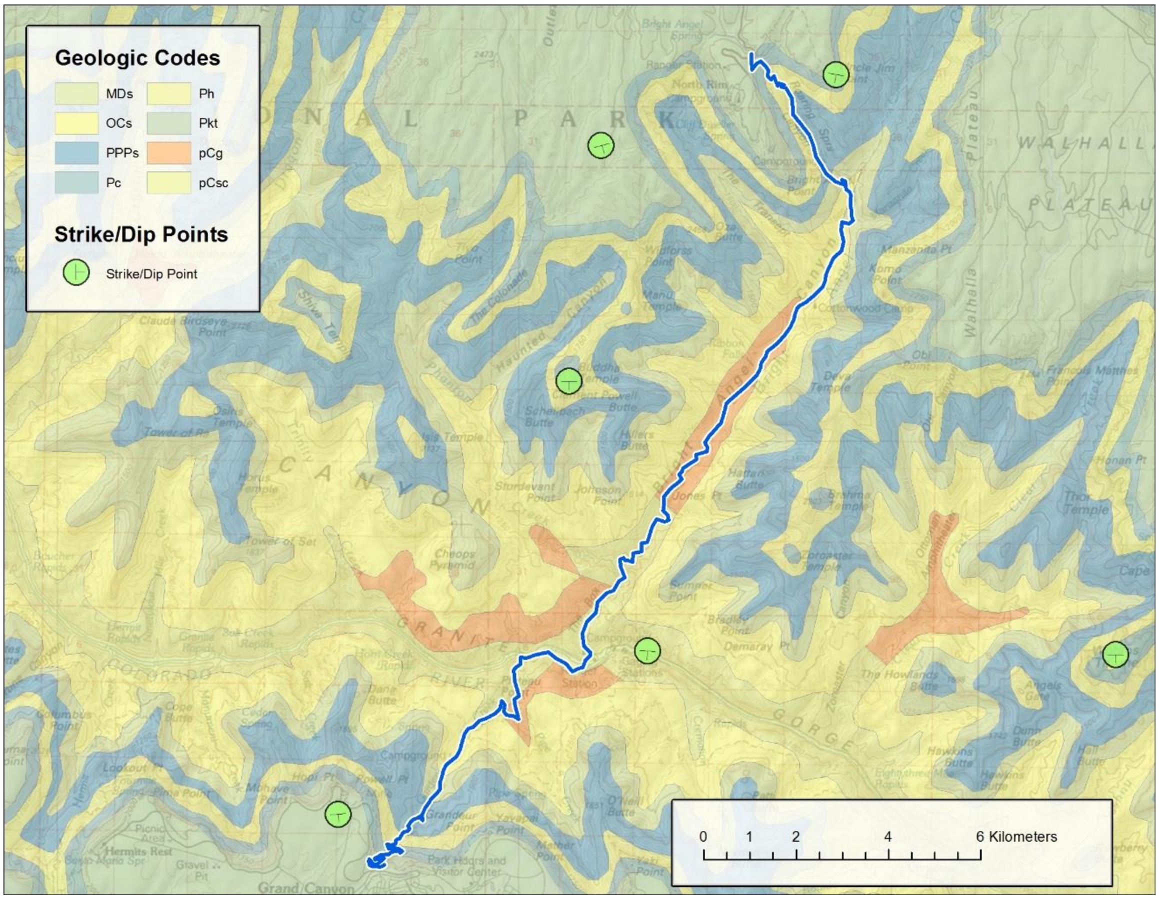
The tool will also give you a report detailing where it saved the EMF file and what the file is named:



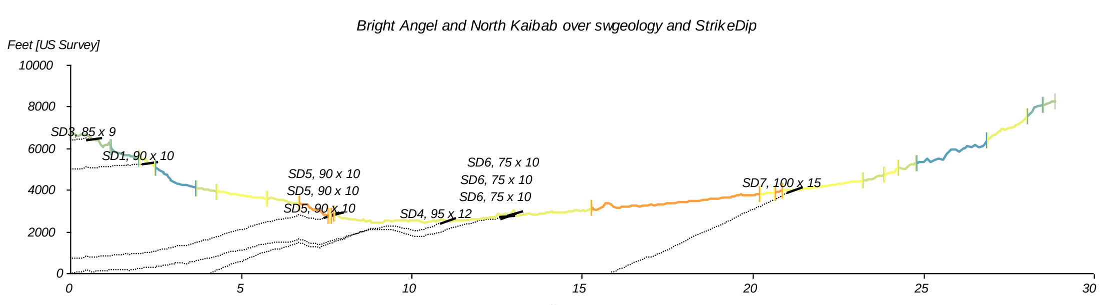
Cross Sections with Strike/Dip Lines Tool

The Cross Sections tool is similar to the Cross Sections tool, but adds the ability to intersect the track/route with strike/dip planes defined from a set of strike/dip points. Output options include all those available for the Elevation Profile and Cross Sections tools, plus additional statistics describing the relationships between the routes and the strike/dip planes.

For example, we may have several points where we have identified strike/dip planes near our trail across the Grand Canyon:



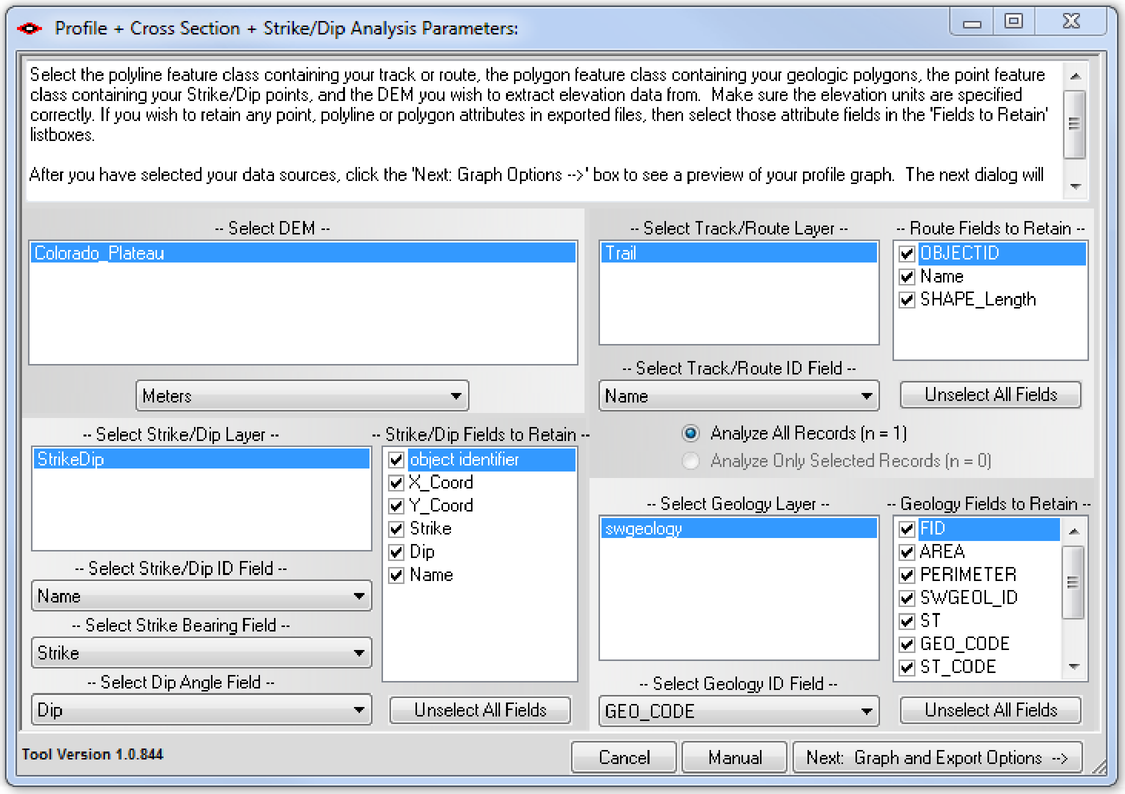
The Cross Sections with Strike/Dip Lines tool allows us to generate the elevational profile divided by geologic types, and with the estimated location of the strike/dip planes below the route:



For details on how this tool calculates strike/dip planes, please see “Appendix C: Strike/Dip Planes” on p. 110.

Using the Tool:

1) Make sure your Route polyline, Geology polygon and Strike/Dip point feature classes, and your DEM raster dataset are loaded into your ArcMap document.
2) Click the **Cross Sections with Shrike/Dip Lines** command to open the *Profile + Cross Section + Strike/Dip Analysis Parameters* dialog.



3) You must specify 14 parameters:
   a) DEM: This is the elevation raster that the polyline(s) will be intersected with.
   b) Units: DEMs typically define elevation in meters or feet, but there is nothing in the dataset itself that explicitly defines the unit. Therefore you must specify the correct unit yourself. The tool defaults to **Meters**.
   c) Track/Route Layer: This is the polyline feature class containing the route(s) to analyze.
   d) Track/Route ID Field: This is the attribute used by the tool to label the graphs.
   e) Track/Route Fields to Retain: The tool offers several output options for graphs and statistical tables. If you would like any of the original Track/Route attributes to be included in those statistical tables, then select those fields here. **Note:** The “Track/Route ID Field” will automatically be retained in all output datasets.

f) Whether to analyze all polylines, or only selected subset: If you have any polylines selected, then you have the option to restrict your analysis to only the selected subset. If you choose to analyze multiple polylines simultaneously, then the tool will overlay the graphs on each other.

g) Geology polygon feature layer. **Note:** This tool was originally designed to intersect routes specifically with geologic polygon feature classes, but it will work just fine with any polygon feature class.

h) Geology ID Field: This is the attribute used by the tool to label the graphs.

i) Geology Fields to Retain: The tool will add these geology attributes to all output tables and feature classes.

j) Strike/Dip point feature layer.

k) Strike/Dip ID Field: This is the attribute used by the tool to label the graphs.

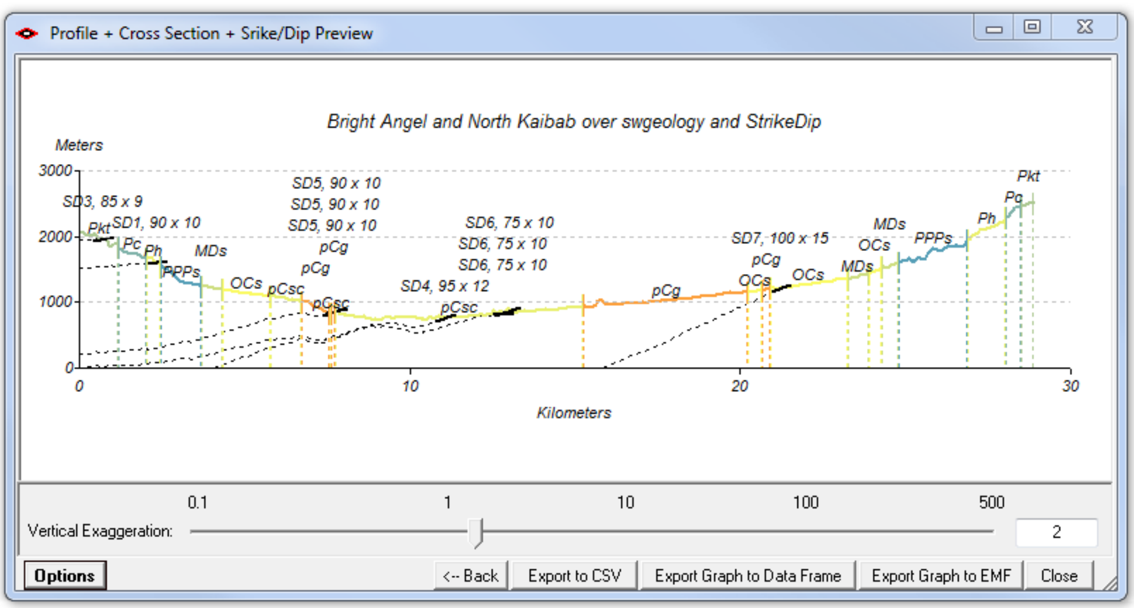
l) Strike/Dip Bearing Field: This is the strike direction, in compass degrees, where due North = 0° and due East = 90°.

m) Strike/Dip Dip Angle Field: This is the angle in inclination, in degrees. **Note:** This angle always points down, and the dip direction is defined as 90° clockwise from the Strike Bearing field as per the American Right-Hand Rule (Jorge 2009, Rocscience 2016).

n) Strike/Dip Fields to Retain: The tool will add these strike/dip attributes to all output tables and feature classes.

Note: There may be issues regarding the coordinate systems of your data. If your data are in different geographic datums, then you **may** need to specify a geographic transformation. Please see Appendix A (p. 102) for details.

After selecting your initial parameters, click the *Next: Graph and Export Options -->* button to preview your profile graph.



If you are graphing a single polyline, then the title will default to the ID value of that feature appended with “over [Your Geology Layer Name] and [Your Strike/Dip Layer Name]”. If you are graphing multiple polylines, the title will default to the name of the feature layer appended with “over [Your Geology Layer Name] and [Your Strike/Dip Layer Name]”.

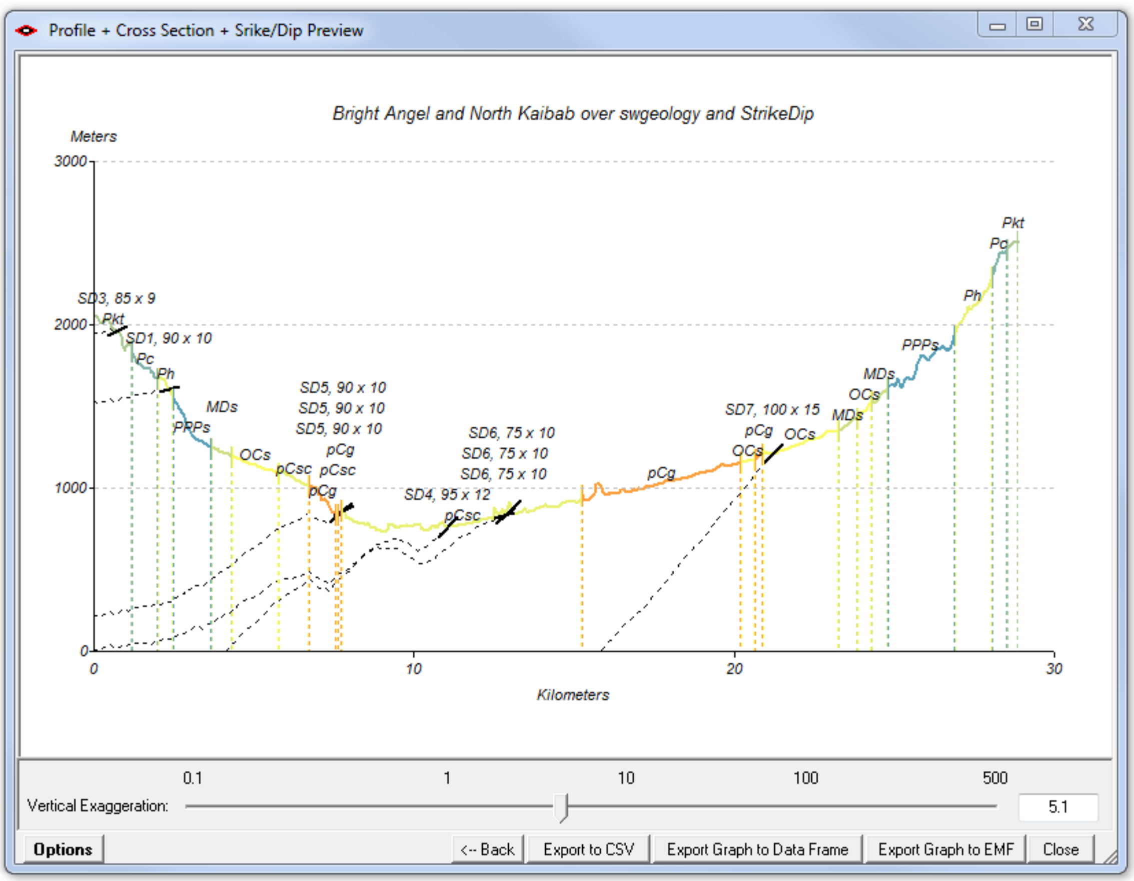
The color of the profile features in the graph are based on the colors of your geologic polygons in your map. If your geologic polygons are transparent or hollow, then the tool assigns random Earth Tone colors adapted from Varian (2004).

Strike/Dip lines and ticks are colored the same color as your Strike/Dip point marker symbols.

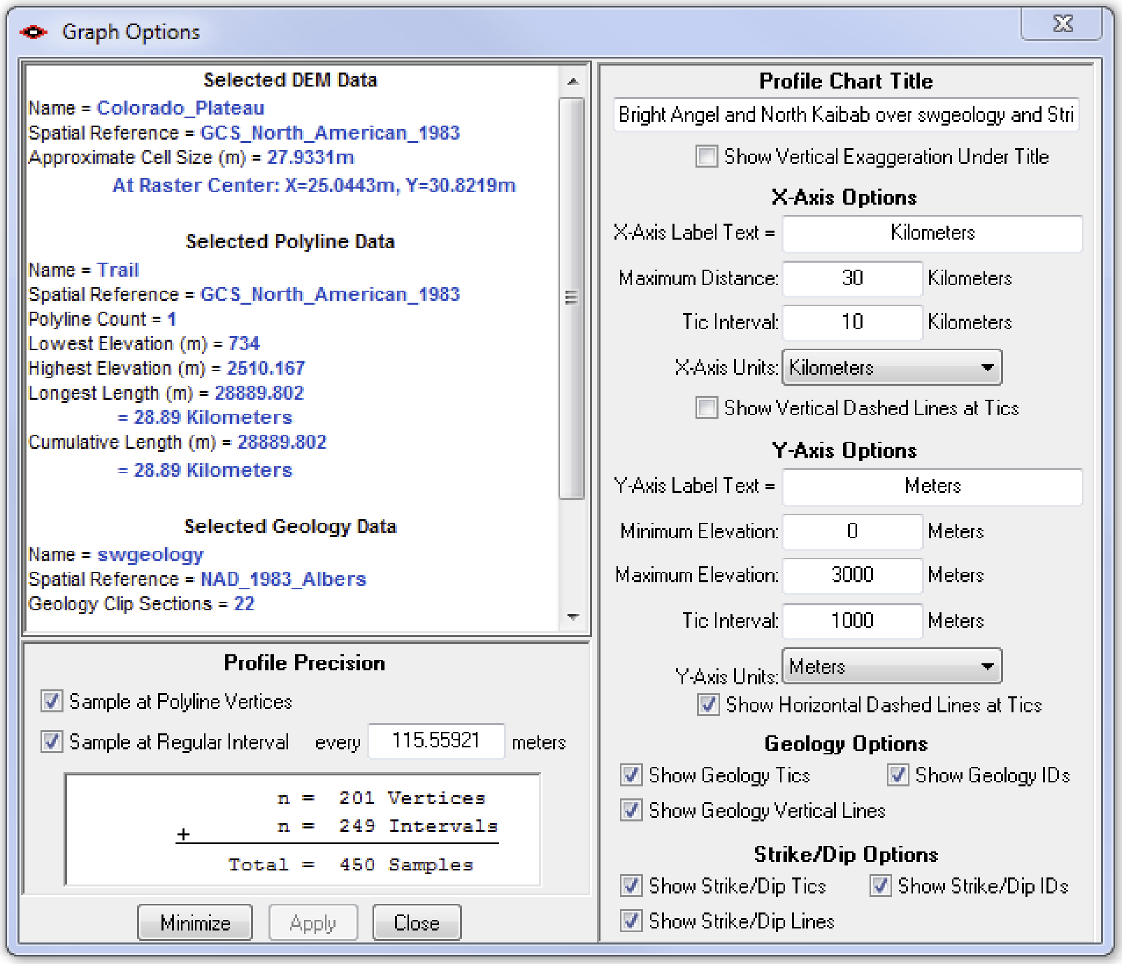
The color under the profile line is based on the color of your route feature in the map. In the example above, I have the route polyline colored white, so the graph region underneath the profile line is also white.

Modifying the graph:

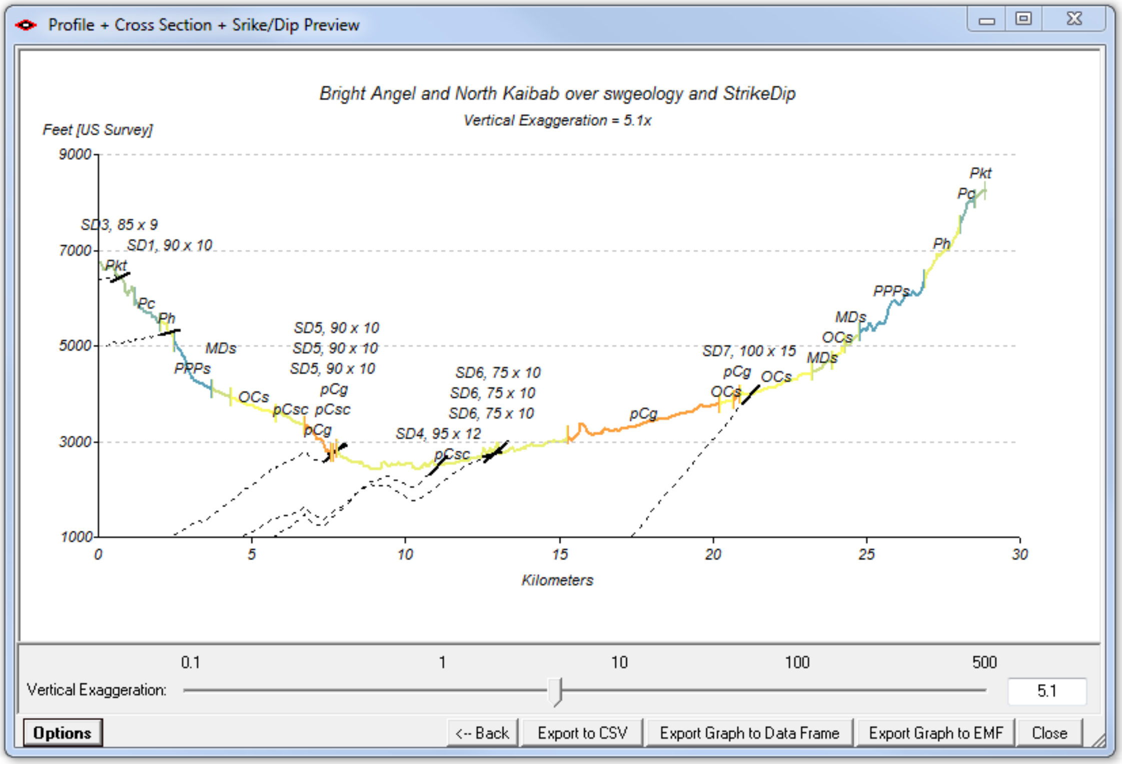
You have several options to modify the graph. Within the preview window itself, you may change the vertical exaggeration by dragging the slider beneath the graph. You may also change the size of the graph by resizing the window itself.



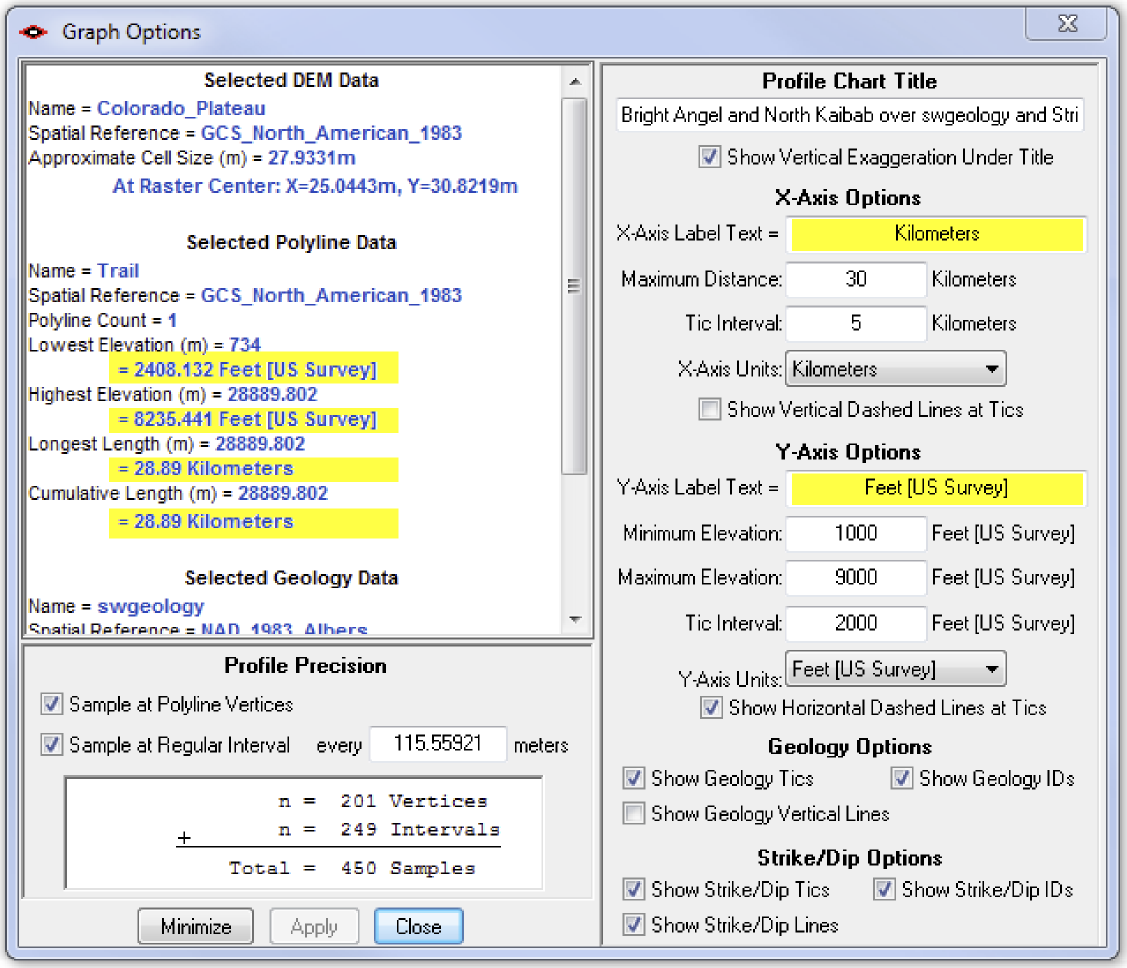
A few more options are available by clicking the *Options* button:



You may change the labels, units, extents and tic intervals of your distance and elevation axes, and whether or not you would like to add dashed lines to the tic marks. You may also specify whether or not you would like to see geologic and/or strike/dip labels, tick marcs or lines in the graph. For example, we could change the elevation units of our Grand Canyon trail profile to *Feet*, reset the interval and remove the Geology vertical dashed lines.



Notice that changing units in the *Options* dialog causes the descriptive information in the upper left corner to change. This descriptive information may be a helpful guide when deciding on appropriate minimum and maximum values to graph:



You may also reset the sampling level for your elevation values. By default, the tool will sample the DEM at every vertex along your route, and also at 250 evenly-distributed points along the route. You may increase or decrease that sampling density in this dialog.

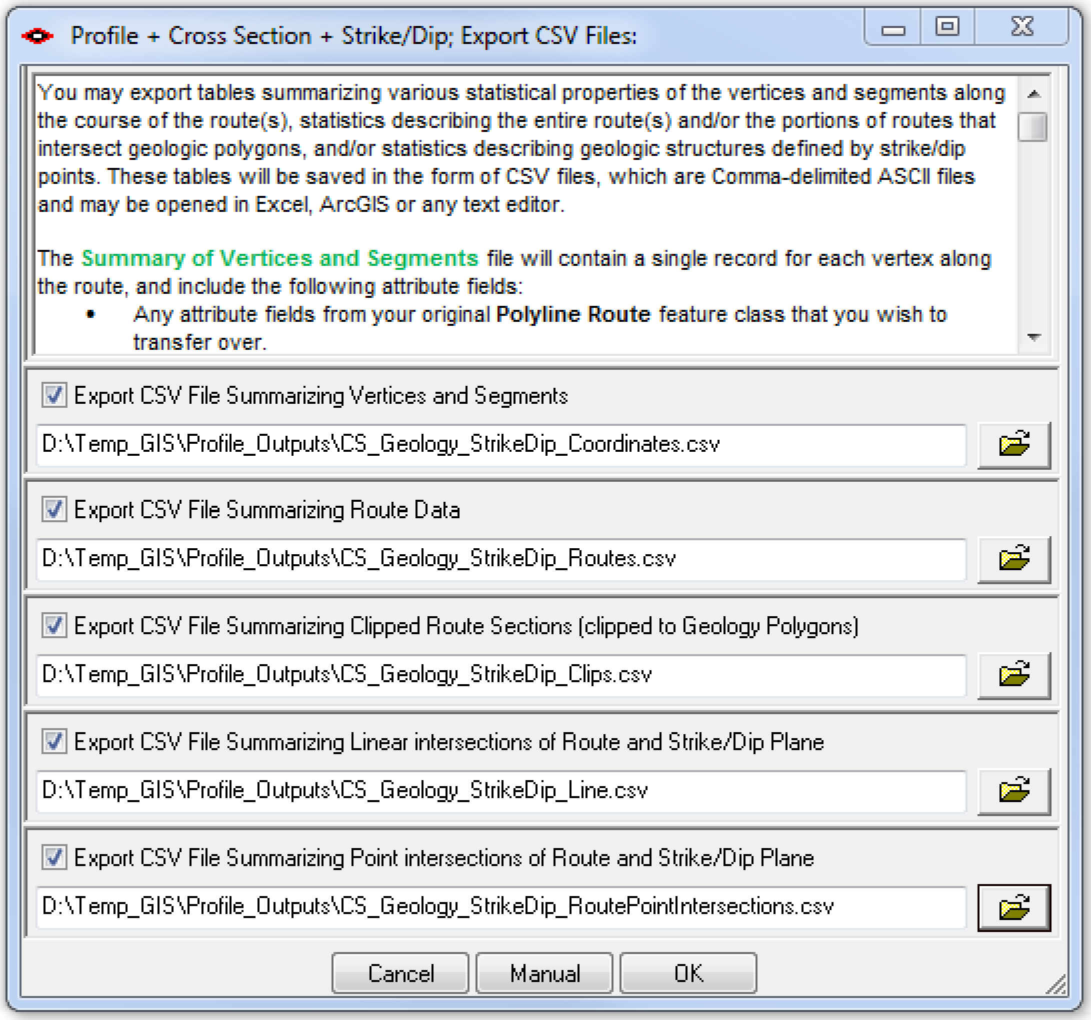
For example, our Grand Canyon trail polyline is almost 29,000m long (see upper left corner of Graph Options window above). By default the tool will sample at all vertices, and then split the trail into 250 sections and sample approximately every 116m (see *Profile Precision* of Graph Options window above).

However, the DEM has a resolution of roughly 28m, and therefore we are only sampling every 4 – 5 cells. If we wanted, we could increase our sampling interval to around 28m in order to take better advantage of the precision of the DEM.

The downside of increasing the sampling precision is that the tool takes longer to generate the data and graphs. You will need to balance your need for tool speed and responsiveness with your requirements for data precision.

Exporting CSV Tables:

You may export tables summarizing various statistical properties of the vertices and segments along the course of the route(s), and/or statistics describing the entire route(s). These tables will be saved in the form of CSV files, which are comma-delimited ASCII files and may be opened in Excel, ArcGIS or any text editor.



This function offers output options for 5 CSV files. One file summarizes statistics for individual vertices along the route, another summarizes entire routes, a third summarizes route segments that intersect geologic polygons, a fourth summarizes the Strike/Dip lines beneath the routes, and a fifth summarizes the intersections between the Strike/Dip lines and the routes on the surface.

The **Summary of Vertices and Segments** file will contain a single record for each vertex along the route, and include the following attribute fields:

- Any attribute fields from your original **Polyline Route** feature class that you wish to transfer over.
- **Latitude**: In the geographic coordinate system of your original **Polyline Route** feature class.
- **Longitude**: In the geographic coordinate system of your original **Polyline Route** feature class.

- **Compass_Bearing:** The compass bearing from the previous vertex to this vertex. The first record will have a compass bearing = -999.
- **Slope_Degrees:** The absolute value of the slope between the previous vertex and this vertex. The first record will have a slope value = -999.
- **Elevation_Meters:** The elevation value of this vertex based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
- **Segment_Geodesic_Distance_Meters:** The distance, in meters, between the previous vertex and this one, calculated using Vincenty's algorithms to estimate geodesic distances over the original Polygon Route feature class spheroid (see Vincenty 1975; also p. 124 of this manual).
- **Segment_Surface_Distance_Meters:** The surface distance, in meters, between the previous vertex and this one, calculated using the Pythagorean theorem to determine the hypotenuse of the triangle formed by the change in elevation and the geodesic distance.
- **Cumulative_Proportion:** The proportion of the original route at this vertex. This proportion is based on the surface distance of the line, not the geodesic distance.
- **Cumulative_Geodesic_Distance_Meters:** The total geodesic distance along the route up to this vertex.
- **Cumulative_Surface_Distance_Meters:** The total surface distance along the route up to this vertex.
- **X_Original_Units:** The X-coordinate in the original units of the source **Polyline Route** feature class. For example, if the source data were in UTM coordinates, then this value would be the vertex Easting value.
- **Y_Original_Units:** The Y-coordinate in the original units of the source **Polyline Route** feature class. For example, if the source data were in UTM coordinates, then this value would be the vertex Northing value.
- **Elevation_Original_Units:** The elevation value in the original units of the source DEM.
- **Exaggeration_Factor:** The exaggeration factor used to adjust the dimensions of the profile graph. This may be useful if you wish to generate a profile graph from these points in some other software package such as **R**.
- **Exaggerated_Elev:** The elevation of the vertex after being multiplied by the exaggeration factor. This is the value that is actually being plotted on the graph, and this value may also be useful if you wish to generate a profile graph from these points in some other software package.

The **Summary of Routes** file will contain a single record for each route analyzed, and will include the following attribute fields:

- Any attribute fields from your original **Polyline Route** feature class that you wish to transfer over.
- **Sample_Points:** The number of DEM values sampled to generate the statistics for this polyline.
- **Start_Latitude:** In the geographic coordinate system of your original **Polyline Route** feature class.
- **Start_Longitude:** In the geographic coordinate system of your original **Polyline Route** feature class.
- **End_Latitude:** In the geographic coordinate system of your original **Polyline Route** feature class.
- **End_Longitude:** In the geographic coordinate system of your original **Polyline Route** feature class.
- **Start_Elevation:** The elevation value of starting point based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
- **End_Elevation:** The elevation of the ending point based on the selected DEM.
- **Min_Elevation:** The elevation of the lowest point based on the selected DEM.
- **Max_Elevation:** The elevation of the highest point based on the selected DEM.
- **Avg_Slope:** The average slope over the course of the route, calculated as the weighted mean of the segment slopes, weighted by the segment surface distances.
- **Slope_StDev:** The standard deviation of slope over the course of the route.
- **Avg_Bearing:** The mean direction of the route, equal to the bearing from the starting point to the ending point of the route (see p. 137 for details).
- **BearingMRL:** The Mean Resultant Length of the route, calculated as the ratio of the geodesic length of the complete route divided by the geodesic distance of the straight line between the starting and ending points (see p. 137 for details). The MRL is the basis of several circular measures of dispersion (see Batschelet 1981, Fisher 1995, Mardia and Jupp 2000). MRL values near 1 indicate little direction variation over the line.
- **Length_Geodesic:** The geodesic length of the route.
- **Length_Surface:** The surface length of the route.
- **Surface Ratio:** The ratio of [Surface Length] / [Geodesic Length]. Values near 1 indicate a flat line, while values > 1 indicate increasing elevational variation.

The **Summary of Clips** file will contain a single record for each section of the route polyline clipped within each intersecting geology polygon, and will include the following attribute fields:

- Any attribute fields from your original **Polyline Route** feature class that you wish to transfer over.
- Any attribute fields from your original **Geology Polygon** feature class that you wish to transfer over.
- **Sample_Points:** The number of DEM values sampled to generate the statistics for this polyline section.
- **Start_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
- **Start_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
- **End_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
- **End_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
- **Start_Elevation:** The elevation value of starting point based on the selected DEM, calculated using Bilinear Interpolation. The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
- **End_Elevation:** The elevation of the ending point based on the selected DEM.
- **Min_Elevation:** The elevation of the lowest point based on the selected DEM.
- **Max_Elevation:** The elevation of the highest point based on the selected DEM.
- **Avg_Slope:** The average slope over the course of the route, calculated as the weighted mean of the segment slopes, weighted by the segment surface distances.
- **Slope_StDev:** The standard deviation of slope over the course of the route section.
- **Avg_Bearing:** The mean direction of the route section, equal to the bearing from the starting point to the ending point of the route (see p. 137 for details).
- **BearingMRL:** The Mean Resultant Length of the route section, calculated as the ratio of the geodesic length of the complete route divided by the geodesic distance of the straight line between the starting and ending points (see p. 137 for details). The MRL is the basis of several circular measures of dispersion (see Batschelet 1981, Fisher 1995, Mardia and Jupp 2000). MRL values near 1 indicate little direction variation over the line.
- **Length_Geodesic:** The geodesic length of the route section.
- **Length_Surface:** The surface length of the route section.
- **Surface_Ratio:** The ratio of [Surface Length] / [Geodesic Length]. Values near 1 indicate a flat line, while values > 1 indicate increasing elevational variation.
- **Start_Position_Geodesic:** The geodesic distance of the beginning of this clipped section, as located on the original route feature.

- **End_Position_Geodesic:** The geodesic distance of the end of this clipped section, as located on the original route feature.

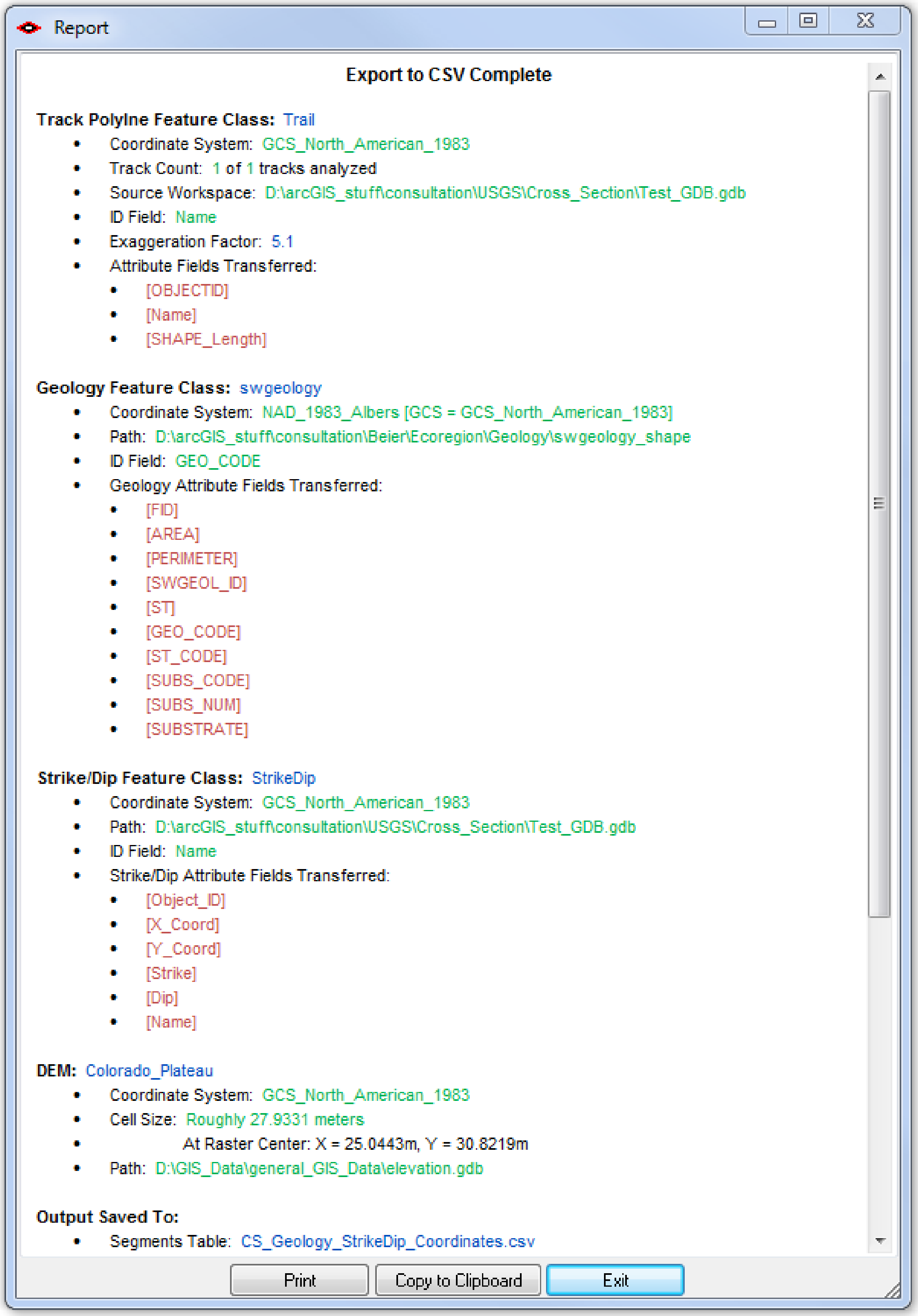
The **Summary of Linear Intersections of Route and Strike/Dip Plane** file will describe the linear intersection between the Strike/Dip plane (as defined by a single point with Strike and Dip angle attributes) and the original route projected vertically down onto that plane. Each record in the file will describe a vertex or sample point along the original route, along with statistics on route and strike/dip plane values at that point. This file will include the following attribute fields:

- Any attribute fields from your original **Polyline Route** feature class that you wish to transfer over.
- Any attribute fields from your original **Strike/Dip Point** feature class that you wish to transfer over. These will automatically include your Strike and Dip angle fields.
- **Latitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **Longitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **Compass_Bearing:** The compass bearing from the previous vertex to this vertex. The first record will have a compass bearing = -999.
- **Route_Elevation_Meters:** The elevation value of this vertex based on the selected DEM, calculated using Bilinear Interpolation. The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
- **Plane_Elevation_Meters:** The elevation value of this location on the Strike/Dip Plane defined by this particular Strike/Dip point.
- **Elevation_Difference:** The elevation value of the Route at this location, minus the elevation on the Strike/Dip Plane at this location.
- **Cumulative_Geodesic_Distance_Meters:** The total geodesic distance along the route up to this vertex., calculated using Vincenty's algorithms to estimate geodesic distances over the original Polygon Route feature class spheroid (see Vincenty 1975; also p. 124 of this manual).
- **Cumulative_Proportion:** The proportion of the original route at this vertex. This proportion is based on the surface distance of the original route, not the geodesic distance of the route or the distance along the strike/dip plane.
- **Exaggeration_Factor:** The exaggeration factor used to adjust the dimensions of the profile graph. This may be useful if you wish to generate a profile graph from these points in some other software package such as **R**.
- **Exaggerated_Elev:** The elevation of the strike/dip plane point after being multiplied by the exaggeration factor. This is the value that is actually being plotted on the graph, and this value may also be useful if you wish to generate a profile graph from these points in some other software package.

The **Summary of Point Intersections of Route and Strike/Dip Plane** file will describe the point intersection between the Strike/Dip plane (as defined by a single point with Strike and Dip angle attributes) and the original route on the surface of the landscape. This feature class will only show those points where the strike/dip plane intersects the route on the surface of the planet. If a strike/dip plane does not intersect the surface at any point along the route, then there will be no record of that strike/dip plane in this dataset. This file will include the following attribute fields:

- Any attribute fields from your original **Polyline Route** feature class that you wish to transfer over.
- Any attribute fields from your original **Strike/Dip Point** feature class that you wish to transfer over. These will automatically include your Strike and Dip angle fields.
- **Latitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **Longitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **Elevation_Meters:** The elevation value at this location based on the selected DEM, calculated using Bilinear Interpolation. The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table. Because this dataset only includes the point intersections of the route and the Strike/Dip plane, this elevation will therefore be the elevation of both the route and the plane at this location.
- **Plane_Relative_Angle:** The angle of inclination of the Strike/Dip plane, in degrees, relative to the compass direction of the route at this point. This value can be used for graphing purposes to orient the route/plane intersection tic mark to be at the same angle as strike/dip line as it hits the surface.
- **Cumulative_Geodesic_Distance_Meters:** The total geodesic distance along the route up to this vertex.
- **Cumulative_Proportion:** The proportion of the original route at this vertex. This proportion is based on the surface distance of the original route, not the geodesic distance of the route or the distance along the strike/dip plane.
- **Exaggeration_Factor:** The exaggeration factor used to adjust the dimensions of the profile graph. This may be useful if you wish to generate a profile graph from these points in some other software package such as **R**.
- **Exaggerated_Elev:** The elevation of the intersection point after being multiplied by the exaggeration factor. This is the value that is actually being plotted on the graph, and this value may also be useful if you wish to generate a profile graph from these points in some other software package.

Upon completion, the tool will display a report window showing where the files were saved.

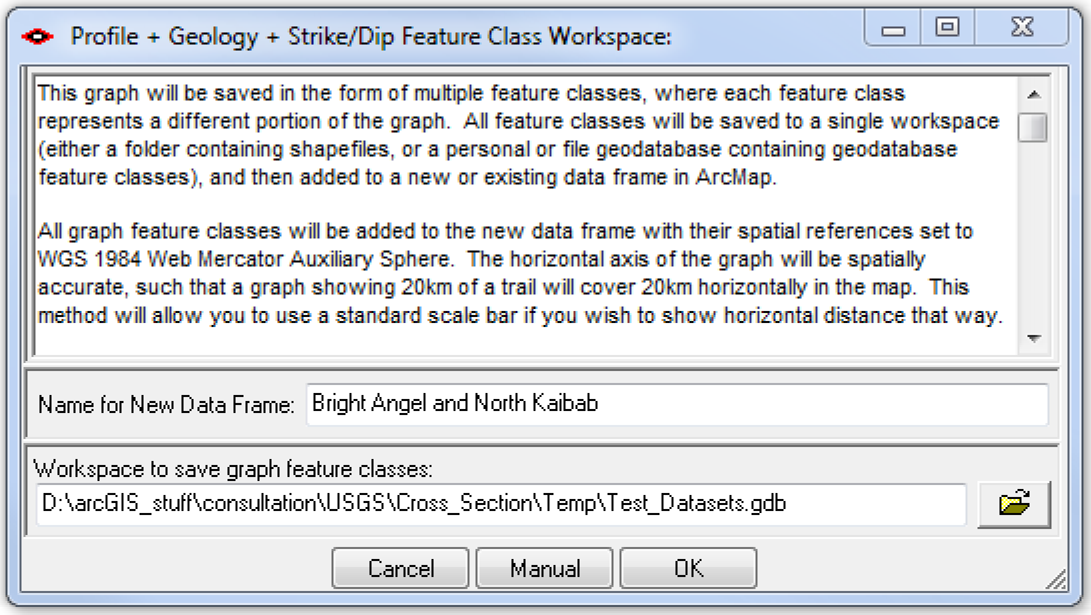


Exporting Graph to Data Frame as Feature Classes:

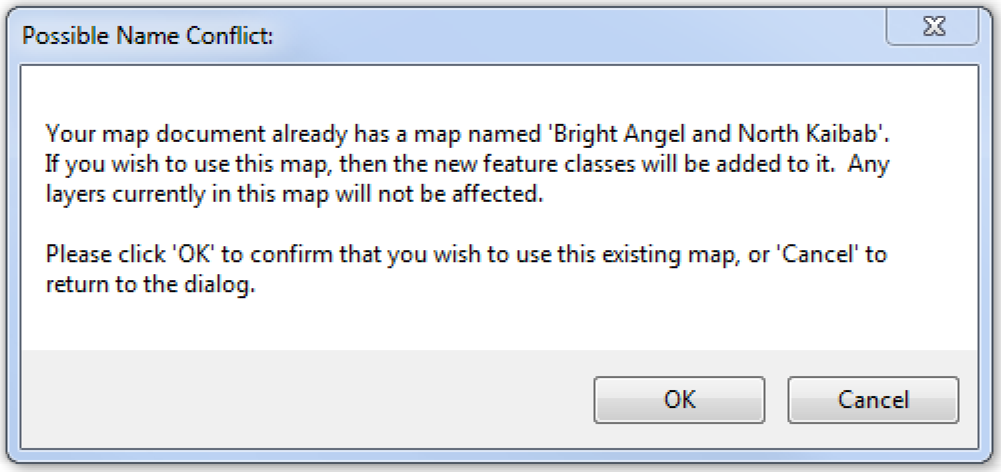
This graph will be saved in the form of multiple feature classes, where each feature class represents a different portion of the graph. All feature classes will be saved to a single workspace (either a folder containing shapefiles, or a personal or file geodatabase containing geodatabase feature classes), and then added to a new or existing data frame in ArcMap.

All graph feature classes will be added to the new data frame with their spatial references set to WGS 1984 Web Mercator Auxiliary Sphere. The horizontal axis of the graph will be spatially accurate, such that a graph showing 20km of a trail will cover 20km horizontally in the map. This method will allow you to use a standard scale bar if you wish to show horizontal distance that way.

You must specify the workspace you wish to use and the name of the new data frame.



This tool will create your new data frame automatically and assign it the name you specify in the dialog. If you specify a data frame name that already exists in your map document, this tool will alert you to the fact and ask you to confirm your choice:



All datasets will be named automatically, based on the name of your Track/Route layer.

Details: This tool will create11 new feature classes representing different aspects of the graph.

1) **Segments Feature Class:** Contains a separate record for each vertex-to-vertex segment along a route. When initially added to the map, it will be symbolized by slope in a blue-to-red color ramp. In addition to any attribute fields from the original route feature class you may choose to transfer, this feature class will also include the following calculated attributes:

- **Start_Latitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **Start_Longitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **End_Latitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **End_Longitude**: In the geographic coordinate system of your original Polyline Route feature class.
- **Geodesic_Length:** The segment length, in meters, calculated using Vincenty's algorithms to estimate geodesic distances over the original Polygon Route feature class spheroid (see Vincenty 1975; also p. 124 of this manual).
- **Surface_Length:** The segment surface length, in meters, calculated using the Pythagorean theorem to determine the hypotenuse of the triangle formed by the change in elevation and the geodesic distance.
- **Slope_Degrees:** The absolute value of the segment slope.
- **Bearing:** The compass bearing of the segment.
- **Start_Elevation:** The elevation value at the beginning of the segment based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this attribute field.

- **Mid_Elevation:** The elevation value at the centerpoint of the segment.
- **End_Elevation:** The elevation value at the end of the segment.
- **End_Proportion:** The proportion of the original route at the segment endpoint. This proportion is based on the surface distance of the line, not the geodesic distance. Values will range from 0 to 1.
- **Total_Geodesic_Distance:** The total geodesic distance, in meters, along the route up to the end of this segment.
- **Total_Surface_Distance:** The total surface distance, in meters, along the route up to the end of this segment.

2) **Polyline Feature Class:** Contains a separate record for each route showing the profile of the route over the DEM. When initially added to the map, it will be symbolized by ID value based on the ID field you select. If you do not select an ID field, it will be symbolized by the Feature Object ID of the original route. In addition to any attribute fields from the original route feature class you may choose to transfer, this feature class will also include the following calculated attributes:

    - **Sample_Points:** The number of DEM values sampled to generate the statistics for this polyline.
    - **Start_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
    - **Start_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
    - **End_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
    - **End_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
    - **Start_Elevation:** The elevation value of starting point based on the selected DEM, calculated using bilinear interpolation (see p. 106). The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
    - **End_Elevation:** The elevation of the ending point based on the selected DEM.
    - **Min_Elevation:** The elevation of the lowest point based on the selected DEM.
    - **Max_Elevation:** The elevation of the highest point based on the selected DEM.
    - **Avg_Slope:** The average slope over the course of the route, calculated as the weighted mean of the segment slopes, weighted by the segment surface distances.
    - **Slope_StDev:** The standard deviation of slope over the course of the route.
    - **Avg_Bearing:** The mean direction of the route, equal to the bearing from the starting point to the ending point of the route.

- **BearingMRL:** The Mean Resultant Length of the route, calculated as the ratio of the geodesic length of the complete route divided by the geodesic distance of the straight line between the starting and ending points. The MRL is the basis of several circular measures of dispersion (see Batschelet 1981, Fisher 1995, Mardia and Jupp 2000). MRL values near 1 indicate little direction variation over the line.
- **Length_Geodesic:** The geodesic length of the route.
- **Length_Surface:** The surface length of the route.
- **Surface Ratio:** The ratio of [Surface Length] / [Geodesic Length]. Values near 1 indicate a flat line, while values > 1 indicate increasing elevational variation.

3) **Polygon Feature Class:** Similar to the Polyline Feature Class, except that it symbolizes the route using a polygon to symbolize the portion of the graph underneath the route profile. Contains a separate record for each route. When initially added to the map, it will be symbolized by ID value based on the ID field you select. If you do not select an ID field, it will be symbolized by the Feature Object ID of the original route. This feature class will contain exactly the same attribute fields and values as the Polyline Feature Class described above.

4) **Clipped Polyline Feature Class:** Contains a separate record for each intersection between the route and a geology polygon, showing the profile of the route over the DEM. When initially added to the map, it will be symbolized by the color of the Geology polygons. In addition to any attribute fields from the original route and geology feature classes you may choose to transfer, this feature class will also include the following calculated attributes:

   - **Sample_Points:** The number of DEM values sampled to generate the statistics for this clipped portion of the route polyline.
   - **Start_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Start_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **End_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **End_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Start_Elevation:** The elevation value of starting point based on the selected DEM, calculated using Bilinear Interpolation. The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
   - **End_Elevation:** The elevation of the ending point based on the selected DEM.
   - **Min_Elevation:** The elevation of the lowest point based on the selected DEM.
   - **Max_Elevation:** The elevation of the highest point based on the selected DEM.
   - **Avg_Slope:** The average slope over the course of the route, calculated as the weighted mean of the segment slopes, weighted by the segment surface distances.

- **Slope_StDev:** The standard deviation of slope over the course of the route.
- **Avg_Bearing:** The mean direction of the route, equal to the bearing from the starting point to the ending point of the route.
- **BearingMRL:** The Mean Resultant Length of the route, calculated as the ratio of the geodesic length of the complete route divided by the geodesic distance of the straight line between the starting and ending points. The MRL is the basis of several circular measures of dispersion (see Batschelet 1981, Fisher 1995, Mardia and Jupp 2000). MRL values near 1 indicate little direction variation over the line.
- **Length_Geodesic:** The geodesic length of the route.
- **Length_Surface:** The surface length of the route.
- **Surface_Ratio:** The ratio of [Surface Length] / [Geodesic Length]. Values near 1 indicate a flat line, while values > 1 indicate increasing elevational variation.
- **Start_Position_Geodesic:** The geodesic distance of the beginning of this clipped section, as located on the original route feature.
- **End_Position_Geodesic:** The geodesic distance of the end of this clipped section, as located on the original route feature.

5) **Clipped Polyline Tic Mark Feature Class:** Contains a separate record for the intersection points between the route and geology polygons, showing a short vertical line that intersects the profile line. This feature class is intended primarily to add aesthetic qualities to the profile graph. When initially added to the map, it will be symbolized by the color of the Geology polygons. This feature class will only include the following calculated attributes:
   - **Left_GeoID:** The geology polygon ID value on the left side of the tick mark.
   - **Right_GeoID:** The geology polygon ID value on the right side of the tick mark.
   - **Label_Value**: A string value composed of [Left_GeoID] + a vertical line ("|") + [Right_GeoID]. This might be useful for labeling purposes in the graph.
   - **Position_Geodesic:** The geodesic distance of this point, as located on the original route feature.
   - **Elevation:** The elevation, in meters, at this point.
   - **Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Longitude:** In the geographic coordinate system of your original Polyline Route feature class.

6) **Clipped Polyline Vertical Line Feature Class:** Contains a separate record for the intersection points between the route and geology polygons, showing a vertical line that extends from the bottom of the graph up to the profile line. This feature class is intended primarily to add aesthetic qualities to the profile graph. When initially added to the map, it will be symbolized

by the color of the Geology polygons. This feature class will only include the following calculated attributes:

- **Left_GeoID:** The geology polygon ID value on the left side of the line.
- **Right_GeoID:** The geology polygon ID value on the right side of the line.
- **Label_Value**: A string value composed of [Left_GeoID] + a vertical line ("|") + [Right_GeoID]. This might be useful for labeling purposes in the graph.
- **Position_Geodesic:** The geodesic distance of this point, as located on the original route feature.
- **Elevation:** The elevation, in meters, at this point.
- **Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
- **Longitude:** In the geographic coordinate system of your original Polyline Route feature class.

7) **Strike/Dip Route-Plane Vertices:** Describes the linear intersection between the Strike/Dip plane (as defined by a single point with Strike and Dip angle attributes) and the original route projected vertically down onto that plane. Each point in the feature class will describe a vertex or sample point along the original route, along with statistics on route and strike/dip plane values at that point. In addition to any attribute fields from the original route and strike/dip feature classes you may choose to transfer, this feature class will also include the following calculated attributes:

   - **Latitude**: In the geographic coordinate system of your original Polyline Route feature class.
   - **Longitude**: In the geographic coordinate system of your original Polyline Route feature class.
   - **Compass_Bearing:** The compass bearing from the previous vertex to this vertex. The first record will have a compass bearing = -999.
   - **Route_Elevation_Meters:** The elevation value of this vertex based on the selected DEM, calculated using Bilinear Interpolation. The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table.
   - **Plane_Elevation_Meters:** The elevation value of this location on the Strike/Dip Plane defined by this particular Strike/Dip point.
   - **Elevation_Difference:** The elevation value of the Route at this location, minus the elevation on the Strike/Dip Plane at this location.
   - **Cumulative_Geodesic_Distance_Meters:** The total geodesic distance along the route up to this vertex, calculated using Vincenty's algorithms to estimate geodesic distances over the original Polygon Route feature class spheroid (see Vincenty 1975; also p. 124 of this manual).

- **Cumulative_Proportion:** The proportion of the original route at this vertex. This proportion is based on the surface distance of the original route, not the geodesic distance of the route or the distance along the strike/dip plane.
- **Exaggeration_Factor:** The exaggeration factor used to adjust the dimensions of the profile graph. This may be useful if you wish to generate a profile graph from these points in some other software package such as **R**.
- **Exaggerated_Plane_Elevation:** The elevation of the strike/dip plane point after being multiplied by the exaggeration factor. This is the value that is actually being plotted on the graph, and this value may also be useful if you wish to generate a profile graph from these points in some other software package.

8) **Strike/Dip Route-Plane Polylines:** Describes the linear intersection between the Strike/Dip plane (as defined by a single point with Strike and Dip angle attributes) and the original route projected vertically down onto that plane. Each polyline in the feature class will describe the portion of the strike/dip plane that lies directly beneath the route polyline. If the ground surface extends **below** the strike/dip plane along any portion of the route, then those portions will be excluded from the dataset. If a single strike/dip plane is broken up this way, then each sub-portion of the final polyline will be saved as a separate feature in the feature class. In addition to any attribute fields from the original route and strike/dip feature classes you may choose to transfer, this feature class will also include the following calculated attributes:

   - **Start_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Start_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **End_Latitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **End_Longitude:** In the geographic coordinate system of your original Polyline Route feature class.
   - **Start_Elevation:** The elevation value of the Strike/Dip segment starting point based on the Strike/Dip plane.
   - **End_Elevation:** The elevation of the Strike/Dip segment ending point based on the Strike/Dip plane.
   - **Length_Geodesic:** The geodesic length of the route.
   - **Start_Position_Geodesic:** The geodesic distance of the beginning of this portion of the original route.
   - **End_Position_Geodesic:** The geodesic distance of the ending of this portion of the original route.
   - **Start_Proportion:** The position of the beginning of this portion of the original route, expressed as a proportion of the entire original route.

- **End_Proportion:** The position of the ending of this portion of the original route, expressed as a proportion of the entire original route.
- **Plane_Parameter_A:** Parameter **A** describing the plane, given the definition [Plane = aX + bY + cZ + d = 0]. This definition is in Cartesian coordinates.
- **Plane_Parameter_B:** Parameter **B** describing the plane, given the definition [Plane = aX + bY + cZ + d = 0]. This definition is in Cartesian coordinates.
- **Plane_Parameter_C:** Parameter **C** describing the plane, given the definition [Plane = aX + bY + cZ + d = 0]. This definition is in Cartesian coordinates.
- **Plane_Parameter_D:** Parameter **D** describing the plane, given the definition [Plane = aX + bY + cZ + d = 0]. This definition is in Cartesian coordinates.

9) **Strike/Dip Route-Plane Point Intersections; Graph Dataset:** Describes the point intersection between the Strike/Dip plane (as defined by a single point with Strike and Dip angle attributes) and the original route on the surface of the landscape. This feature class will only show those points where the strike/dip plane intersects the route on the surface of the planet. If a strike/dip plane does not intersect the surface at any point along the route, then there will be no record of that strike/dip plane in this dataset. In addition to any attribute fields from the original route and strike/dip feature classes you may choose to transfer, this feature class will also include the following calculated attributes:

   - **Latitude**: In the geographic coordinate system of your original Polyline Route feature class.
   - **Longitude**: In the geographic coordinate system of your original Polyline Route feature class.
   - **Elevation_Meters:** The elevation value at this location based on the selected DEM, calculated using Bilinear Interpolation. The vertex is projected into the DEM datum and coordinate system prior to analysis if necessary. If the original DEM is not in meters, then the values are converted to meters in this table. Because this dataset only includes the point intersections of the route and the Strike/Dip plane, this elevation will therefore be the elevation of both the route and the plane at this location.
   - **Plane_Relative_Angle:** The angle of inclination of the Strike/Dip plane, in degrees, relative to the compass direction of the route at this point. This value can be used for graphing purposes to orient the route/plane intersection tic mark to be at the same angle as strike/dip line as it hits the surface.
   - **Cumulative_Geodesic_Distance_Meters:** The total geodesic distance along the route up to this vertex.
   - **Cumulative_Proportion:** The proportion of the original route at this vertex. This proportion is based on the surface distance of the original route, not the geodesic distance of the route or the distance along the strike/dip plane.

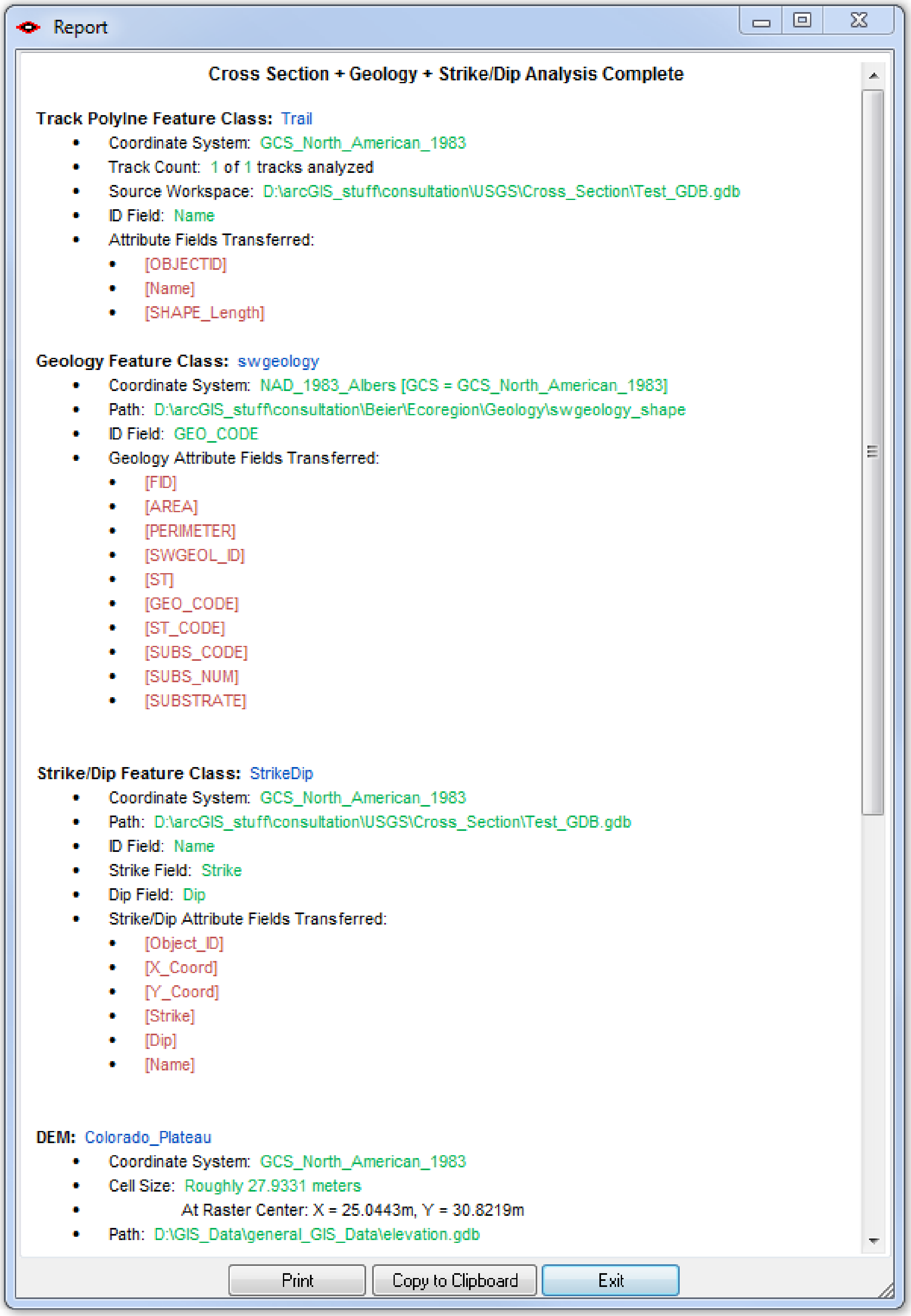
- **Exaggeration_Factor:** The exaggeration factor used to adjust the dimensions of the profile graph. This may be useful if you wish to generate a profile graph from these points in some other software package such as **R**.
- **Exaggerated_Elev:** The elevation of the intersection point after being multiplied by the exaggeration factor. This is the value that is actually being plotted on the graph, and this value may also be useful if you wish to generate a profile graph from these points in some other software package
- **Plane_Parameter_A:** Parameter **A** describing the plane, given the definition [Plane = aX + bY + cZ + d = 0]. This definition is in Cartesian coordinates.
- **Plane_Parameter_B:** Parameter **B** describing the plane, given the definition [Plane = aX + bY + cZ + d = 0]. This definition is in Cartesian coordinates.
- **Plane_Parameter_C:** Parameter **C** describing the plane, given the definition [Plane = aX + bY + cZ + d = 0]. This definition is in Cartesian coordinates.
- **Plane_Parameter_D:** Parameter **D** describing the plane, given the definition [Plane = aX + bY + cZ + d = 0]. This definition is in Cartesian coordinates.

10) **Strike/Dip Route-Plane Point Intersections; Spatial Dataset:** This dataset is identical to (9) above, except that it is saved as a true spatial dataset of the route/plane intersections which can be mapped along with the original route. Intersection points will all lie along the original route. Because this dataset is mapped in geographic space rather than graph space, it is **not** added to the graph data frame. However, it is available in the same workspace if the user wishes to add it to a map.

11) **Graph_Lines:** Simply shows the reference lines of the graph, including axes, tick marks and horizontal/vertical references. Attribute values include the name of the line (X-Axis, Y-Axis, X-Tic, Y-Tic, X-Reference and Y-Reference), and a label value for that line.

This tool will also add graphic text boxes for label values, axis names and the chart title. **Note:** These graphics can be converted to annotation by right-clicking data frame name and choosing "Convert Labels to Annotation". This option helps the labels look better if you add the graph to a layout. See also a known issue with exported graphic text on p. 96.

Upon completion, the tool will show you a report detailing what it did:



Report

Cross Section + Geology + Strike/Dip Analysis Complete

Track Polylne Feature Class: Trail
- Coordinate System: GCS_North_American_1983
- Track Count: 1 of 1 tracks analyzed
- Source Workspace: D:\arcGIS_stuff\consultation\USGS\Cross_Section\Test_GDB.gdb
- ID Field: Name
- Attribute Fields Transferred:
  - [OBJECTID]
  - [Name]
  - [SHAPE_Length]

Geology Feature Class: swgeology
- Coordinate System: NAD_1983_Albers [GCS = GCS_North_American_1983]
- Path: D:\arcGIS_stuff\consultation\Beier\Ecoregion\Geology\swgeology_shape
- ID Field: GEO_CODE
- Geology Attribute Fields Transferred:
  - [FID]
  - [AREA]
  - [PERIMETER]
  - [SWGEOL_ID]
  - [ST]
  - [GEO_CODE]
  - [ST_CODE]
  - [SUBS_CODE]
  - [SUBS_NUM]
  - [SUBSTRATE]

Strike/Dip Feature Class: StrikeDip
- Coordinate System: GCS_North_American_1983
- Path: D:\arcGIS_stuff\consultation\USGS\Cross_Section\Test_GDB.gdb
- ID Field: Name
- Strike Field: Strike
- Dip Field: Dip
- Strike/Dip Attribute Fields Transferred:
  - [Object_ID]
  - [X_Coord]
  - [Y_Coord]
  - [Strike]
  - [Dip]
  - [Name]

DEM: Colorado_Plateau
- Coordinate System: GCS_North_American_1983
- Cell Size: Roughly 27.9331 meters
- At Raster Center: X = 25.0443m, Y = 30.8219m
- Path: D:\GIS_Data\general_GIS_Data\elevation.gdb

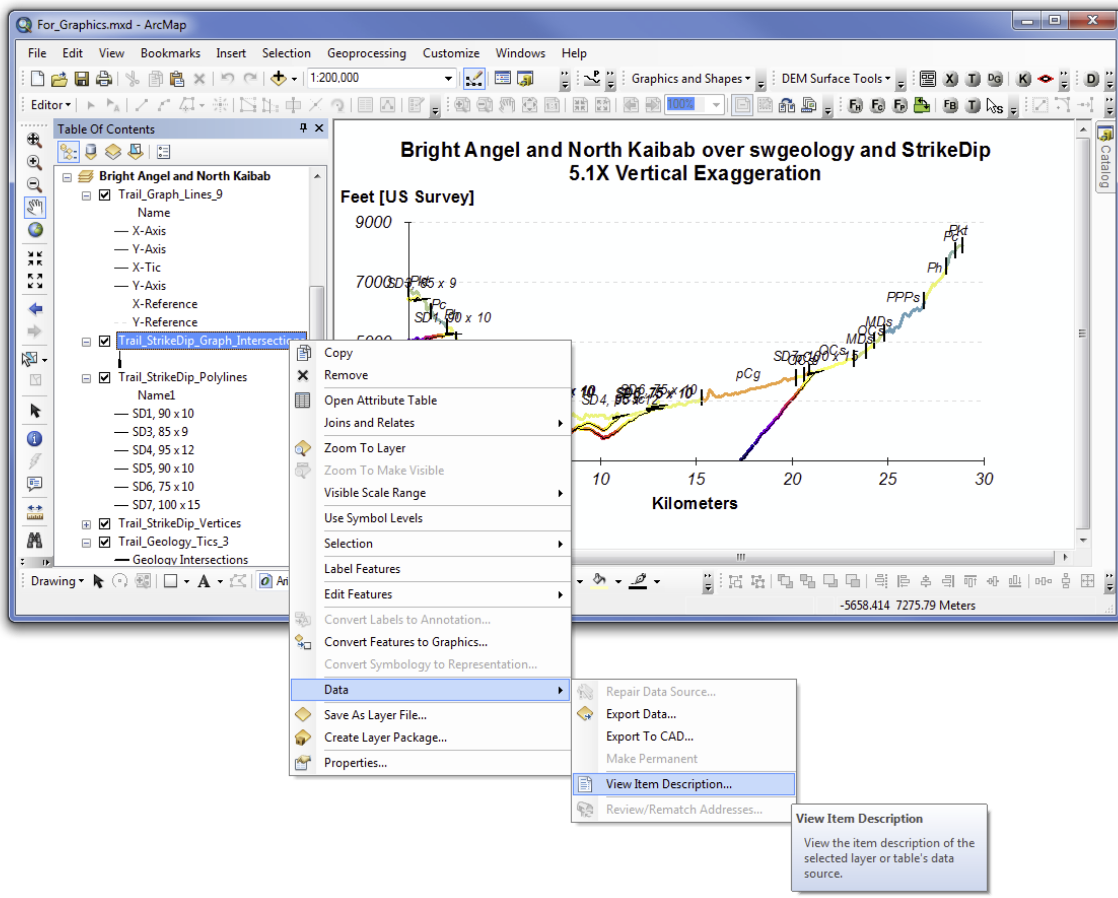
Print | Copy to Clipboard | Exit

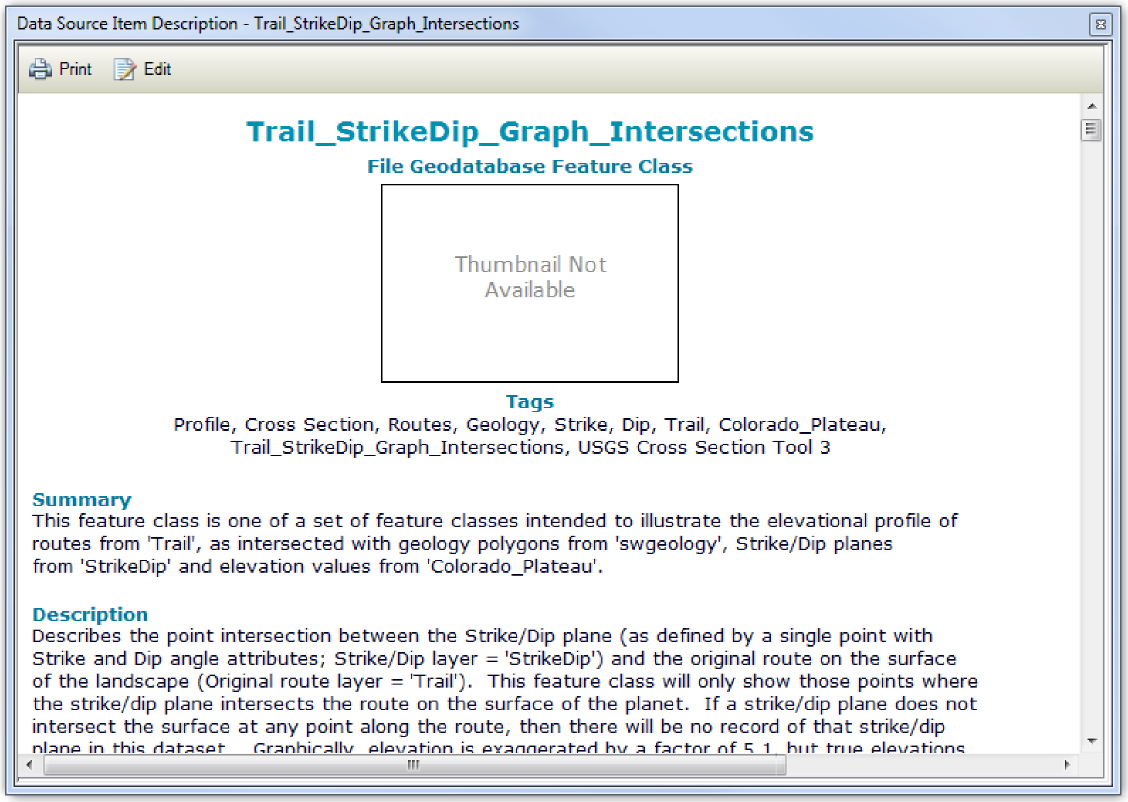
Your new data frame will open automatically, displaying all the elements of the graph. By default, the Geology Segments feature class will be set to visible and will be the primary way the route profile will be symbolized. However, like any feature class, this layer can be turned off and the "Trail Segments" layer can be turned on. (which by default symbolizes the route profile by steepness of slope). Or, you may resymbolize any feature layer by any attribute to fit your preferences.

If you had the strike/dip lines visible in the graph, then they will also appear here in the data frame graph in both point and polyline format. The point format will be symbolized in a rainbow ramp based on the distance below the route.

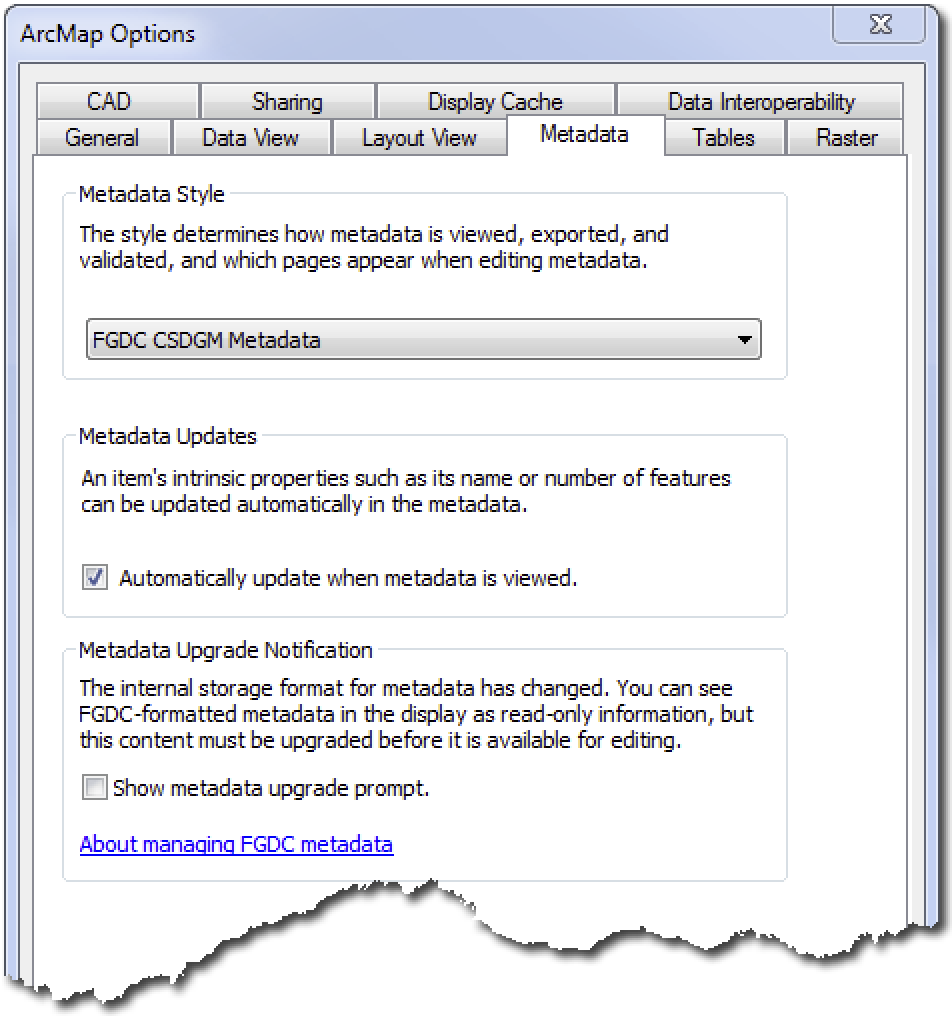
Another advantage to the feature class format is that you can edit the graph elements using the standard ArcMap Editor tools.

Finally, all graph element feature classes include metadata detailing the analysis options you specified and defining all the attribute fields. Simply right-click on the feature class, click on "Data", and then click "Show Item Description":



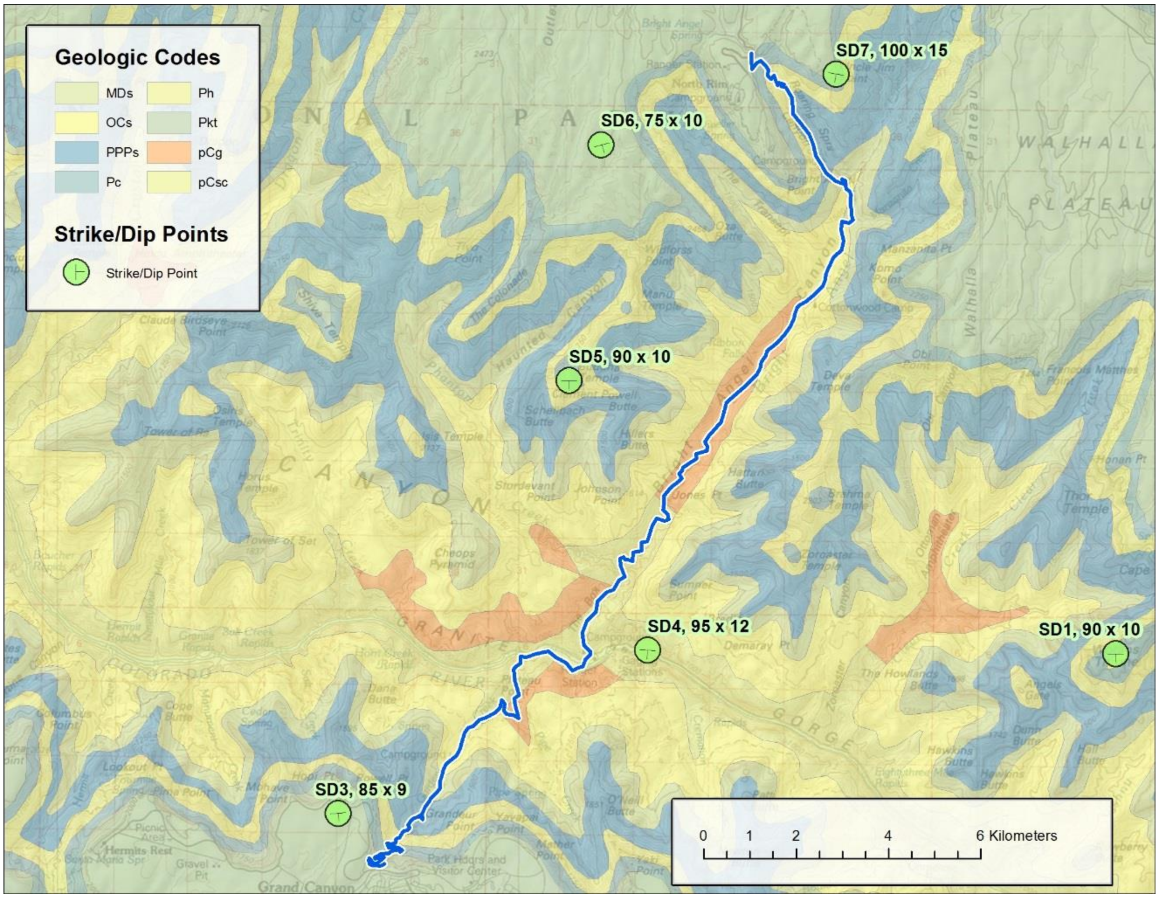


Note: If you do not see the field definitions in the metadata, then you may have ArcMap set to only show you the simplest "Item Description" form of metadata. This is easy to change if you want. Simply click the "Customize" menu, then ArcMap Options. Then click the "Metadata" tab and choose a different metadata style.

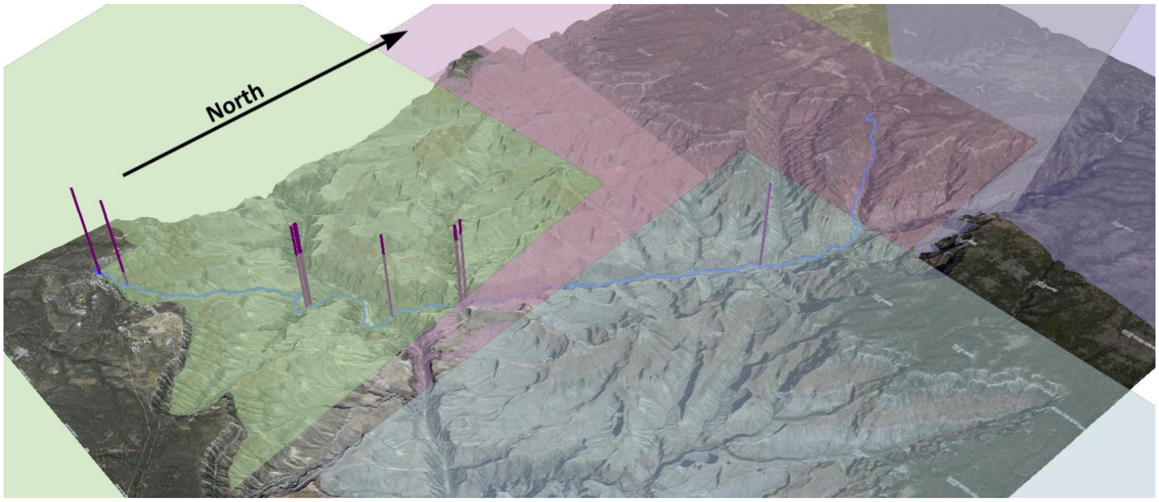


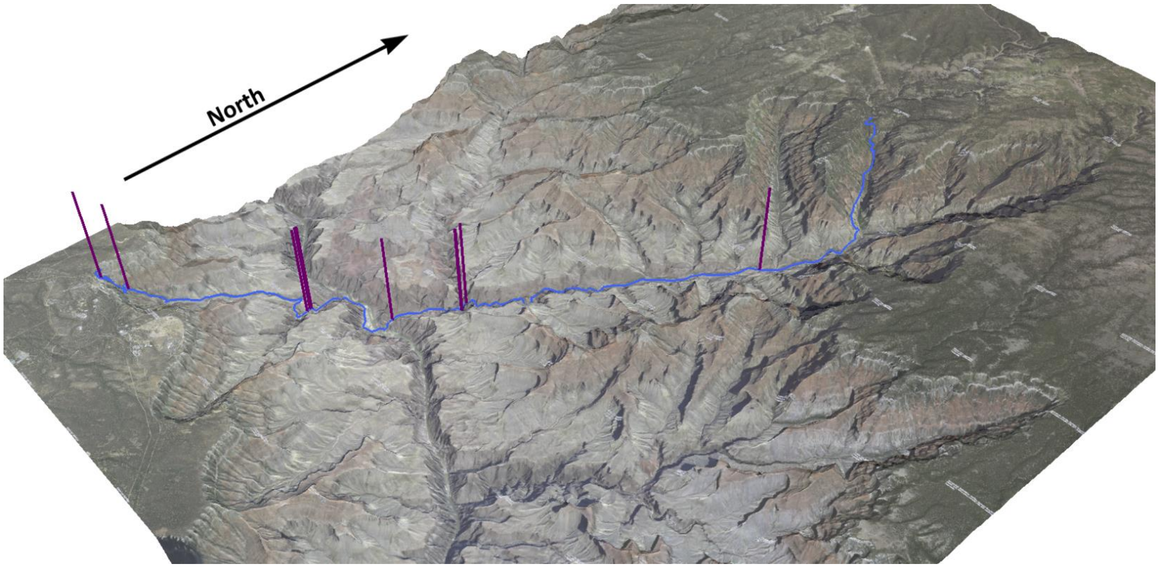
Note that this function created an additional feature class named **[Your_Trail_Name]_[Your_Strike/Dip_Name]_Spatial_Intersection** that is not added to, nor intended for the graph, but instead can be added to your original map if you wish. This point feature class shows the intersection points of the Strike/Dip planes with the routes on the surface of the landscape.

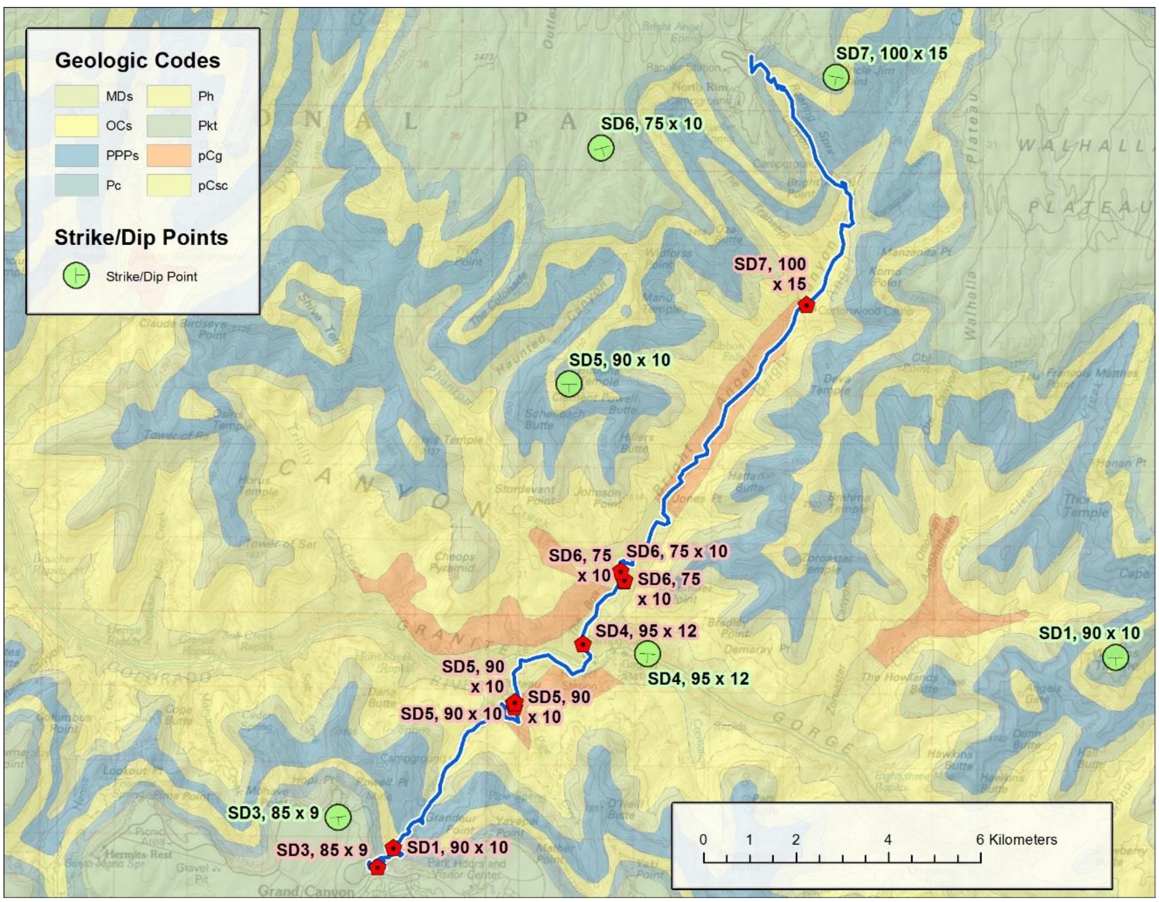
For example, given the original route and the strike/dip points:



The tool identifies all those points along the trail where the strike/dip planes intersect the actual trail on the surface on the landscape:





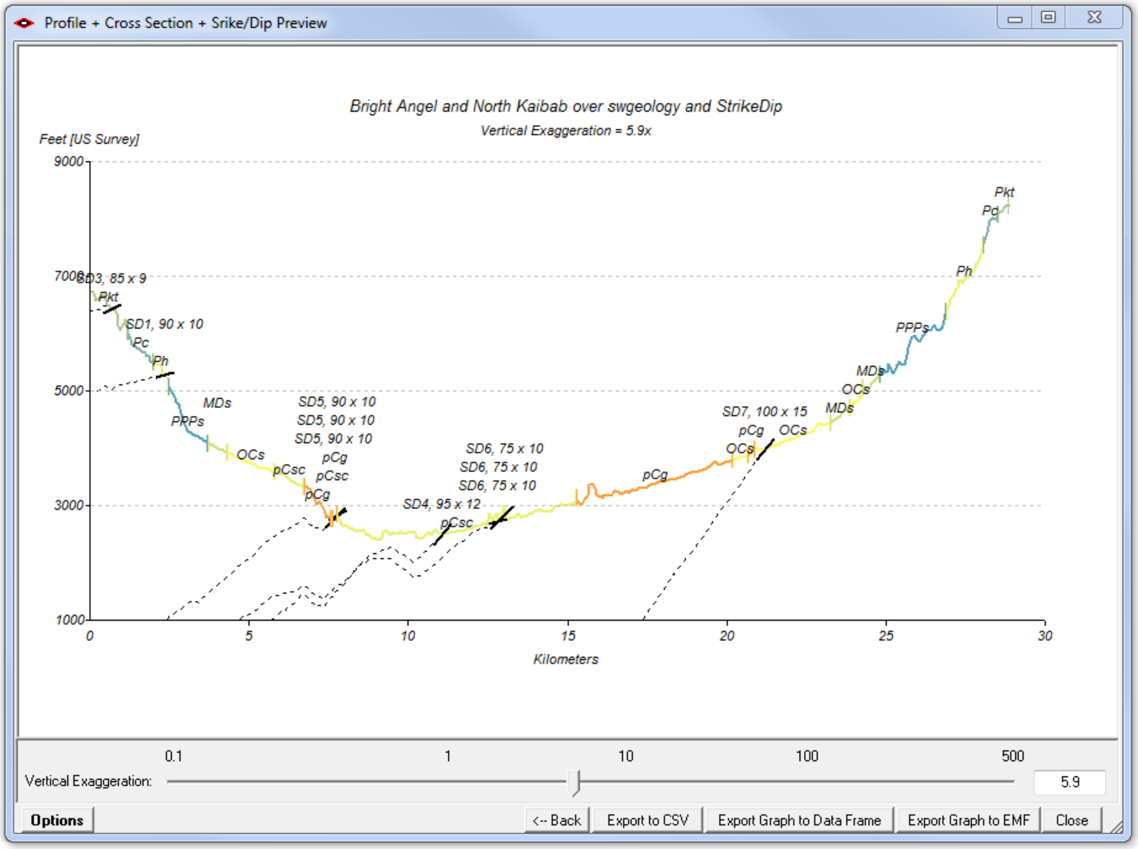


Export the Graph as an EMF file:

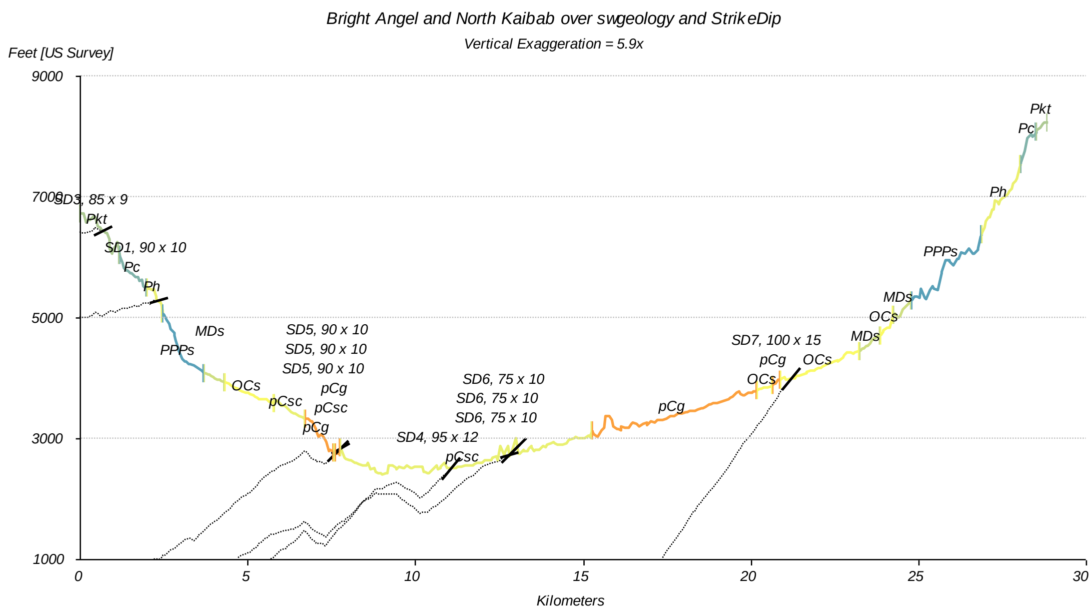
This option simply redraws the graph in the dialog onto an EMF (Windows Enhanced Metafile) surface and saves it to your hard drive. It also adds the EMF file as a graphic to your layout.

Click the *Export Graph to EMF* button and the tool will do everything automatically. The new EMF file will be named according to your graph title and saved in the same folder alongside your current ArcMap document (*.mxd file).

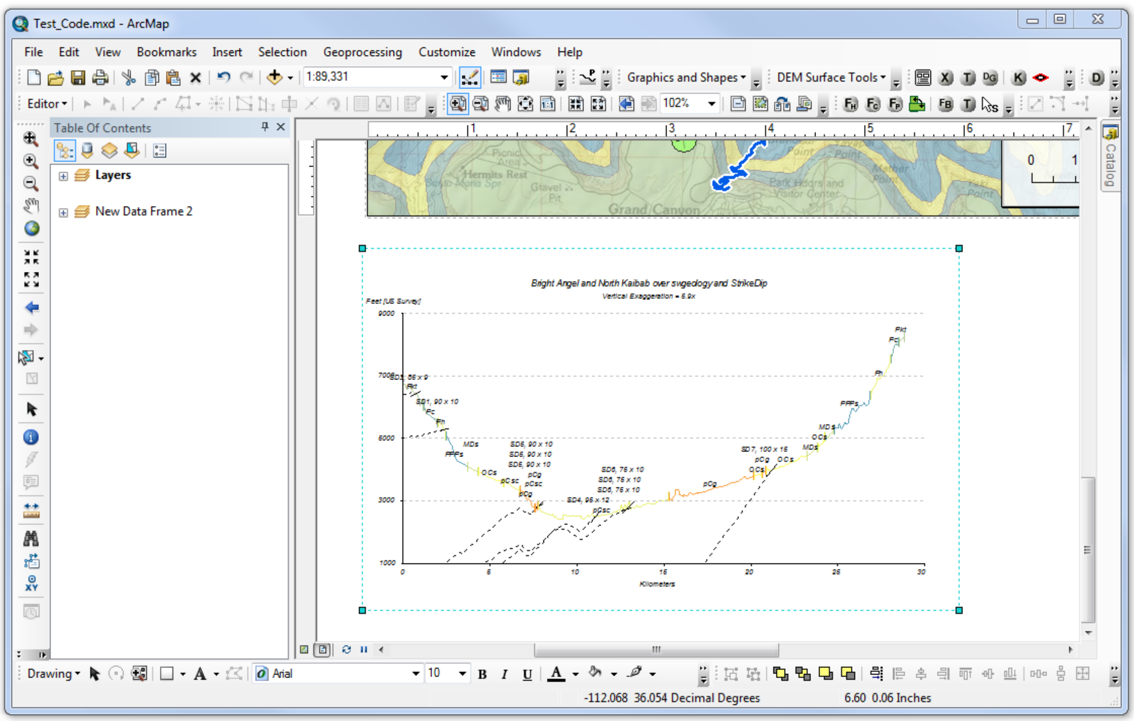
The EMF file can be opened and imported into several files, including Microsoft Word. For example, given the graph below,



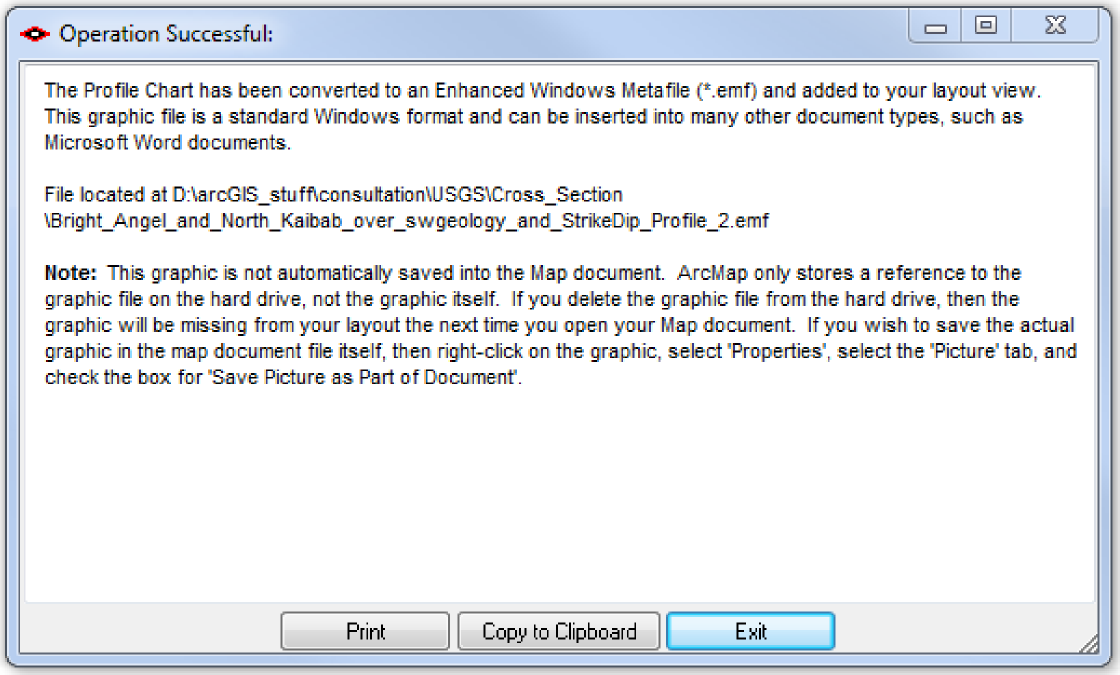
I have exported the graph to an EMF file and loaded it into this document below:



Upon completion, the tool will add the EMF file as a new graphic in your layout.



The tool will also give you a report detailing where it saved the EMF file and what the file is named:


Operation Successful:
The Profile Chart has been converted to an Enhanced Windows Metafile (*.emf) and added to your layout view. This graphic file is a standard Windows format and can be inserted into many other document types, such as Microsoft Word documents.
File located at D:\arcGIS_stuff\consultation\USGS\Cross_Section \Bright_Angel_and_North_Kaibab_over_swgeology_and_StrikeDip_Profile_2.emf
Note: This graphic is not automatically saved into the Map document. ArcMap only stores a reference to the graphic file on the hard drive, not the graphic itself. If you delete the graphic file from the hard drive, then the graphic will be missing from your layout the next time you open your Map document. If you wish to save the actual graphic in the map document file itself, then right-click on the graphic, select 'Properties', select the 'Picture' tab, and check the box for 'Save Picture as Part of Document'.
Print
Copy to Clipboard
Exit

Known Issues:

Export to Graphs Text:

Each tool has an option to export the graphs to a new data frame in the form of shapefiles. These options also create graphic text elements in the data frame to serve as the graph title, axis labels, tic labels and feature labels.

These text elements are initially set to scale with the map, so they should shrink if you zoom out and grow if you zoom in. They appear to do this correctly until you shift to the Map Layout, at which point the scaling seems to get corrupted.

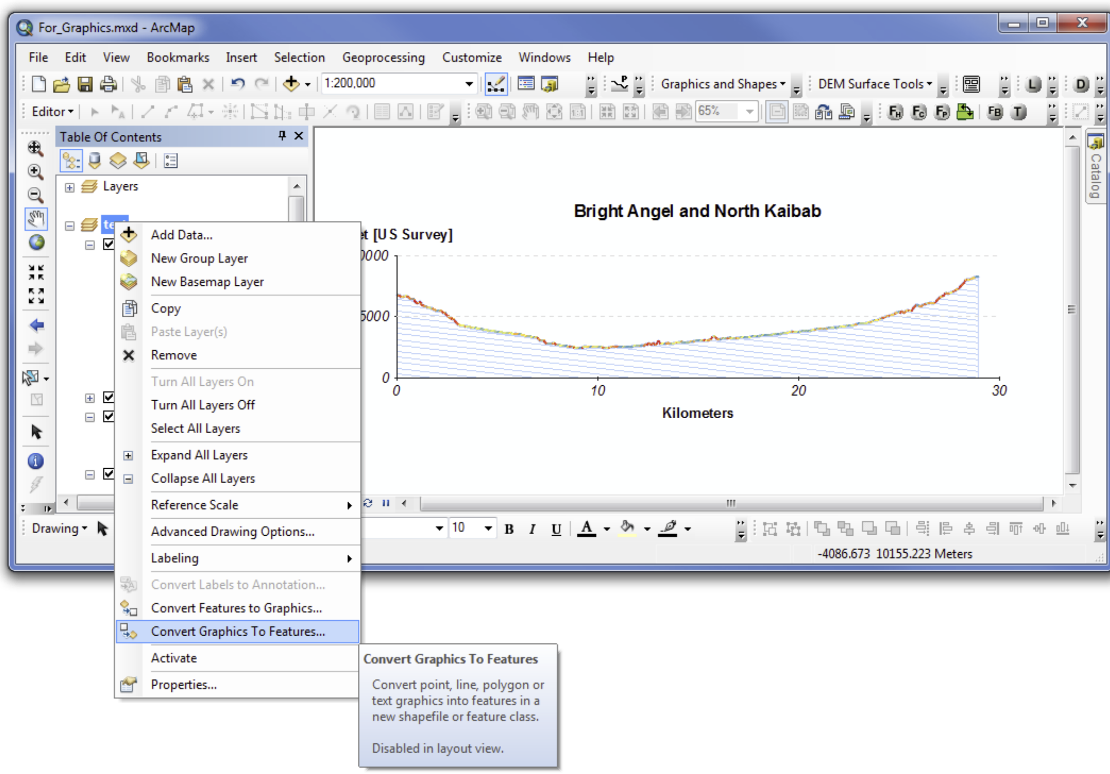
Therefore, the text elements may become aesthetically unappealing as soon as you switch to the layout.

Workaround:

Future revisions of the tool may fix this issue. In the meantime, you have two options:

1) As soon as you create the graph in the new data frame, you can convert the graphic text elements to annotation. Annotation text is much more stable than graphic text when zooming in and out or changing projections.

   Simply right-click on your new data frame and choose "Convert Graphics to Features".



2) All the feature classes in the graph have labels. You can use the standard ArcMap labeling tools to generate your own labels for the axes, tic marks and internal graph elements (geologic polygon and strike/dip intersections). The ArcMap labeling functions

(especially using the Maplex label engine) may work better at placing graph labels than this extension anyway.

Incorrect Elevations if route does not lie completely within DEM:

Currently this tool interprets null DEM values to be a very large negative number. Therefore if the route goes off the edge of a DEM, goes through a hole in the DEM or otherwise goes over null cells, then the elevation at those points may be interpreted to be something odd and unreasonable like -3280800 or -99999.

Workaround:

Currently the only workaround is to use a new DEM raster that completely encompasses the route(s).

Planetocentric vs. Planetographic Coordinate Systems

This tool is designed to assist in the analysis of the surface of non-terrestrial sites, such as other planets, the Earth's moon, or the moons of other planets. The shapes of these large objects are often modeled with an oblate ellipsoid (similar to a sphere, but squashed vertically around the axis of rotation). All well and good, but we run into an issue with how latitude is defined on Earth vs. other planetary objects.

Latitudes on Earth are generally reported in **geodetic** coordinates, while latitudes on non-terrestrial objects are generally reported in **geocentric** coordinates (*not* to be confused with the "geocentric model of the universe", where everything rotates around the Earth. In fact, the concept would be more accurately referred to as **planetocentric** coordinates, which are explained on p. 135).

This tool would be marginally more accurate if it converted all planetocentric latitude/longitude values to planetographic before analysis, since the distance and direction functions assume planetographic coordinates. However, the author of this tool has not figured out a way to determine automatically whether a given coordinate system is based on a planetographic vs. a planetocentric datum. Therefore, the only way to guarantee that these conversions are made is to require the user to specify whether each input dataset comes from a planetographic vs. planetocentric coordinate system, which has the potential to cause much more confusion that it would solve.

With regards to the actual profile charts, any planetographic vs. planetocentric error is likely to be so small as to be unnoticeable. Also, if the underlying datum is a **sphere** rather than an oblate ellipsoid, then there will be no error because planetographic and planetocentric coordinates are the same in this case.

If users desire that this tool **should** correctly transform between planetographic and planetocentric coordinates, then please contact the author at jeffj@jennessent.com and let's discuss. There are internal functions in the code that can make this conversion, so the only issue is how to specify that the conversion is needed. Maybe we can come up with a creative way to let the tool know.

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Revisions

Version 1.0.808 (June 14, 2016):

- Initial Release

Version 1.0.858 (June 23, 2016):

- Fixed error in which the output graph composed of feature classes would have the options for specifying vertical and horizontal guide lines reversed. For example, if the user wanted lines drawn horizontally across the graph at each Y-axis tic mark, but did not want vertical lines drawn at each X-axis tic mark, then the "Export Graph to Data Frame" would switch these and only draw vertical lines.
- Updates to Manual.
- Fixed an error in which the graphing functions would crash if there was no change in elevation at all over the course of the line.
- Cosmetic changes to various dialogs.
- Modified "Export to Data Frame" functions to force ArcMap to switch to data view before adding text elements.
- Fixed a scaling issue in the preview graph windows that showed an incorrect exaggeration under certain circumstances.
- Fixed a bug that would crash the Preview Options window if maximum values were set < minimum values.
- Fixed error in Strike/Dip output feature classes in which the Strike/Dip ID value was not properly added if the user did not specify an ID values, which in turned crashed the symbolization code.
- Fixed error in Strike/Dip analysis that would crash the tool if no route vertexes had elevations (i.e. if the route polyline completely missed the DEM raster).

Appendices

Appendix A: Concerning Projections and Datums

All tools analyze multiple datasets, and therefore must accommodate the possibility that those datasets may be mapped in different projections and/or datums. The tool takes a few strategies to maximize accuracy given different coordinate systems.

1) All measures of distance and direction along the route are calculated using spheroidal geometry based on Vincenty's equations for calculations on the spheroid (Vincenty 1975) with minor algebraic modifications by Veness (Veness 2015*a*). Therefore all vector data are projected into geographic (Latitude/Longitude) coordinates before analysis.

2) The exception to this rule regards the extraction of elevation values from the DEM. Projecting rasters always introduces error, so this tool will avoid that issue by always projecting the elevation sampling locations into the DEM spatial reference rather than vice versa.

3) Details regarding specific tools:

    a) The *Elevation Profile of Polyline* tool  does the following:

        i) Sample points are extracted from the Track/Route features at every vertex and at a regular interval, depending on user preferences.

        ii) These sample points are projected into the DEM coordinate system.

        iii) DEM values are interpolated using bilinear interpolation (see p. 106), and the elevation values are saved with the original unprojected vertex.

    b) The *Cross Sections* tool  does the following:

        i) Track/Route features are projected into the Geology polygon feature class coordinate system, and used to select all intersecting geologic features.

        ii) Track/Route features are intersected with geology polygons to find intersection points along the track. These intersection points are saved as proportion values along the route (i.e. the projected track may intersect a polygon at two points, and these points lie at 50% and 75% along the length of the route). Rather than project the intersection points back into the original track/route coordinate system, the tool just generates new sample points at 50% and 75% along the original feature.

        iii) These polygon intersection points, plus all track/route vertices and points along a regular interval, are then projected into the DEM coordinate system to get the elevation values.

    c) The *Cross Sections with Strike/Dip Lines* tool  does the following:

        i) Track/Route features are projected into the Geology polygon feature class coordinate system as described above.

        ii) Strike/Dip points are projected into the Track/Route feature class coordinate system before any analysis is done.

iii) All intersection points derived from strike/dip planes, geology polygon intersections, track/route vertices and regular intervals, are projected into the DEM coordinate system before interpolating elevation values.

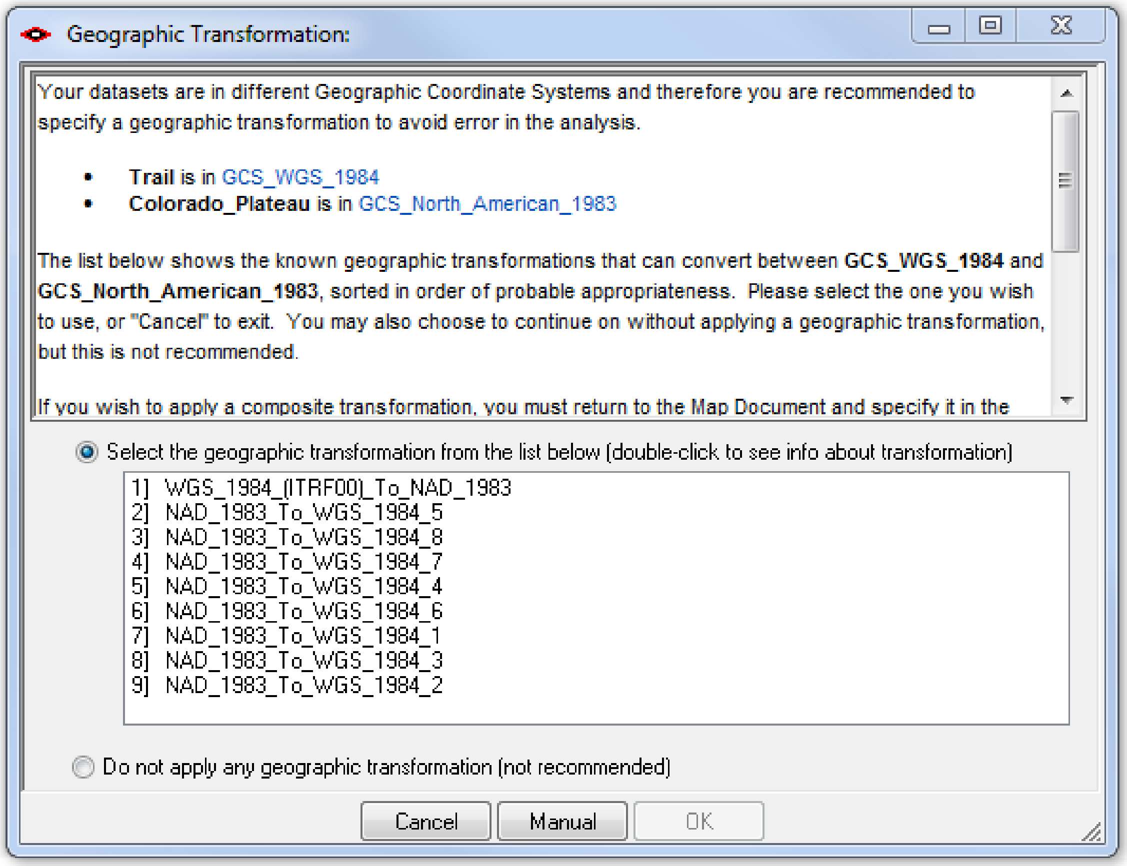
4) All necessary projections between coordinate systems *in the same datum* are handled internally by the tool and do not require inputs from the user. **However**, if the datasets are in different datums, then the tool **might** need to get additional information from the user.

   There are often multiple ways to convert between datums and ArcMap does not automatically know which geotransformation method is best. However, ArcMap will often alert the user if datasets from different datums are loaded into the same map and give the user the opportunity to specify the correct geotransformation. **If** the datasets are mapped in different datums, and **if** the user has specified a geotransformation in the Layer Properties, then this tool will use that geotransformation when projecting datasets.

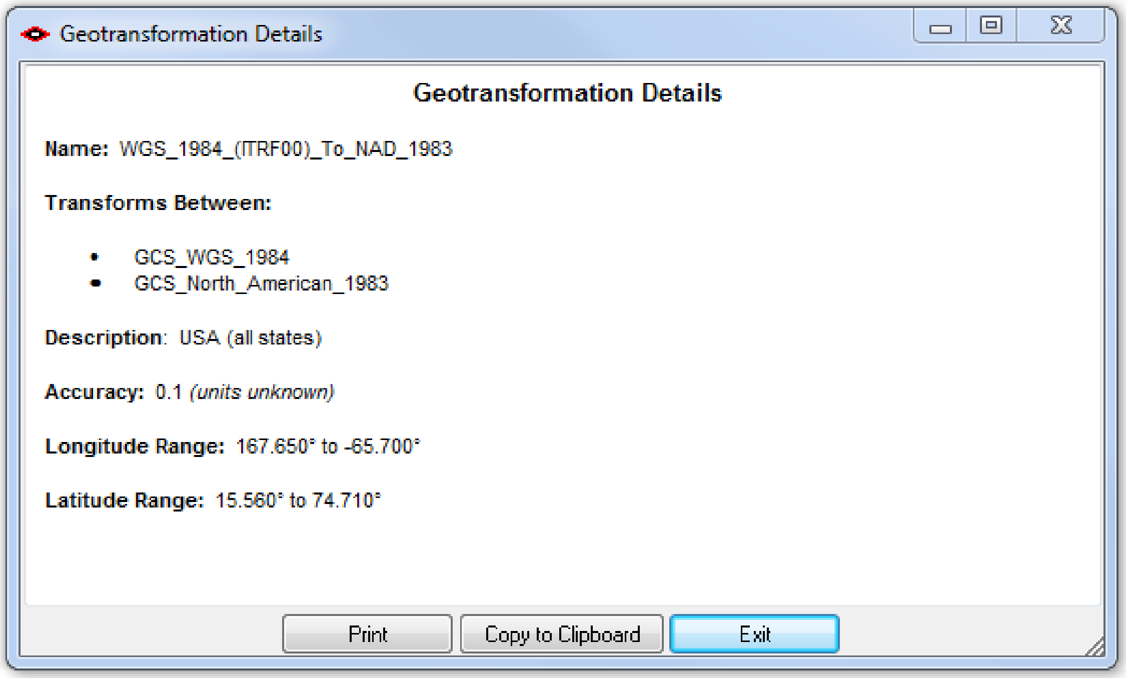
   On the other hand, if the datasets are in different datums and ArcMap **can't** find an appropriate geotransformation in the Layer Properties, then the tool will ask you to specify the correct transformation before proceeding.

   This tool will look through the current database of transformations and identify which ones are designed to transform between the dataset datums. If the tool can find information on known accuracy of those transformations, and what region they are designed for, then this tool will sort them based on these two factors.

   If the tool is able to find appropriate transformations, then it will show you the sorted list in the dialog below and ask you to select the one you wish to use.



Naturally the geotransformation names are often obscure and provide little guidance to selection. If you want to know what information the tool was able to find on the geotransformation, then you may double-click on any of the items in the list to see details.



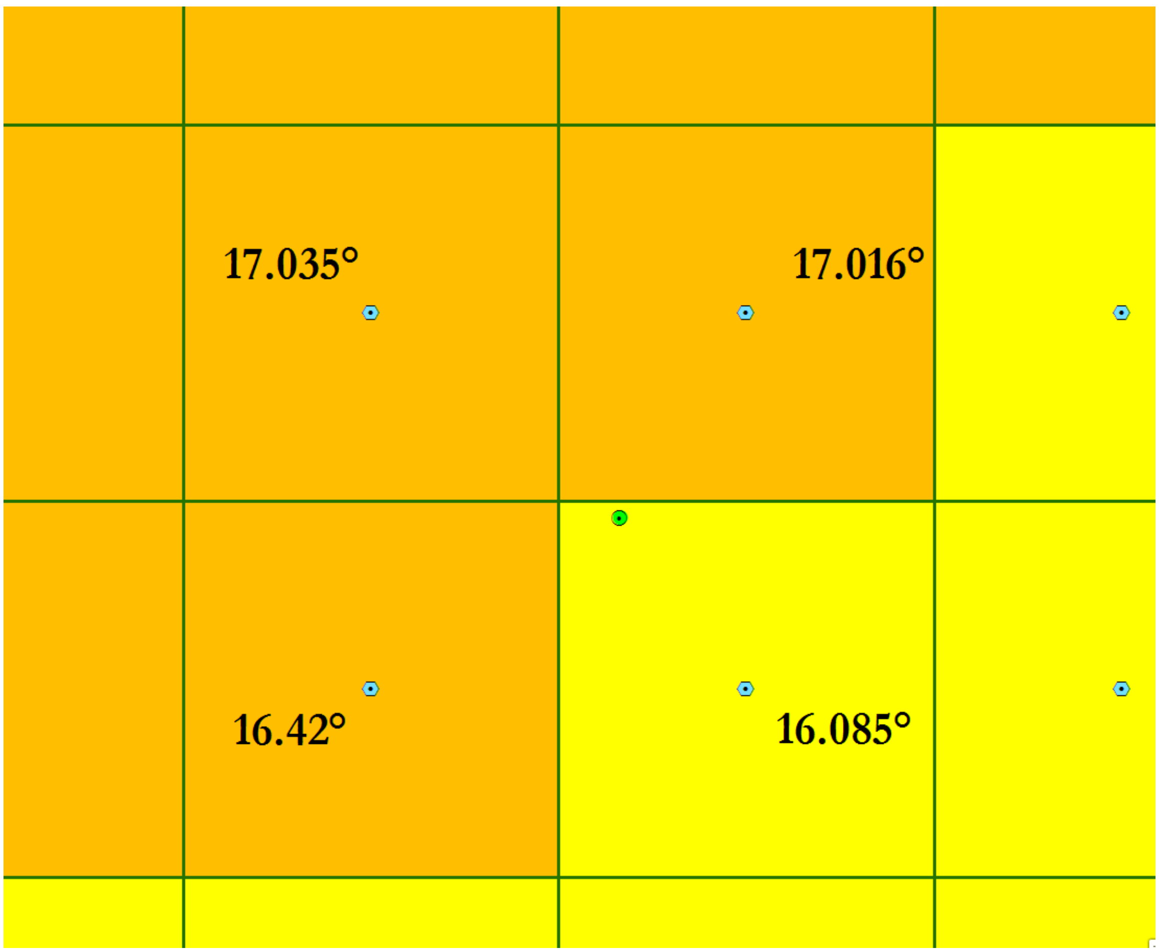
You may also choose to continue on without applying a geographic transformation, but this is not recommended.

If you wish to apply a composite transformation, you must return to the Map Document and specify it in the data frame properties.

Appendix B: Concerning Bilinear Interpolation

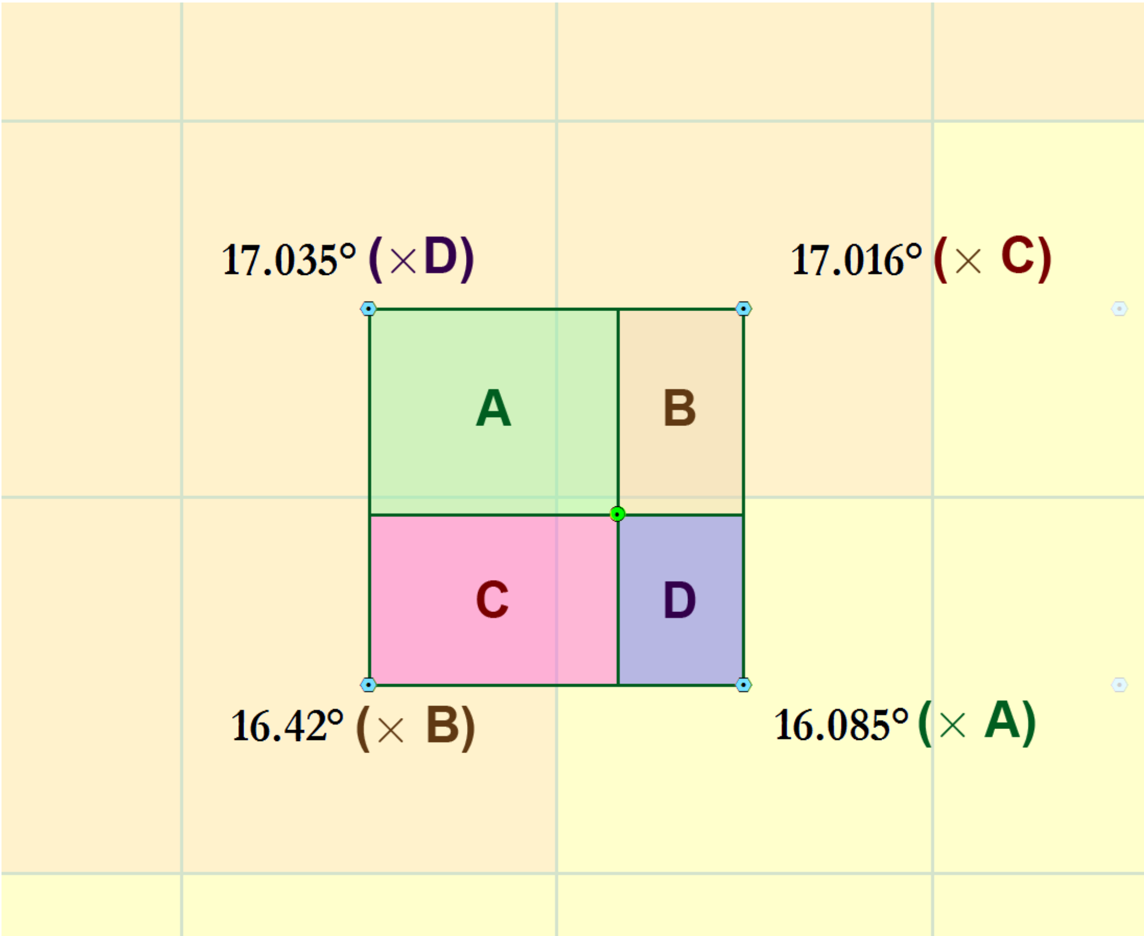
Bilinear Interpolation as a method of estimating the value at a point based on a weighted average of the 4 closest raster cells in a 2 × 2 neighborhood around that point. It is a good way to take advantage of information from the local neighborhood of cells in a continuous raster (continuous in the sense that the data are not categorical, like vegetation type or land ownership, but rather follow a continuous distribution like slope or elevation). It generally gives you a better estimate of the actual value at that point on the landscape than taking the exact value at the intersecting cell.

For example, suppose we have a *Slope* raster with cell values as illustrated below. We want to interpolate the slope at the green point in the middle:



If we took the exact value at this cell, we would say the slope at the green point is 16.085°. However, it seems reasonable to assume that the slope at our point is probably influenced by the slopes at all 4 of these cells. Therefore we would like to take some sort of weighted average of these four slope values.

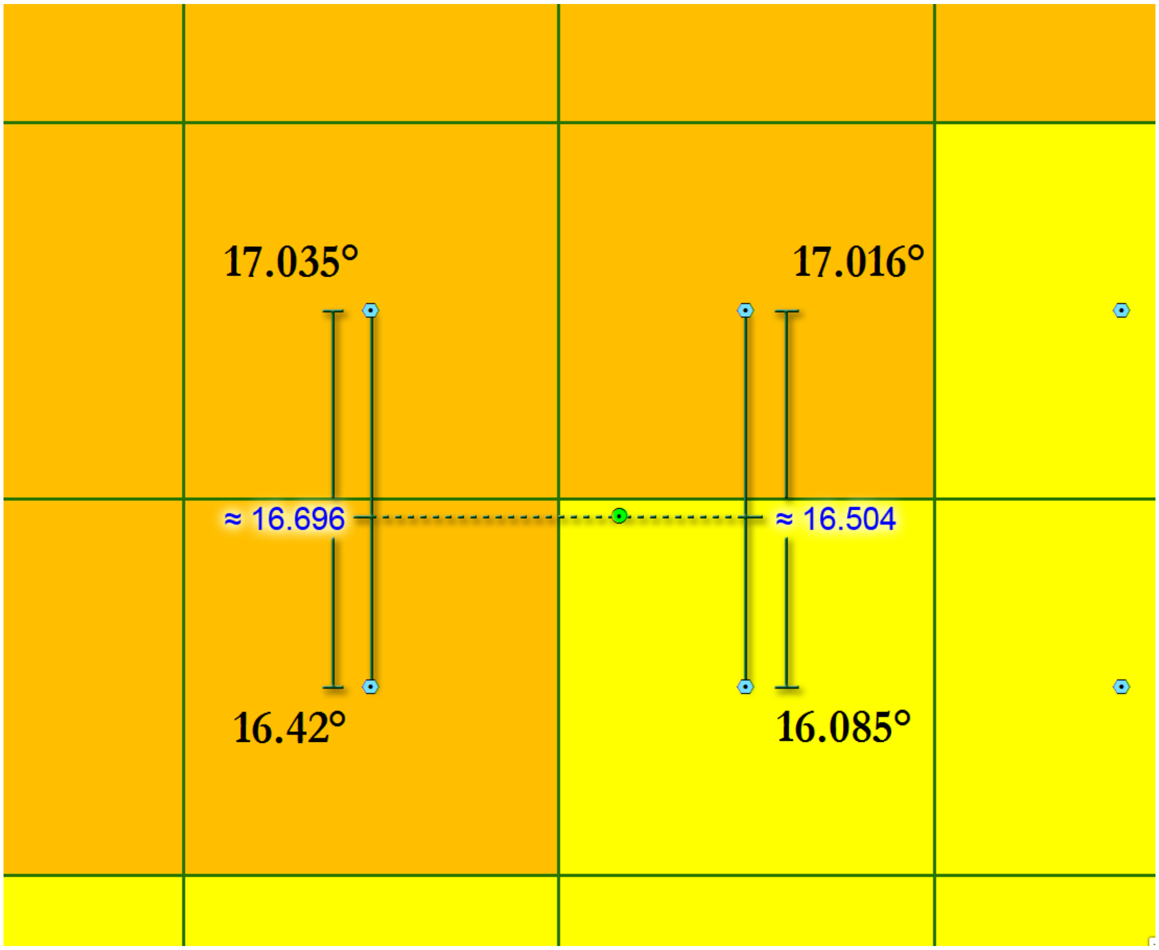
Bilinear interpolation weights the 4 values using the following strategy:



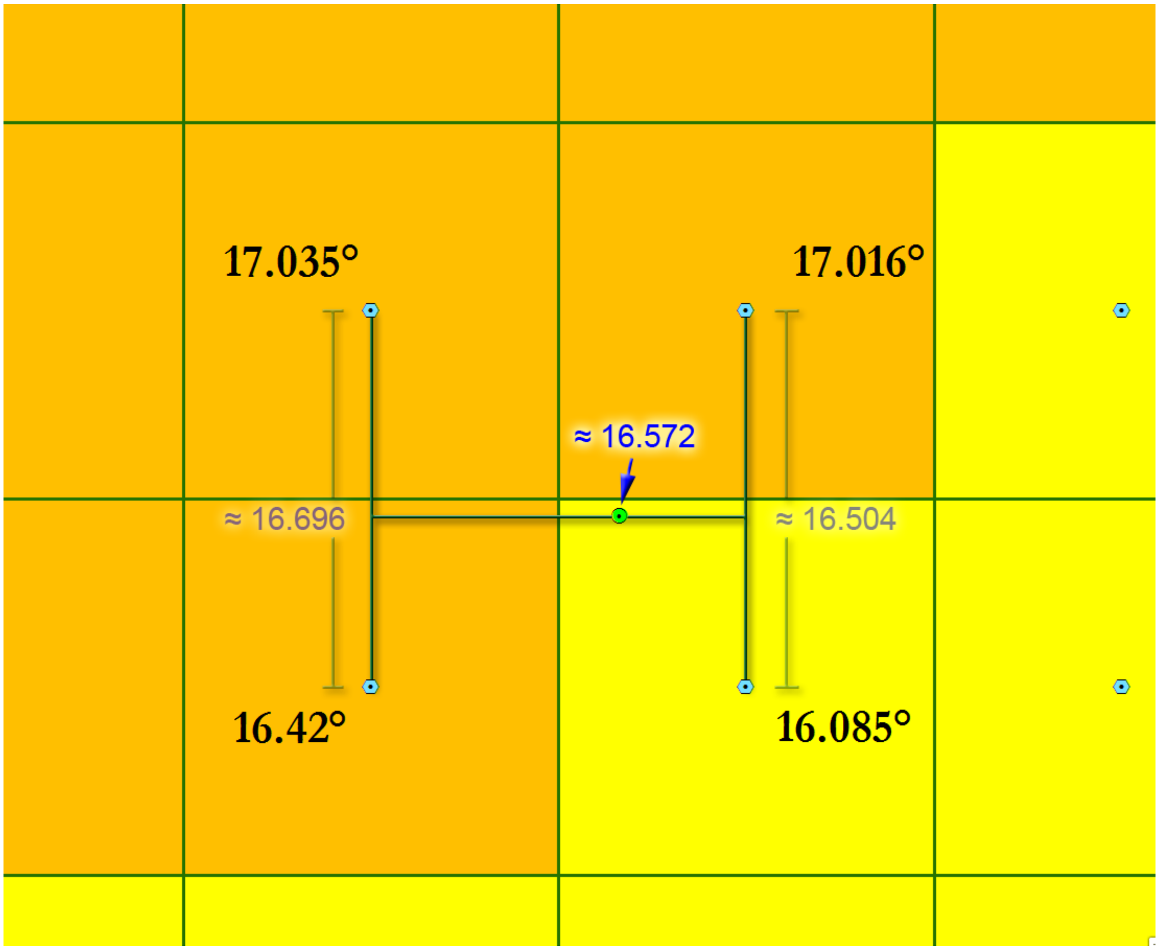
Draw lines connecting each cell center, then draw lines vertically and horizontally over our point. This splits the region into 4 quadrants. Each cell value is weighted by the area of the opposite quadrant.

For example, the point is actually in the lower right cell, and therefore we would expect that value (16.085°) to be weighted the highest. The quadrant opposite this cell (labeled "A" in the image above) is the largest quadrant. Therefore the value 16.085° is weighted by the area of Quadrant A. The lower left cell (16.42°) is weighted by the area of Quadrant B, the upper right cell is weighted by the area of Quadrant C, and the upper left corner is weighted by the area of Quadrant D.

This method is name "Bilinear" interpolation because mathematically the value is interpolated along two lines. For example, we first interpolate two values along the vertical axes connecting the two cells on the right and the two cells on the left:



We then interpolate horizontally between our two new points to get the value at our point in question:



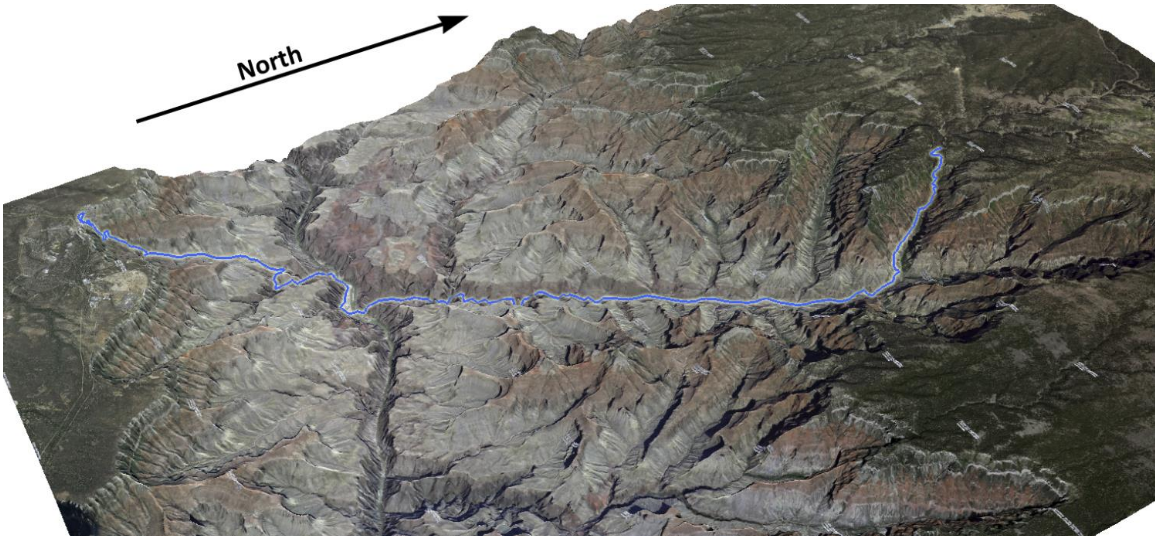
It doesn't actually matter which axes you start with. We could have initially interpolated horizontally, and then vertically, and we would have come up with the same value.

Appendix C: Strike/Dip Planes

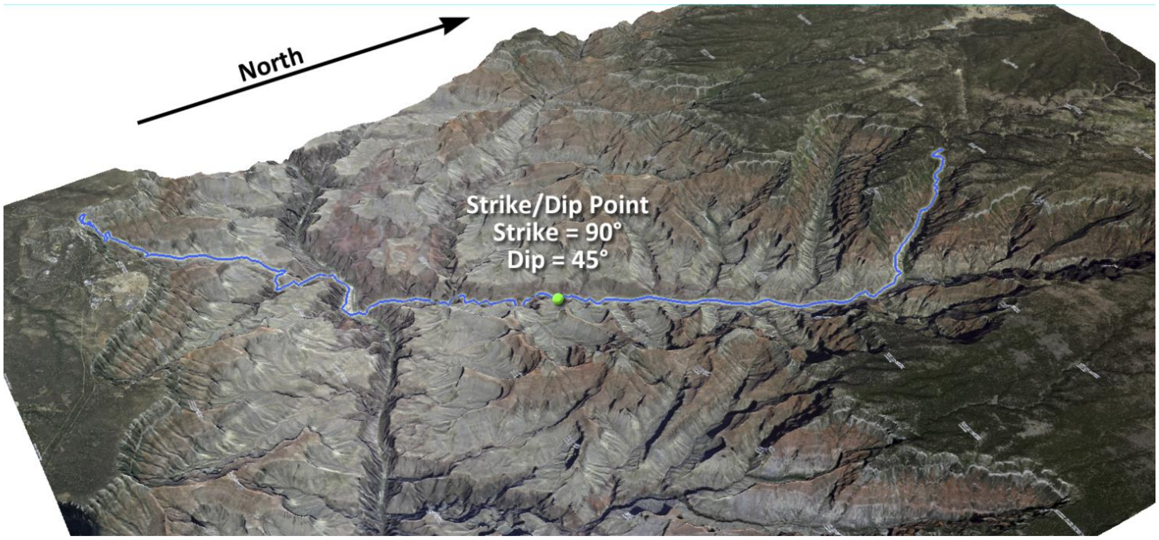
Estimating Strike/Dip Planes:

This tool creates a strike/dip plane for each strike/dip point, and then calculates the elevation of that strike/dip plane at every sample point along the route.

For example, consider our trail across the Grand Canyon:

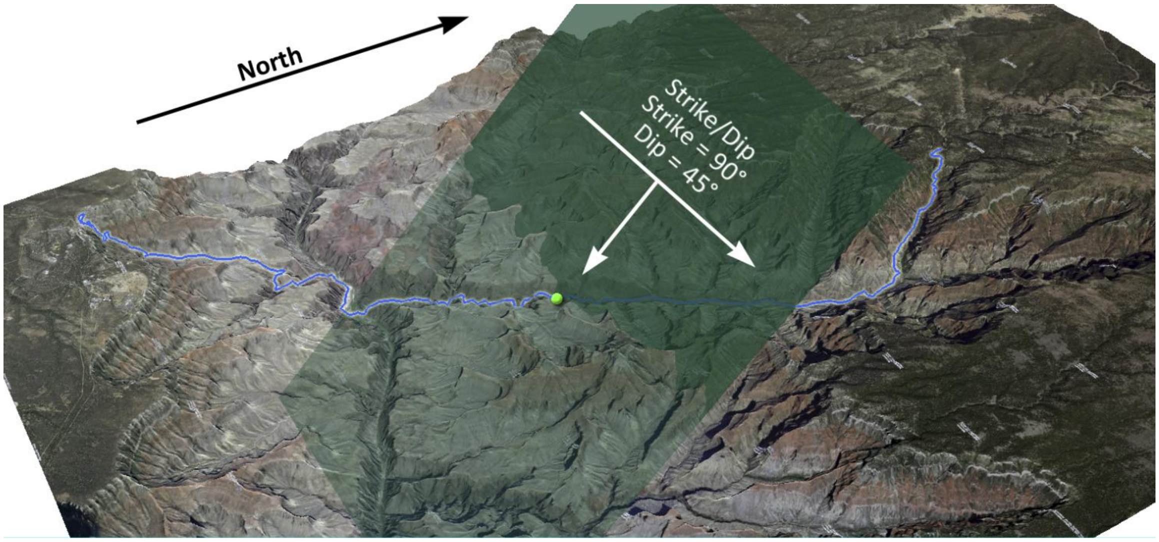


Suppose that a geologic extrusion is observed near the trail, with a dip angle of 45° and a strike direction of 90°:

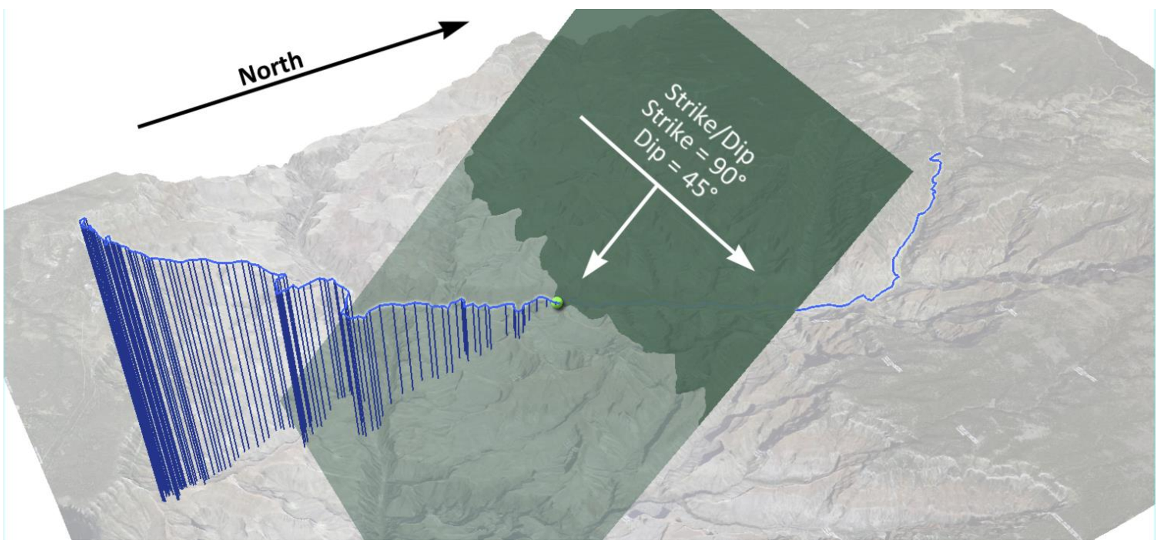


This tool understands the strike and dip directions to follow the **American Right-Hand Rule** (Jorge 2009, Rocscience 2016), in which "Strike" means the compass direction of the geologic feature as it intersects the ground surface, such that it slopes down at 90° to the right of that direction. "Dip" means the angle, in degrees, that it slopes downward.

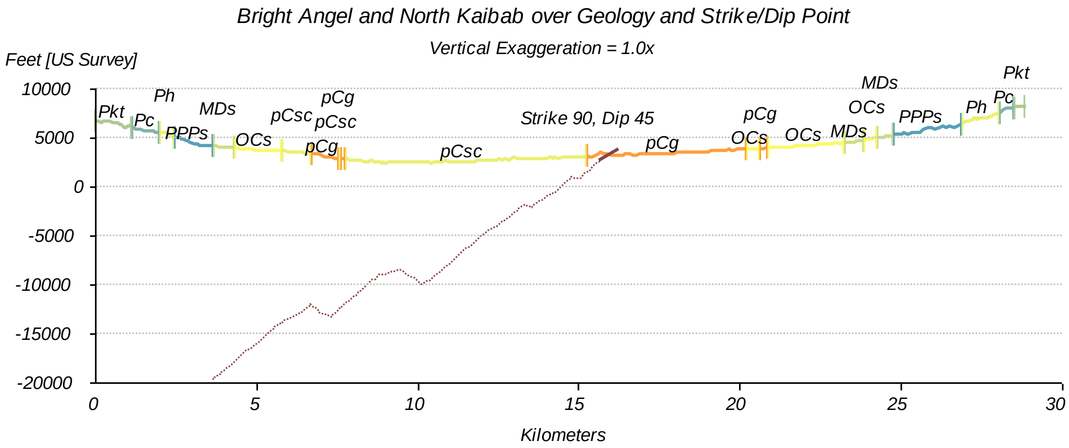
Given this definition, this tool will generate 3-dimensional strike/dip plane that intersects the surface at the given point. In this case, the tool has a strike angle of 90° (due east), which means that it slopes down at 180° (due south). The dip angle is 45°, so we can image the strike/dip plane to intersect the Grand Canyon like this:



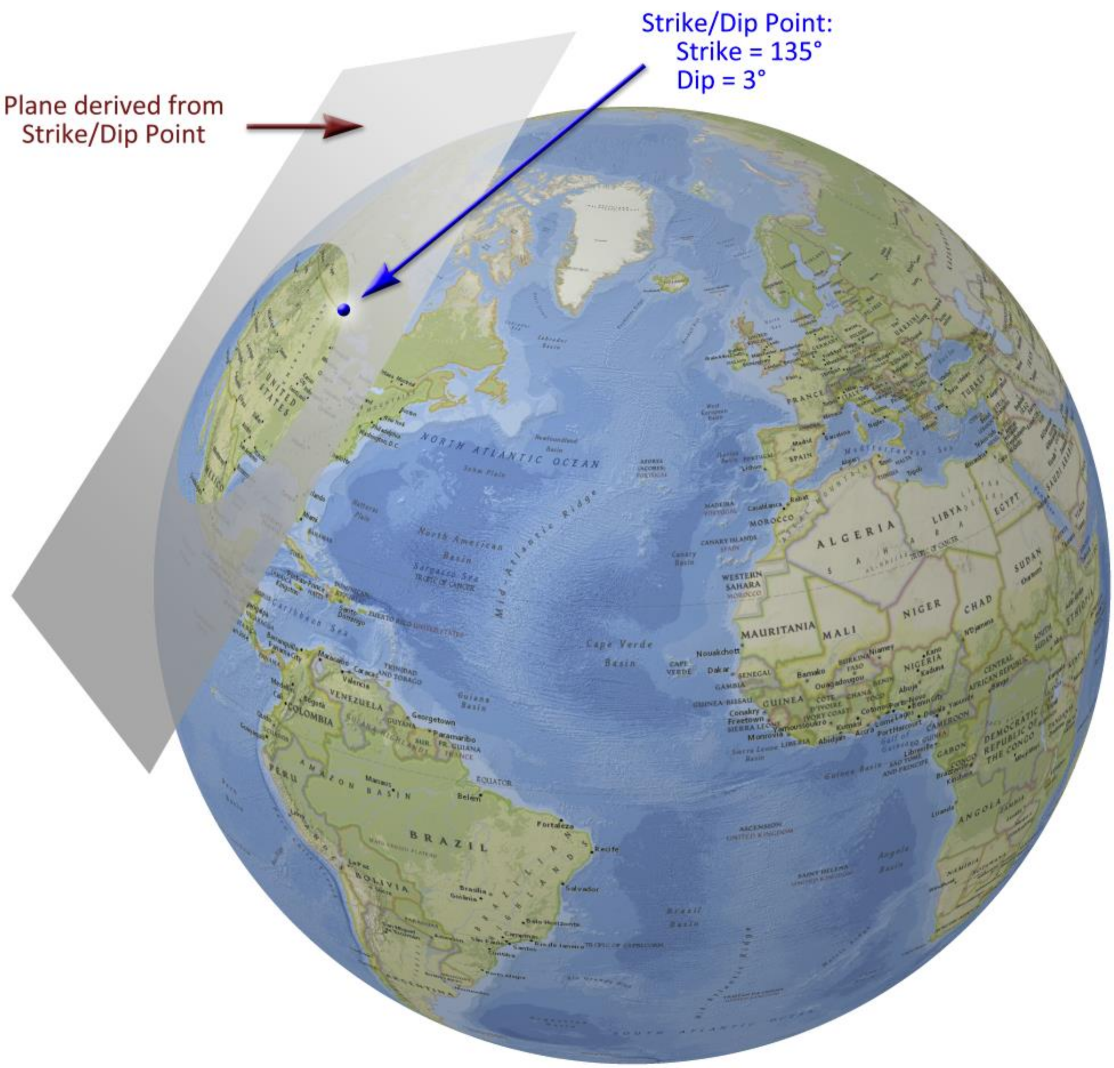
The tool then calculates the elevation of both the trail and the strike/dip plane at every sample point along the trail:



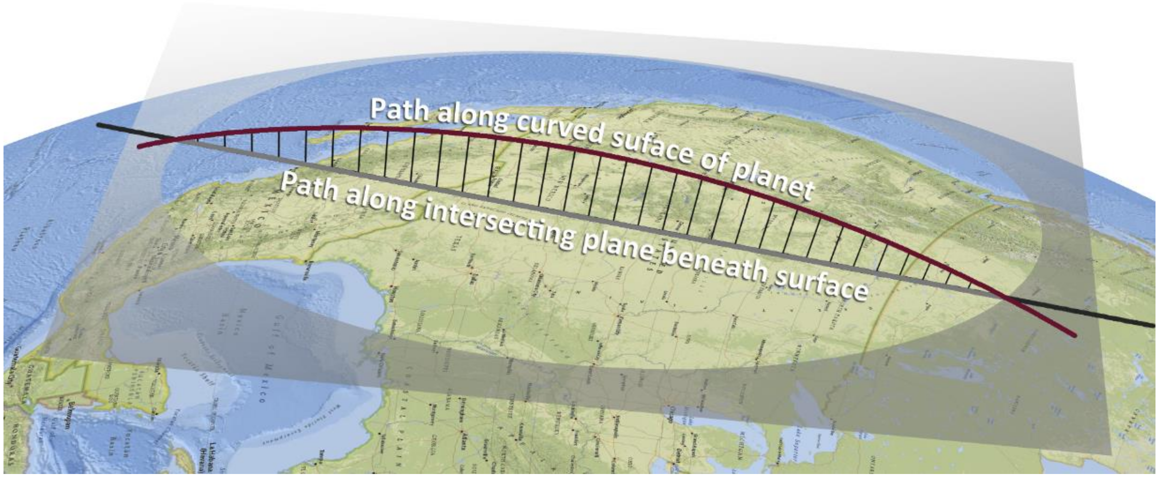
The tool then generates a chart that shows the relative depth to the strike/dip plane at every point along the route:



Because we are intersecting a plane with the curved surface of the planet, the plane will not follow the same dip angle relative to the surface. For example, if the plane dips beneath the surface at 45°, then the angle relative to the surface will immediately begin to decrease, and continue to decrease as the planet curves above it. Eventually the plane will exit the planet at the same angle it entered it.



If you graph a line that goes completely across the intersecting ellipsoidal cap, then the strike/dip line will dip beneath the surface at the expected angle, but then curve back up and exit the surface at the same angle.



<u>**Generating a Plane from Lat/Long Coordinates:**</u>

This tool works entirely from Latitude and Longitude coordinates, which necessitates a slightly more complicated method to generate the strike/dip plane than it would if the data were projected and we could assume the surface of the planet was truly flat. Recall that Latitude and Longitude are polar measures on a spheroid rather than linear measures in a Cartesian system.

We start with a latitude, longitude, strike angle and dip angle. We want to define a plane from these 4 values. This tool defines the plane from three 3D points using methods described by Dawkins (Dawkins 2016*a*).

Given that we are starting with lat/long, strike and dip, it is fairly easy to define 3 points that we know will be on the plane, then use those three points to actually define the plane in 3D Cartesian space.

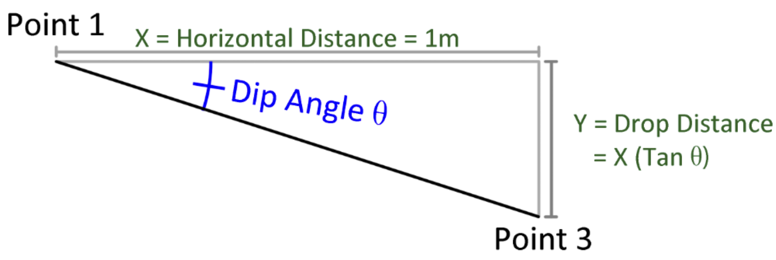
Point 1 will be the Lat/Long value, at the current elevation + the distance from the spheroid to spheroid origin at that lat/long location.

Point 2 will be located at [Strike Angle]° from Point 1, at some arbitrary distance (I'm using 1m, but the results come out the same for other distances). The elevation of Point 2 will be the same elevation as Point 1, plus the distance from the spheroid to spheroid origin at Point 2's lat/long location.

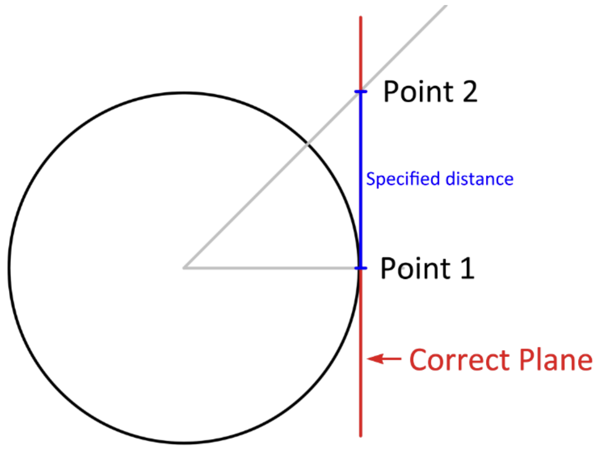
Point 3 will be located at [Strike Angle + 90 (i.e. the angle of the dip direction)]° from Point 1, again at some arbitrary distance. Based on the definition of Tangent on a right triangle:

$$\text{Tan}\,\theta = \frac{\text{Length of Opposite Edge (what we're after)}}{\text{Length of Adjacent Edge (horizontal distance)}}$$

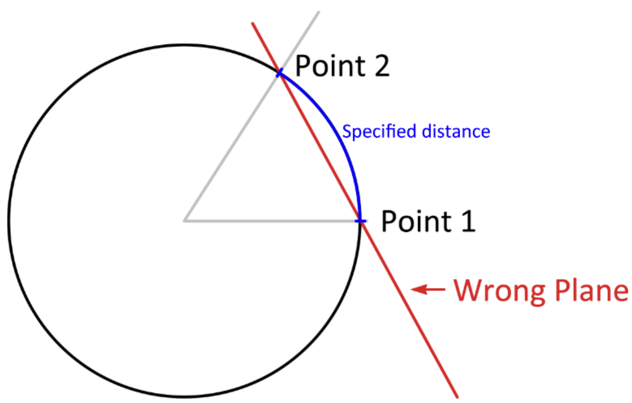
The elevation of Point 3 is therefore calculated as the elevation at Point 1 minus the [tangent of the dip angle] × [Horizontal Distance]:



The actual Lat/Long coordinates, and elevations at those coordinates, of the two new points are tricky to calculate because our functions that determine new coordinates based on a distance and bearing from a source location assume that we are traveling over the curved surface of a spheroid. In other words, if we want a point **on the plane** that is X distance from our source point, at a particular bearing, then we want Point 2 on the illustration below:



Unfortunately our functions take us our specified distance over the spheroid, and therefore give us this:

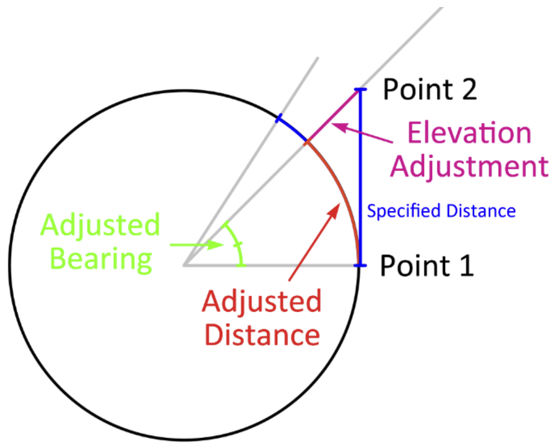


This issue applies to both Point 2 (along strike direction at same elevation as strike/dip point) and Point 3 (along dip direction, at lower elevation than strike/dip point).

We have two options:

Option 1: We could convert the origin point to 3D Cartesian space first, and then generate the other two points based on distances and bearings in 3D Cartesian space. This is complicated because the original strike and dip angles are based on spheroid surface at a particular latitude and longitude coordinate, and would therefore need to be rotated and transformed into 3D Cartesian space. There might be an easy way to do this but it was not immediate apparent to the author of this tool.

Option 2: We could adjust the latitude, longitude and elevation of Points 2 and 3 by applying some basic trig functions on the geographic coordinate system sphere. The author chose this method.



We calculate the **adjusted bearing** using the definition of the tangent (where Point 2 will be located on the tangent line, and therefore elevated off the surface of the planet some small amount):

$$\text{Tan}\,\theta = \frac{\text{Specified Distance}}{\text{Radius}}$$

$$\theta = \arctan\left(\frac{\text{Specified Distance}}{\text{Radius}}\right)$$

From the adjusted bearing, we can calculate the correct shift distance (**adjusted distance**) to move over the curved surface of the spheroid to find the vector that will intersect our desired plane at exactly the specified distance from the origin point.

$$\text{Adjusted Distance} = \theta r$$

where:

$$\theta = \text{Adjusted Bearing}$$

$$r = \text{Sphere Radius}$$

Note that this method uses the radius of a **sphere** rather than the radius at that point of a **spheroid**. This is the sphere that has the same volume as the data spheroid. These functions will be slightly inaccurate if the geographic spatial reference is based on an oblate ellipsoid rather than a sphere. However, given that the primary use of these tools will be for data in sphere-based coordinate systems (such as GCS_Mars_2000_Sphere), the author used these simple functions to adjust the plane points rather than try to figure out the elliptic integral method necessary to calculate over the ellipsoid.

Finally, we adjust the elevation at the new point by calculating the distance from the origin to the new point, and subtracting that from the radius. The distance from the origin to the new point is calculated using the Pythagorean Theorem.

$$\text{Adjusted Elevation} = \sqrt{(\text{Radius})^2 + (\text{Specified Distance})^2} - \text{Radius}$$

So now we have 3 points that we know are on the correct plane, and we know their locations in terms of Latitude, Longitude and Elevation. We also know the dimensions of the sphere or oblate ellipsoid the coordinates are mapped onto.

The plane itself is not defined by Latitude and Longitude, but rather by a 3-dimensional Cartesian coordinate system centered at the ellipsoid centroid. Based on methods described by Iliffe (2000), we convert our 3 points into 3-dimensional Cartesian coordinates (see also p. 129).

The basic strategy for converting these three points to a plane is as follows (see (Dawkins 2016*a*):

1) Generate two vectors along this plane. We can use our 3 points to do this by calculating vectors from one point to the other two. A vector between two points can be obtained by simply subtracting the coordinates of the head point from the coordinates of the tail point (see (Dawkins 2016*b*).

$$\text{Point A} = (x_1, y_1, z_1)$$
$$\text{Point B} = (x_2, y_2, z_2)$$
$$\text{Point C} = (x_3, y_3, z_3)$$
$$\overrightarrow{AB} = (x_2 - x_1, y_2 - y_1, z_2 - z_1)$$
$$\overrightarrow{AC} = (x_3 - x_1, y_3 - y_1, z_3 - z_1)$$

2) Calculate the cross product of these two vectors, which gives us the vector that is orthogonal to these two vectors. The formula for the cross product of two 3D vectors is from p. 339 of Meyer (2000).

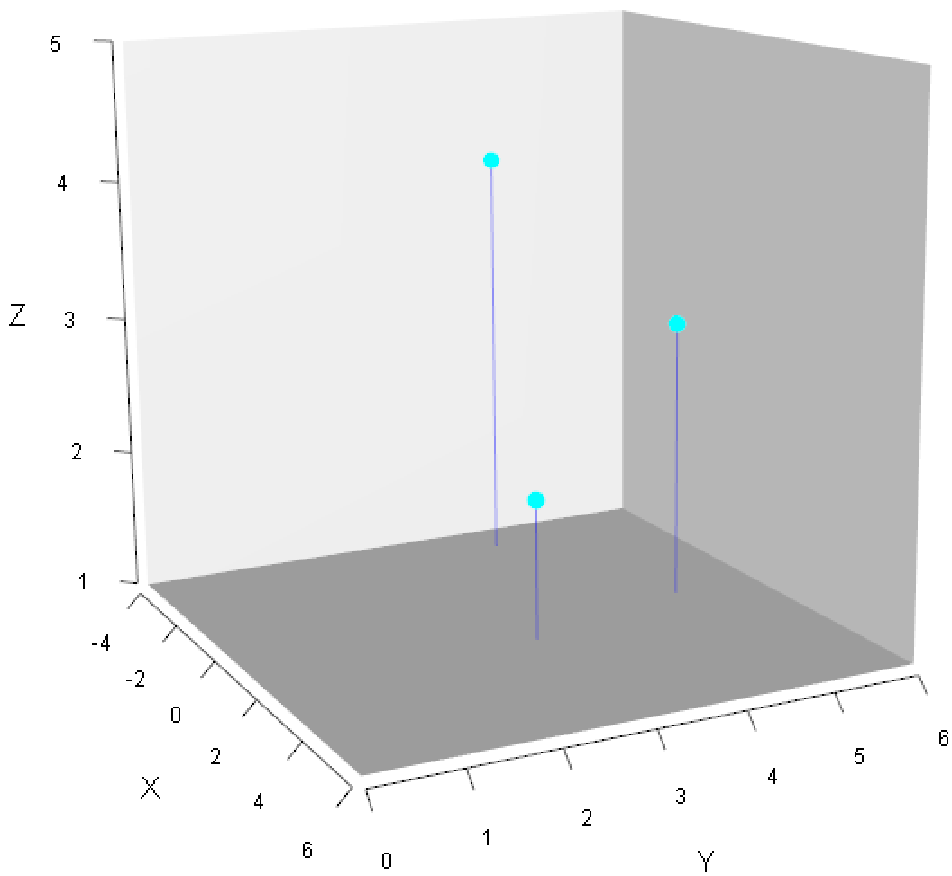
$$\overrightarrow{AB} = (x_1, y_1, z_1)$$
$$\overrightarrow{AC} = (x_2, y_2, z_2)$$
$$\overrightarrow{AB} \times \overrightarrow{AC} = ([y_1z_2 - y_2z_1], [x_1z_2 - x_2z_1], [x_1y_2 - x_2y_1])$$

3) The equation of the plane filled out as follows (Dawkins 2016*a*):

$$\text{Equation of the Plane:}$$
$$ax + by + cz = d$$
$$where:$$
$$(a,b,c) = \overrightarrow{AB} \times \overrightarrow{AC}$$
$$\text{Given a point on the plane}: (x,y,z)$$
$$d = (a \cdot x) + (b \cdot y) + (c \cdot z)$$

4) For example, suppose we had 3 points:

$$P_1 = (2,3,2) \qquad P_2 = (1,5,3) \qquad P_1 = (-3,4,4)$$



Assuming the points are not collinear (and ours won't be, since we derived them from strike and dip angles which are perpendicular to each other), then we can generate our two vectors over the plane as follows:

$$\overrightarrow{P_1P_2} = (1-2, 5-3, 3-2) = (-1, 2, 1)$$
$$\overrightarrow{P_1P_3} = (-3-2, 4-3, 4-2) = (-5, 1, 2)$$

Parameters A, B and C of the equation for the plane are calculated from the cross product of these two vectors:

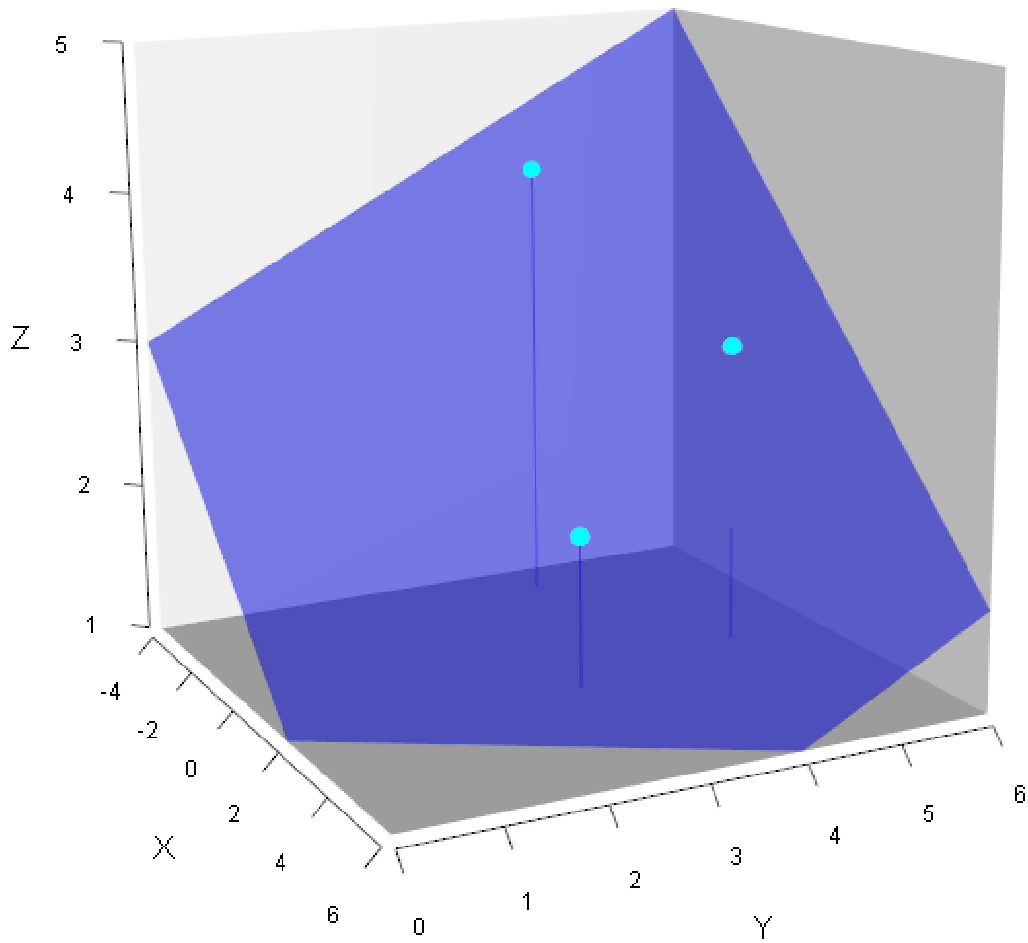
$$\overrightarrow{P_1P_2} = (1-2, 5-3, 3-2) = (-1, 2, 1)$$
$$\overrightarrow{P_1P_3} = (-3-2, 4-3, 4-2) = (-5, 1, 2)$$
$$\overrightarrow{P_1P_2} \times \overrightarrow{P_1P_3} = ([(2\cdot 2)-(1\cdot 1)], [(1\cdot -5)-(2\cdot -1)], [(-1\cdot 1)-(-5\cdot 2)])$$
$$= (3, -3, 9)$$

Parameter D is obtained by multiplying A, B and C by the coordinates of any point on the plane. Here I use Point 1, but note that parameter D would come out the same for Points 2 and 3:

$$\text{Given a point on the plane} : (x, y, z)$$
$$(a, b, c) = \overrightarrow{P_1P_2} \times \overrightarrow{P_1P_3} = (3, -3, 9)$$
$$d = (a \cdot x) + (b \cdot y) + (c \cdot z)$$
$$\text{Point } 1 = (2, 3, 2)$$
$$\text{Therefore } d = 6 - 9 + 18 = 15$$

Therefore the equation of the plane given these three points is:

$$\text{Equation of Plane: } ax + by + cz = d$$
$$2x - 3y + 9z = 15$$
$$or:$$
$$2x - 3y + 9z - 15 = 0$$



Calculating the Elevation of a Plane at a Point

The elevation of the plane at a point requires a few steps:

1) First the lat/long point must be converted to a 3D Cartesian Vector (see p. 129). This vector starts at the ellipsoid centroid and extends to the ellipsoid surface at the specified latitude and longitude. The "elevation" of this point at the ellipsoid surface is calculated as the magnitude of the vector (i.e. the length) at those lat/long coordinates on the ellipsoid.

2) Next, the vector is intersected with the strike/dip plane (see (Auroux 2007, Mitra 2012). The intersection of a vector and a plane produces a new vector that is basically clipped off at the plane.

   If the vector extending from the ellipsoid centroid to infinity does intersect the strike/dip plane at any point (and it is extremely unlikely that it will not), then that point will occur where the X, Y and Z values of the vector equal the X, Y and Z values of the plane.

   Basically, if the lat/long coordinates convert to:

$$\text{Intersecting Vector: } V = \left(v_x, v_y, v_z\right)$$

Then we want to find the value *T* where *V* scaled by *T* lies on the plane.

We solve for *T* after plugging in the X, Y and Z values of the vector (each multiplied by *T*) into the formula for the plane.

$$\text{Equation of Plane: } ax + by + cz = d$$

$$\text{Intersecting Vector: } V = \left(v_x, v_y, v_z\right)$$

Substitute X, Y and Z components of vector into Plane:

$$av_xT + bv_yT + cv_zT = d$$

Solve for T:

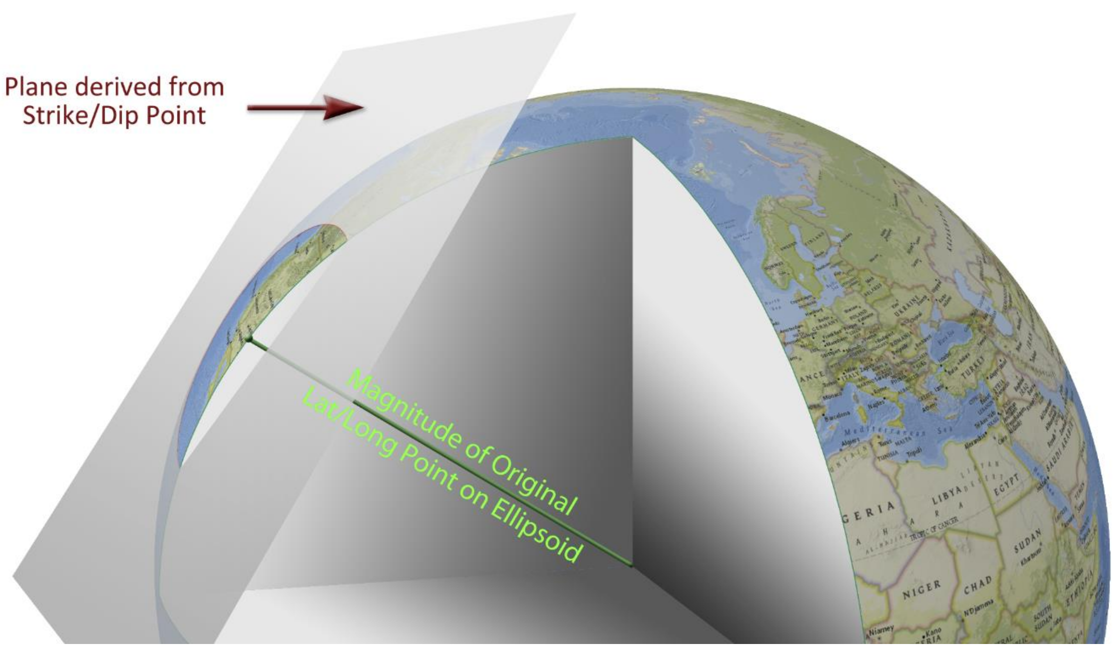
$$T = \frac{d}{av_x + bv_y + cv_z}$$

Multiply vector components by T to get intersection point:

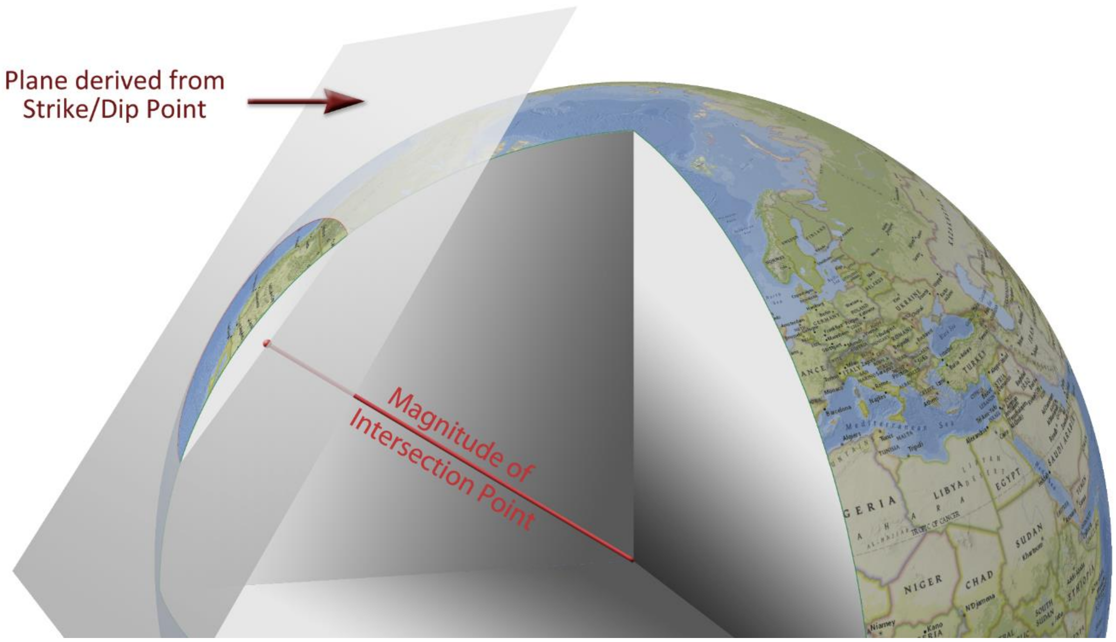
$$\text{Intersection Point: } V_1 = \left(v_xT, v_yT, v_zT\right)$$

3) The ellipsoid surface is defined as an elevation of 0. This value is also the magnitude of the original lat/long point on the ellipsoid. The elevation of this strike/dip plane intersection point is simply the magnitude of intersection vector subtracted from the magnitude of the vector that intersects the ellipsoid surface:

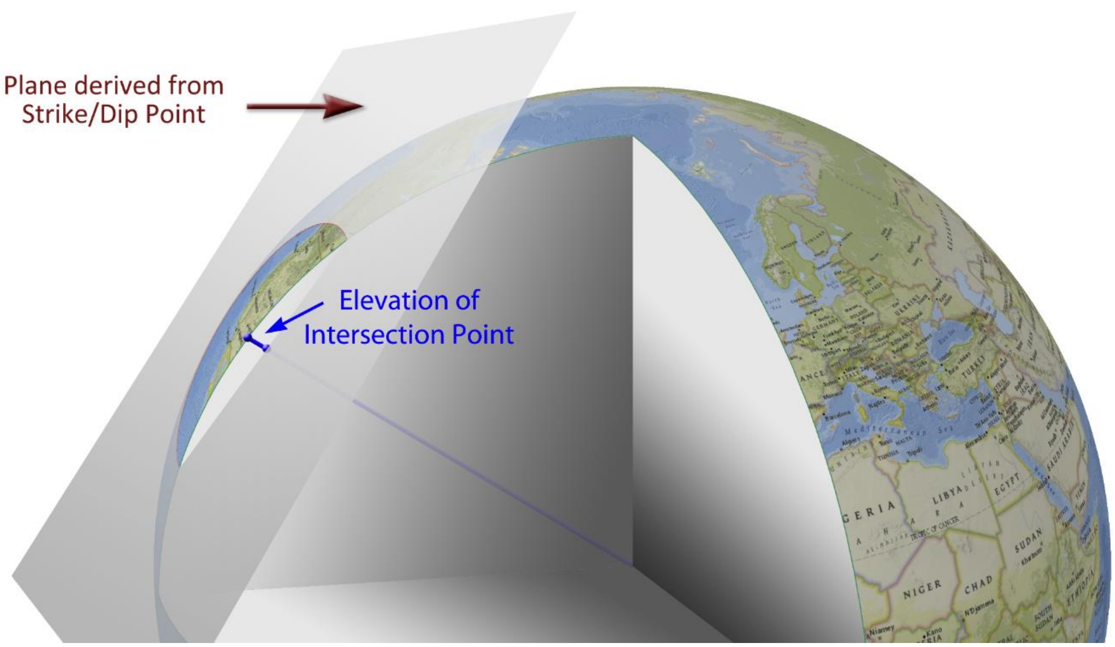
$$\text{Magnitude of original Lat/Long point on Ellipsoid} = \sqrt{{v_x}^2 + {v_y}^2 + {v_z}^2}$$



$$\text{Magnitude of Intersection Point} = \sqrt{(v_x T)^2 + (v_y T)^2 + (v_z T)^2}$$



$$\text{Elevation of Intersection Point} = \sqrt{{v_x}^2 + {v_y}^2 + {v_z}^2} - \sqrt{(v_x T)^2 + (v_y T)^2 + (v_z T)^2}$$



Appendix D: General Geometric Functions

Vincenty's equations for Calculations on the Spheroid

Thaddeus Vincenty, among many other ground-breaking achievements (Chovitz 2002) wrote some of the primary methods to calculate distances over a spheroid and to determine the location of a new point on a spheroid given an origin and initial bearing. He used an iterative approach in both cases to narrow down the error to an acceptable level. The equations below are numbered according to Vincenty's 1975 paper, with some modifications by Veness (Veness 2015*b*):

Terms used by Vincenty:

- $a, b =$ major and minor semiaxes of the ellipsoid
- $f =$ flattening $\dfrac{a-b}{a}$
- $\phi_1 =$ geodetic latitude, positive north of the equator, of first point P_1
- $\phi_2 =$ geodetic latitude, positive north of the equator, of second point P_2
- $L =$ difference in longitude, positive east
- $s =$ length of geodesic (i.e. distance between P_1 and P_2 in units of a, b)
- $\alpha_1 =$ initial azimuth of the geodesic connecting P_1 to P_2
- $\alpha_2 =$ ending azimuth of the geodesic connecting P_1 to P_2
- $\alpha =$ azimuth of the geodesic at the equator
- $u^2 = \dfrac{\cos^2\alpha\left(a^2-b^2\right)}{b^2}$
- $U_1 = \arctan(1-f)\tan\phi_1$ (i.e. reduced latitude of ϕ_1)
- $U_2 = \arctan(1-f)\tan\phi_2$ (i.e. reduced latitude of ϕ_2)
- $\sigma =$ angular distance between P_1 and P_2 on the sphere
- $\sigma_1 =$ angular distance on the sphere from the equator to P_1
- $\sigma_m =$ angular distance on the sphere from the equator to midpoint on the line
- $\lambda =$ difference in longitude on an auxiliary sphere
- $\lambda' =$ iterated estimate of λ, beginning at 2π (Veness 2015*b*)

Using Vincenty's Equations to Calculate Distance and Azimuths on a Spheroid

Vincenty gives both "Direct" and "Inverse" formulae. The "Inverse" formula is used to calculate the distance between two points on the spheroid, and the initial and final azimuths of the geodesic curve connecting those two points. Numbers on the right margin refer to Vincenty's equation numbers. **NOTE:** This extension automatically uses the WGS 84 spheroid in all spheroid-based calculations.

Do the following (**NOTE:** steps below include some minor algebraic modifications by Chris Veness which simplify the coding a bit):

Initially set $\lambda' = 2\pi$

while $\left|\lambda-\lambda'\right|>10^{-12}$ $\quad$ (Threshold suggested by Veness [2015*b*]; $\cong 0.006$ mm at equator)

$$\sin\sigma=\sqrt{\left(\cos U_2\sin\lambda\right)^2+\left(\cos U_1\sin U_2-\sin U_1\cos U_2\cos\lambda\right)^2} \quad [14]$$

$$\cos\sigma=\sin U_1\sin U_2+\cos U_1\cos U_2\cos\lambda \quad [15]$$

$$\sigma=\arctan[2]\left(\sin\sigma,\quad \cos\sigma\right) \quad [16]^{i}$$

$$\sin\alpha=\frac{\cos U_1\cos U_2\sin\lambda}{\sin\sigma} \quad [17]$$

$$\cos^2\alpha=1-\sin^2\alpha \qquad \text{(Trig identity; included by Veness [2015}b\text{])}$$

$$\cos\left(2\sigma_m\right)=\cos\sigma-\frac{2\sin U_1\sin U_2}{\cos^2\alpha} \quad [18]$$

$$C=\frac{f}{16}\cos^2\alpha\left[4+f\left(4-3\cos^2\alpha\right)\right] \quad [10]$$

$$\lambda'=\lambda \qquad \text{(Introduced by Veness [2015}b\text{])}$$

$$\lambda=L+\left(1-C\right)f\sin\alpha\left\{\sigma+C\sin\sigma\left[\cos\left(2\sigma_m\right)+C\cos\sigma\left(-1+2\cos^2\left(2\sigma_m\right)\right)\right]\right\} \quad [11]^{ii}$$

Loop[iii] until $\left|\lambda-\lambda'\right|\le 10^{-12}$

$$A=1+\frac{u^2}{16384}\left\{4096+u^2\left[-768+u^2\left(320-175u^2\right)\right]\right\} \quad [3]$$

$$B=\frac{u^2}{1024}\left\{256+u^2\left[-128+u^2\left(74-47u^2\right)\right]\right\} \quad [4]$$

$$\Delta\sigma=B\sin\sigma\left\{\cos\left(2\sigma_m\right)+\tfrac{1}{4}B\left[\cos\sigma\left(-1+2\cos^2\left(2\sigma_m\right)\right)-\tfrac{1}{6}B\cos\left(2\sigma_m\right)\left(-3+4\sin^2\sigma\right)\left(-3+4\cos^2\left(2\sigma_m\right)\right)\right\}\right] \quad [6]$$

Final Distance $s=bA\left(\sigma-\Delta\sigma\right)$ [19]

Initial Azimuth[iv] $\alpha_1=\arctan[2]\left(\cos U_2\sin\lambda,\quad \cos U_1\sin U_2-\sin U_1\cos U_2\cos\lambda\right)$ [20][v]

Final Azimuth[iv] $\alpha_2=\arctan[2]\left(\cos U_1\sin\lambda,\quad -\sin U_1\cos U_2+\cos U_1\sin U_2\cos\lambda\right)$ [21][v]

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[i] Arctan[2] function described on p. 53.

[ii] Algebraic modification by Veness (2015*b*) from original Vincenty (1975) equation.

[iii] Veness suggests setting a maximum number of iterations possible because (as Vincenty points out) the formulas could go into an infinite loop if the two points are nearly antipodal.

[iv] Azimuths are in radians. See p. 53 for information on converting back to degrees.

[v] Arctan[2] function described on p. 53.

Using Vincenty's Equations to Calculate the Position of a Point on the Spheroid

Vincenty gives both "Direct" and "Inverse" formulae. The "Direct" formula calculates the position of the new point on the spheroid given an initial point, bearing and distance. Numbers on the right margin refer to Vincenty's equation numbers.

$$\tan U_1 = (1-f)\tan\phi_1$$

$$\cos U_1 = \frac{1}{\sqrt{1+\tan^2 U_1}} \qquad \text{(Trig identity; included by Veness [2015}b\text{])}$$

$$\sin U_1 = \tan U_1 \cos U_1 \qquad \text{(Trig identity; included by Veness [2015}b\text{])}$$

$$\sigma_1 = \arctan[2](\tan U_1, \quad \cos\alpha_1)$$ [1][v]

$$\sin\alpha = \cos U_1 \sin\alpha_1$$ [2]

$$\cos^2\alpha = 1 - \sin_2\alpha \qquad \text{(Trig identity; included by Veness [2015}b\text{])}$$

$$A = 1 + \frac{u^2}{16384}\left\{4096 + u^2\left[-768 + u^2\left(320 - 175u^2\right)\right]\right\}$$ [3]

$$B = \frac{u^2}{1024}\left\{256 + u^2\left[-128 + u^2\left(74 - 47u^2\right)\right]\right\}$$ [4]

$$\sigma = \frac{s}{bA} \qquad \text{(First approximation)}$$

Initially set $\sigma' = 2\pi$

while $|\sigma - \sigma'| > 10^{-12}$ (Threshold suggested by Veness [2015*b*]; $\cong 0.006$ mm at equator)

$$\cos(2\sigma_m) = \cos(2\sigma_1 + \sigma)$$ [5][vi]

$$\Delta\sigma = B\sin\sigma\left\{\cos(2\sigma_m) + \tfrac{1}{4}B\left[\cos\sigma\left(-1 + 2\cos^2(2\sigma_m)\right) - \tfrac{1}{6}B\cos(2\sigma_m)\left(-3 + 4\sin^2\sigma\right)\left(-3 + 4\cos^2(2\sigma_m)\right)\right\}\right]$$ [6]

$$\sigma' = \sigma \qquad \text{(Introduced by Veness [2015}b\text{])}$$

$$\sigma = \frac{s}{bA} + \Delta\sigma$$ [7]

Loop[vii] until $|\sigma - \sigma'| \le 10^{-12}$

---

vi Algebraic modification by Veness (2015*b*) from original Vincenty (1975) equation.

vii Veness suggests setting a maximum number of iterations possible because (as Vincenty points out) the formulas could go into an infinite loop if the two points are nearly antipodal.

$$\phi_2 = \arctan[2]\left(\sin U_1 \cos\sigma + \cos U_1 \sin\sigma \cos\alpha_1, \right.$$
$$\left. (1-f)\sqrt{\left[\sin^2\alpha + \left(\sin U_1 \sin\sigma - \cos U_1 \cos\sigma \cos\alpha_1\right)^2\right]}\right)$$ [8] [viii,vi]

$$\lambda = \arctan[2]\left(\sin\sigma \sin\alpha_1, \quad \cos U_1 \cos\sigma - \sin U_1 \sin\sigma \cos\alpha_1\right)$$ [9] [viii, vi]

$$C = \frac{f}{16}\cos^2\alpha\left[4 + f\left(4 - 3\cos^2\alpha\right)\right]$$ [10]

$$L = \lambda - (1-C) f \sin\alpha \left\{\sigma + C\sin\sigma\left[\cos\left(2\sigma_m\right) + C\cos\sigma\left(-1 + 2\cos^2\left(2\sigma_m\right)\right)\right]\right\}$$ [11]

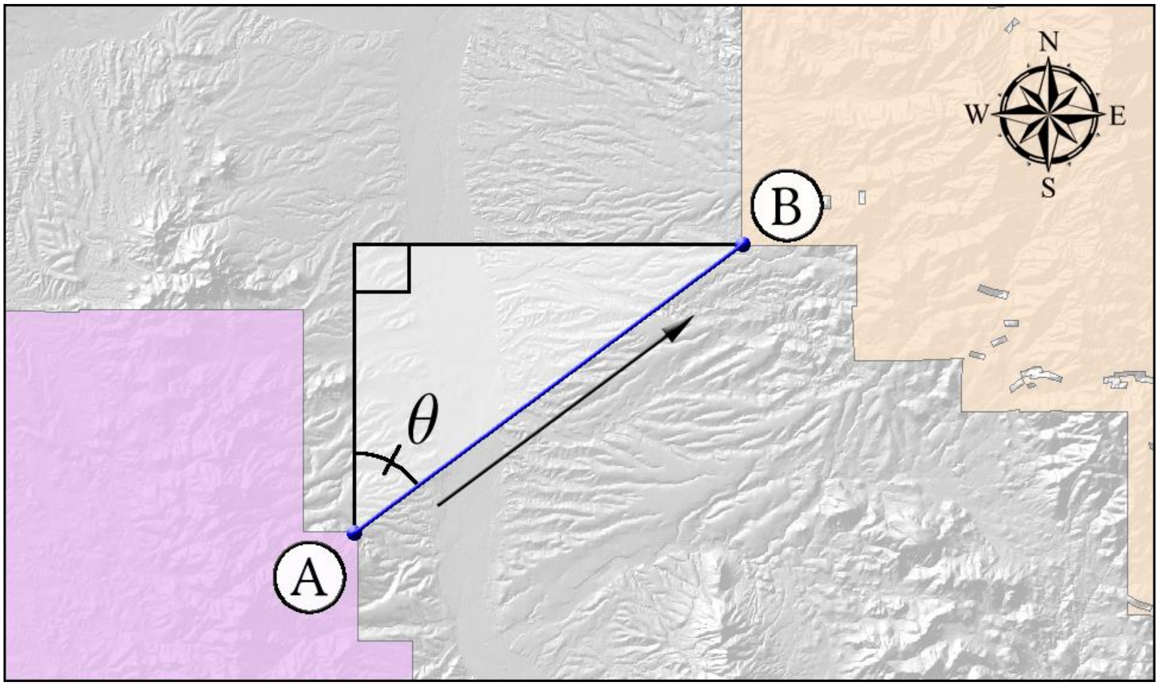
Reverse Azimuth[ix] $\alpha_2 = \arctan[2]\left(\sin\alpha, \quad -\sin U_1 \sin\sigma + \cos U_1 \cos\sigma \cos\alpha_1\right)$ [12] [vi]

$P_2 = \left(\phi_2, \; \lambda_1 + L\right)$ [ix]

[viii] Arctan[2] function described on p. 53.

[ix] Values are in radians. See p. 53 for information on converting back to degrees.

Calculating the Azimuth Between Points on a Plane



The azimuth (or bearing) between points A and B is calculated as follows:

Given that:

$\Delta x = \text{Point } B \text{ x-coordinate} - \text{Point } A \text{ x-coordinate}$

$\Delta y = \text{Point } B \text{ y-coordinate} - \text{Point } A \text{ y-coordinate}$

If If $\Delta x = 0$ and $\Delta y = 0$ then $\theta = -9999$ (i.e. No Direction)

Else if $\Delta y = 0$ then:

If $\Delta x < 0$ then $\theta = -90^\circ$

If Else If $\Delta x = 0$ then $\theta = 0^\circ$

Else If $\Delta x > 0$ then $\theta = 90^\circ$

Else:

$$\theta_a = \frac{\arctan\left(\frac{\Delta x}{\Delta y}\right) * 180}{\pi}$$

If $\Delta y \geq 0$ then $\theta = \theta_a + 180$

Else:

If $\Delta x \leq 0$ then $\theta = \theta_a$

Else if $\Delta x > 0$ then $\theta = \theta_a + 360$

Converting between Latitude / Longitude and Cartesian Coordinates

Latitude / Longitude to Cartesian Coordinate on the Sphere:

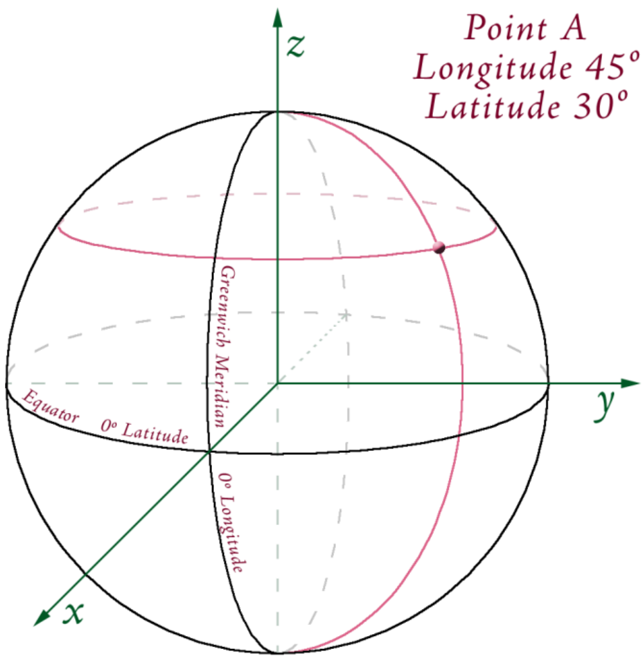
Given a Latitude and Longitude in Degrees, calculate X, Y and Z as follows:

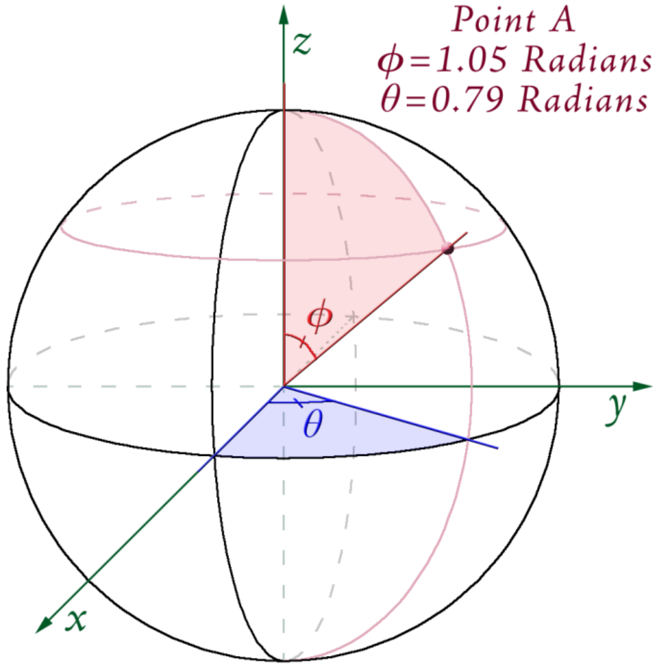
$$\mathrm{X} = R\sin\phi\cos\theta$$
$$\mathrm{Y} = R\sin\phi\sin\theta$$
$$\mathrm{Z} = R\cos\phi$$

where:

$$\phi = \frac{(90 - \text{Latitude})\pi}{180} = \text{Angle from North Pole down to Latitude, in Radians}$$
$$\theta = \frac{(\text{Longitude})\pi}{180} = \text{Angle from Greenwich to Longitude, in Radians}$$
$$R = \text{Radius of Sphere}$$

For example, a point at 30º Latitude and 45º Longitude would be converted to ϕ = 1.05 radians and ϑ = 0.79 radians:





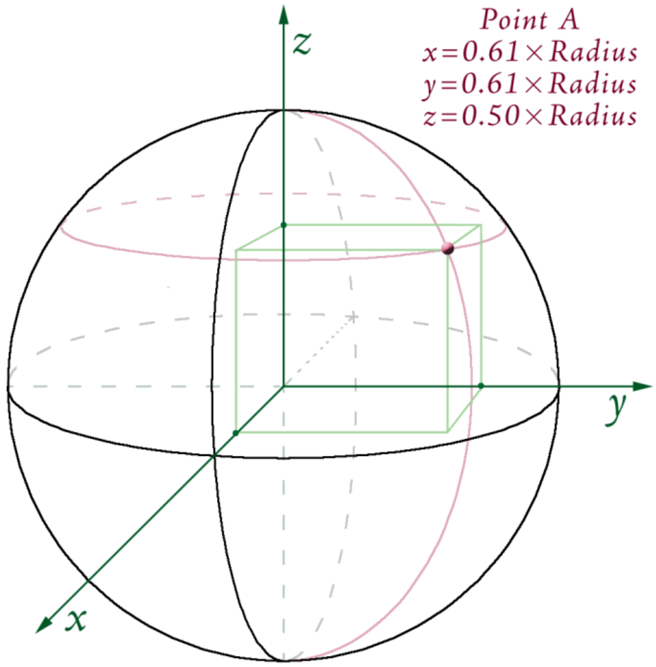
NOTE: Be careful with the terms ϕ and ϑ! This document treats ϕ as the angle south from the North Pole, and ϑ as the angle east from Greenwich. However, the literature is not consistent with these two terms! Much of the literature uses these exact two symbols, but for the other angle (i.e. ϕ for east/west and ϑ for north/south).

Using the formula above, calculate X, Y and Z from ϕ and ϑ.

$$\mathrm{X} = R\sin\phi\cos\theta = R\sin(1.05)\cos(0.79) = 0.61R$$

$$\mathrm{Y} = R\sin\phi\sin\theta = R\sin(1.05)\sin(0.79) = 0.61R$$

$$\mathrm{Z} = R\cos\phi = R\cos(1.05) = 0.5R$$



NOTE: As with ϕ and ϑ, the literature is inconsistent regarding how to write the X, Y and Z coordinates of a 3-dimensional point. If a point is located at X, Y, Z, some sources will write the coordinates as (X,Y,Z) while other sources will write it as (Z,X,Y). If you write coordinates in either of these formats, please identify which format you are using!

<u>Cartesian to Latitude / Longitude Coordinates on the Sphere:</u>

$$\phi = \arctan[2]\left(\sqrt{X^2 + Y^2},\ Z\right) = \text{Angle from North Pole down to Latitude, in radians}$$

$$\theta = \arctan[2](Y,\ X) = \text{Angle from Greenwich to Longitude, in radians}$$

where $\arctan[2] =$ Arctangent, adjusted for quadrant (see General Geometric Functions)

$$\text{Latitude} = 90 - \phi\left(\frac{180}{\pi}\right)$$

$$\text{Longitude} = \theta\left(\frac{180}{\pi}\right)$$

<u>Converting Between Latitude / Longitude and Cartesian Coordinates on the Spheroid:</u>

As illustrated in Chapter 2 of Iliffe (2000), the formulas above can be adapted to oblate spheroids (such as a planet). If you refer to Iliffe's text, please be aware that his formulae define ϕ as Latitude, rather than as $(90 - \text{Latitude})$. The formulae below are modified from Iliffe's formulae to make them consistent with the conversion formulae for the sphere above.

Latitude / Longitude to Cartesian:

Given a Latitude and Longitude in Degrees, Spheroid Equatorial and Polar Axes, and an optional height above the spheroid, calculate X, Y and Z as follows:

$$\mathrm{X} = (\nu + h)\sin\phi\cos\theta$$
$$\mathrm{Y} = (\nu + h)\sin\phi\sin\theta$$
$$\mathrm{Z} = \left(\left(1 - e^2\right)\nu + h\right)\cos\phi$$

where:

$$\phi = \frac{(90 - \text{Latitude})\pi}{180} = \text{Angle from North Pole down to Latitude, in Radians}$$
$$\theta = \frac{(\text{Longitude})\pi}{180} = \text{Angle from Greenwich to Longitude, in Radians}$$
$$a = \text{Spheroid equatorial radius (i.e. semi-major axis)}$$
$$b = \text{Spheroid polar radius (i.e. semi-minor axis)}$$
$$e^2 = \text{Spheroid eccentricity (squared)} = \frac{a^2 - b^2}{a^2}$$
$$\nu = \frac{a}{\sqrt{1 - e^2\cos^2\phi}}$$
$$h = \text{Height aove the spheroid}$$

<u>Cartesian to Latitude / Longitude Coordinates on the Spheroid:</u>

$$\text{Latitude} = 90 - \phi\left(\frac{180}{\pi}\right)$$
$$\text{Longitude} = \theta\left(\frac{180}{\pi}\right)$$

where:

$$\phi = \text{arctan[2]}\left(P - e^2 a\cos^3 u,\ \mathrm{Z} + \varepsilon b\sin^3 u\right) = \text{Angle from North Pole down to Latitude, in radians}$$
$$\theta = \text{arctan[2]}(\mathrm{Y},\ \mathrm{X}) = \text{Angle from Greenwich to Longitude, in radians}$$
$$a = \text{Spheroid equatorial radius (i.e. semi-major axis)}$$
$$b = \text{Spheroid polar radius (i.e. semi-minor axis)}$$
$$P = \sqrt{\mathrm{X}^2 + \mathrm{Y}^2}$$
$$u = \text{arctan[2]}(\mathrm{Z}a, Pb)$$
$$e^2 = \text{Spheroid eccentricity (squared)} = \frac{a^2 - b^2}{a^2}$$
$$\varepsilon = \frac{e^2}{1 - e^2}$$
$$\text{arctan[2]} = \text{Arctangent, adjusted for quadrant (see General Geometric Functions)}$$

Arctan[2] Function

Various functions in this extension calculate arctangents. However, there is a problem with the basic function arctan because it does not account for quadrant. For example, given that $\tan A = \frac{\Delta Y}{\Delta X}$, then $\arctan \frac{\Delta.Y}{\Delta X} = A$, where A is in radians. However, this simple arctan function does not properly account for the signs of ΔX and ΔY and will only return values ranging between $\pm\frac{\pi}{2}$. The arctan[2] function checks the signs of ΔX and ΔY and returns a value of A radians that correctly ranges from $-\pi$ to π.

Unfortunately, Visual Basic 6 does not have a function to calculate arctangent in this manner. Many programming languages such as C++, PHP, C# and VB.NET include the “atan2” function which does the trick. You simply specify X and Y separately and the function determines the quadrant. **NOTE:** Microsoft Excel also has an “atan2” function, but for some reason the Excel version takes the ΔX and ΔY values in the order of (x, y) while all other implementations in the civilized world appear to take these values in the order of (y, x). Therefore be careful if you use this function in both your code and in Excel!

Given the lack of an Atan2 function in VB6 and VBA, I wrote my own function as follows:

```
Const dblPi As Double = 3.14159265358979
Public Function atan2(Y As Double, X As Double) As Double
  If X > 0 Then
    atan2 = Atn(Y / X)
  ElseIf X < 0 Then
    If Y = 0 Then
      atan2 = (dblPi - Atn(Abs(Y / X)))
    Else
      atan2 = Sgn(Y) * (dblPi - Atn(Abs(Y / X)))
    End If
  Else    ' IF X = 0
    If Y = 0 Then
      atan2 = 0
    Else
      atan2 = Sgn(Y) * dblPi / 2
    End If
  End If
End Function
```

Converting between Radians and Decimal Degrees

$$\text{Radians clockwise from North} = Degrees\left(\frac{\pi}{180}\right)$$

$$\text{Degrees clockwise from North} = Radians\left(\frac{180}{\pi}\right)$$

Spherical Radius Derived from Spheroid

When applying spherical functions, this extension assumes a sphere with the same volume as the actual data spheroid. For example, if the data used the WGS 84 spheroid (with semi-major axis = 6378137m, and semi-minor axis = 6356752.31424518m), then the spherical functions would be applied to a sphere with a radius of 6371000.79000915 meters derived as follows:

WGS 84 Spheroid:

$$\text{Semi-major axis } (a) = 6378137.0 \text{ m}$$

$$\text{Semi-minor axis } (b) = 6356752.31424518 \text{ m}$$

Volume of WGS 84 Spheroid:

$$V = \frac{4}{3}\pi a^2 b \qquad (\text{WGS 84 is an oblate spheroid})$$

Volume of Sphere with Radius R:

$$V = \frac{4}{3}\pi R^3$$

Therefore solve for R when $\frac{4}{3}\pi R^3 = \frac{4}{3}\pi a^2 b$

$$R^3 = a^2 b \qquad (\text{Like terms cancel})$$

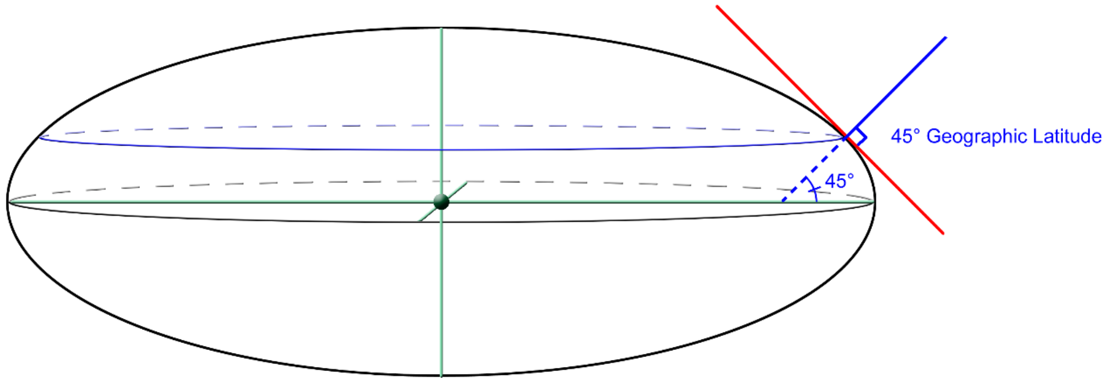
$$R = \sqrt[3]{a^2 b} = \sqrt[3]{\left(6378137.0^2\right)\left(6356752.31424518\right)}$$

$$= 6371000.79000915 \text{ m}$$

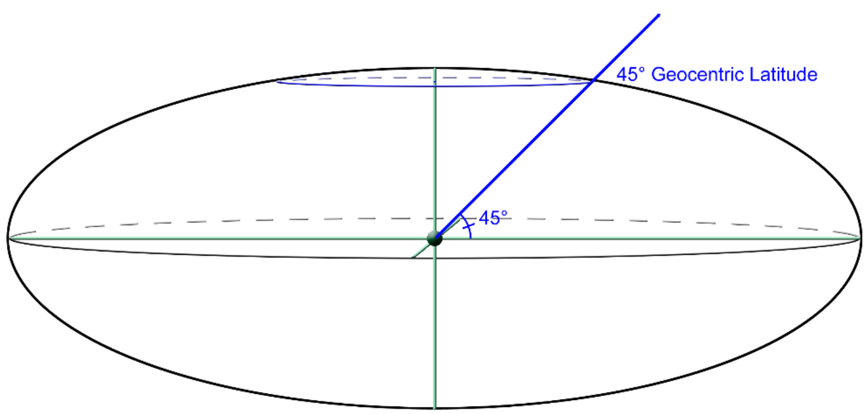
Planetocentric vs. Planetographic Coordinate Systems

For this tool, the terms Planetocentric (or Geocentric) and Planetographic (or Geographic, sometimes Geodetic) refer to the method of defining Latitude values on the surface of the spheroid.

Historically, latitude at a point on the earth has been determined by measuring the angle from the horizon at that point to some fixed reference point in space (the North Star, for example). Technically, this method produces the angle between the Normal of the spheroid (i.e. the vector perpendicular to the surface of the spheroid) at that point. Latitude coordinates produced by this method are referred to as Geographic (or Geodetic) coordinates. Planetary spheroids are typically slightly flattened spheres, so the Normal of the spheroid does not actually intersect the centroid of the planet. The illustration below greatly exaggerates the flattening to demonstrate this concept.



An alternative method would be to use the center of the spheroid as a reference point, and define "Latitude" as the angle between a line connecting the spheroid center to the point on the surface, and another line connecting the spheroid center to a point on the spheroid equator. Latitude coordinates produced by this method are referred to as Geocentric coordinates.



Because the prefix "Geo" implies Earth-based measures, I have substituted the prefix "Planeto" to create more general terms. **Note:** Most earth-based projections and datums are Planetographic, while most extra-terrestrial datums are Planetocentric.

Note: Longitude values are unaffected by whether the data are Planetocentric or Planetographic. The difference between Planetocentric and Planetographic latitude values depends on the flattening of the spheroid, where greater flattening leads to greater differences. If the spheroid were a true sphere (with no flattening), then Planetocentric and Planetographic latitudes would be identical.

EQUATIONS

(Adapted from p. 17 of Snyder [1987])

$$\text{Planetocentric Latitude } (\psi) = \frac{180\left(\arctan\left(\left(\frac{b}{a}\right)^2 \tan\left(\frac{\phi\pi}{180}\right)\right)\right)}{\pi}$$

$$\begin{aligned} \text{where } \phi &= \text{Planetographic Latitude} \\ a &= \text{Semi-major axis radius} \\ b &= \text{Semi-minor axis radius} \end{aligned}$$

$$\text{Planetographic Latitude } (\phi) = \frac{180\left(\arctan\left(\left(\frac{a}{b}\right)^2 \tan\left(\frac{\psi\pi}{180}\right)\right)\right)}{\pi}$$

$$\begin{aligned} \text{where } \psi &= \text{Planetocentric Latitude} \\ a &= \text{Semi-major axis radius} \\ b &= \text{Semi-minor axis radius} \end{aligned}$$

Analyzing Directional Data: Circular Statistics

Before beginning this section, I want to emphasize two important points that people very often make mistakes with:

1) **Do not calculate the mean direction using the arithmetic mean!** This is especially frustrating because the arithmetic mean is sometimes correct and sometimes wildly incorrect. For example, the mean direction of 90° and 180° is 135°, which coincidentally is equal to the arithmetic mean $\left(\frac{90+180}{2}=135\right)$. But what is the mean direction of 359° and 1°? They are both pointing almost due north ($\pm$ 1°), and clearly the true mean direction is exactly due north. However, the arithmetic mean gives us 180° $\left(\frac{359+1}{2}=180\right)$, which is due *south* and exactly the opposite of the correct answer. The correct way to calculate the mean direction is described below.

2) **If you apply a Sine or Cosine transformation, make sure to convert the values to radians first!** Most analytical software and programming languages have sine and cosine functions, but these functions usually assume the values are in *radians*, not *degrees*. There are exactly 2π (~6.28) radians in a circle. This means that the software will assume that a difference of 3.14 (i.e. π) units is equivalent to going halfway around the circle. If your data are in degrees, then the software will interpret a change in 2° to be roughly equivalent to going a third of the way around the circle. Fortunately it is easy to convert to radians using the following formula:

   Degrees to Radians: $$Radians = \frac{Degrees \times \pi}{180} = \frac{Degrees \times (3.14159265358979)}{180}$$

   It is possible that your software has a function that allows you to calculate sines and cosines from degrees (many calculators do), but even in this case you must remember to set the switch correctly.

Fortunately there are well-established methods available for analyzing circular or periodic data such as movement direction or aspect. The circular nature of the data lead to very specific and interesting approaches to calculating measures of central tendency and dispersion (see also (Jenness 2015). Some of the basic descriptive statistics are:

MEAN DIRECTION AND MEAN RESULTANT LENGTH

Where: $\theta =$ Direction in Radians

$$C = \sum_{i=1}^{n} \cos\theta_i \qquad S = \sum_{i=1}^{n} \sin\theta_i \qquad R^2 = C^2 + S^2$$

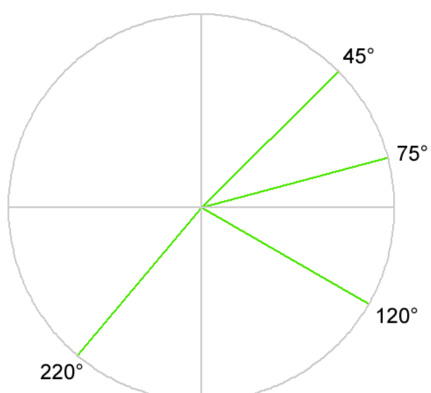
Mean Direction:
$$\bar{\theta} = \begin{cases} \tan^{-1}(S/C) & S > 0,\ C > 0 \\ \tan^{-1}(S/C) + \pi & C < 0 \\ \tan^{-1}(S/C) + 2\pi & S < 0,\ C > 0 \\ \pi/2 & S > 0,\ C = 0 \\ -\pi/2 & S < 0,\ C = 0 \end{cases}$$

Resultant Length: $R = \sqrt{R^2}$

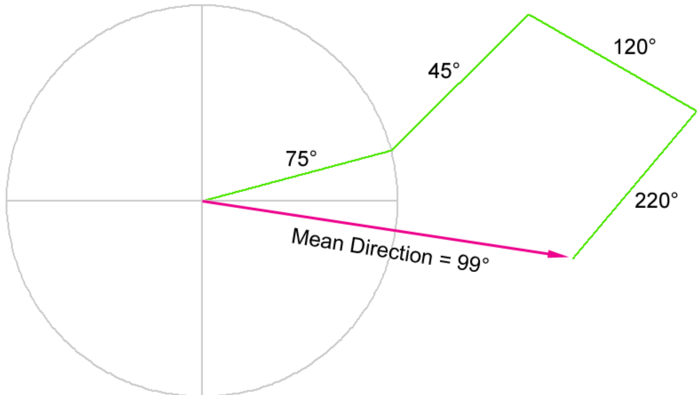
Mean Resultant Length: $\bar{R} = \dfrac{R}{n}$

The equations for mean direction look a little confusing, but the logic is actually very intuitive. It is simply a process of vector addition, where each direction value is a single vector. Vector addition essentially connects all the direction vectors into a path, and the mean direction is just the direction from the origin to the last point on the path.

For example, consider a scenario with 4 direction values at 45°, 75°, 120° and 220°:

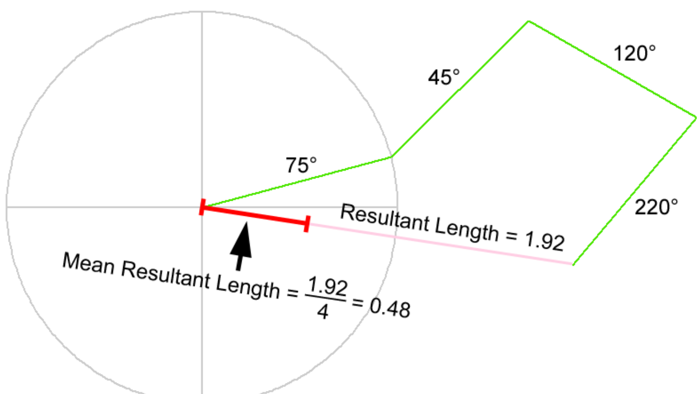


We connect the 4 bearings in a path (vector addition just adds up the ΔX and ΔY components of each vector, which is the same as treating each bearing as a segment in a path). It does not matter what order we connect the vectors in; they will always end up at the same point. The **Mean Direction** is the bearing from the start of the path to the end of the path.



On a side note, this is also the way to calculate the mean direction of an actual observed movement path. If you have a series of locations from a GPS collar on an elk, for example, and you wonder what average direction the animal moved over the day, then that average direction is simply the direction from the first GPS location of the day to the last.

The **Mean Resultant Length** $\bar{R}$ is the basis for several values of dispersion (analogous to variance or standard deviation), and is calculated as the straight-line distance from the starting point to the ending point of the path divided by the total length of the path. If the segments are unit vectors (e.g. aspect values from an aspect raster, where each aspect value has the same weight as any other), then this can be simplified to dividing by the number of segments or observations.



Notice that the mean resultant length has a potential range of 0 to 1. If all the vectors pointed in exactly the same direction, the *resultant length* would then be equal to the total path length and the *mean resultant length* would be equal to 1. This is the scenario with the minimum possible variance or dispersion in the vectors. The more the path wanders around, the shorter both the *resultant length* and the *mean resultant length* will be. If the path ended back at the origin, then both values would be equal to 0.

CIRCULAR VARIANCE AND STANDARD DEVIATION:

Mardia and Jupp (2000), Fisher (1995) and Batschelet (1981) describe circular statistics analogous to variance and standard deviations, all based on the mean resultant length $\bar{R}$.

Circular Variance: $V = 1 - \bar{R}$ (Mardia & Jupp, Fisher)

Angular Variance: $s^2 = 2\left(1 - \bar{R}\right)$ (Batschelet)

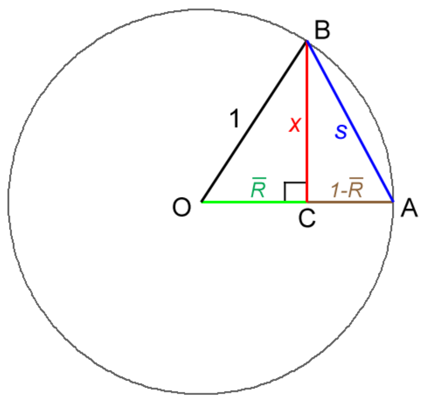
Circular Standard Deviation: $v = \sqrt{\left(-2\ln\bar{R}\right)}$ (In Radians) (Mardia & Jupp, Fisher)

Angular Deviation: $s = \sqrt{s^2} = \sqrt{2\left(1 - \bar{R}\right)}$ (In Radians) (Batschelet)

The *Circular Standard Deviation* and *Angular Deviation* are both in units of Radians, but these can easily be converted to Degrees.

Radians to Degrees: $Degrees = \dfrac{180}{\pi}\left(Radians\right)$

Batchelet points out that *circular standard deviation* and the *angular deviation* tend to be close to each other for high values of $\bar{R}$ (i.e. near 1). However, as $\bar{R}$ tends toward 0, *circular standard deviation* tends toward ∞ while *angular deviation* tends toward a maximum value of $\sqrt{2}$. Batchelet, citing Seyfarth and Barth (1972), presents a geometric derivation of angular deviation which also provides a visual sense of what the concept means.



Given a unit circle with Radius = 1, and with:

- Point *A* defined as on the circle horizontal from the Origin *O*
- Point *C* defined as $\bar{R}$ distance along segment *OA* (remember that $\bar{R}$ will always be between 0 and 1)
- Point *B* defined as on the circle vertical from Point *C*

Then ***s*** (angular deviation) is just the length of the line connecting points A and B (also known as the *Chord* of $\overset{\frown}{AOB}$). The angular deviation can therefore be calculated by applying the Pythagorean theorem to $\Delta\, BCO$ and $\Delta\, ABC$:

From the Pythagorean Theorem on ΔBCO:

$$x^2 + \bar{R}^2 = 1^2$$
$$\therefore x^2 = 1 - \bar{R}^2$$

From the Pythagorean Theorem on ΔABC:

$$s^2 = \left(1 - \bar{R}\right)^2 + x^2$$

Substituting for x^2:

$$\begin{aligned} s^2 &= \left(1 - \bar{R}\right)^2 + \left(1 - \bar{R}^2\right) \\ &= \left(1 - \bar{R}\right)\left(1 - \bar{R}\right) + 1 - \bar{R}^2 \\ &= 1 - 2\bar{R} + \bar{R}^2 + 1 - \bar{R}^2 \\ &= 2 - 2\bar{R} \\ &= 2\left(1 - \bar{R}\right) \end{aligned}$$
$$\therefore s = \sqrt{2\left(1 - \bar{R}\right)}$$

Based on this illustration, it is easy to see that $s = 0$ when $\bar{R} = 1$, and that $s = \sqrt{2}$ when $\bar{R} = 0$

Note: A mean resultant length $\left(\bar{R}\right)$ near 1 always implies a tightly focused set of directions, but a mean resultant length near 0 does **not** necessarily imply a high amount of variation or dispersion. All it implies is that the directions balance each other out. This can occur with a uniform distribution of directions, in which case there truly would be high dispersion. It can also occur, however, if you have a number of bearings in one direction and an equal number in the opposite direction. For example, perhaps you have a bird with distinct and separate roost and forage locations. Every day the bird travels to the forage location and then returns to the roost location. In this scenario, the bird only goes in two distinct and opposite directions (to the forage location, and then back to the roost location). The bird's movement directions are highly focused and predictable, but the mean resultant length would be 0 and consequently the variance would be high. As with most situations, plotting the distribution of the data is a good way to understand what is really happening.

Just as with standard statistics, there are a number of circular distributions and sophisticated analytical techniques available. These go beyond the scope of this discussion, but please refer to (Jammalamadaka and SenGupta 2001), Mardia and Jupp (2000), Zar (1999; see especially ch. 26 and 27), Fisher (1995) and Batschelet (1981) for some good texts on circular statistics, distributions (i.e. the Fisher, Von Mises and Wrapped Normal distributions), circular hypothesis testing and other analytical techniques. There is also a good circular statistical package for R, originally based on Jammalamadaka and SenGupta's text. As of June, 2016, the manual for this package can be viewed at [http://cran.wustl.edu/web/packages/circular/circular.pdf.](http://cran.wustl.edu/web/packages/circular/circular.pdf)