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Planar Orientation Tools: an ArcMap toolbox for working with planar orientations in GeMS

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# Introduction

Geologists measure orientations of planar features—most commonly bedding, but also foliation, faults, dikes and joints—in the course of describing the Earth. These measurements facilitate prediction of the distribution of rock units where there is no outcrop or no access, allow tests of the consistency of observations, and are fundamental to unravelling the history of Earth deformation.

This report presents software tools that (1) use numerous XYZ positions taken from remotely-sensed data (e.g., high-resolution digital elevation models [DEMs]) to calculate the strike and dip (orientation) of planar features, (2) extrapolate the intersection of planar features with topography from their local points of measurement to lines across the broader landscape, (3) project planar orientations onto a cross-section plane perpendicular to a defined projection axis and solve for apparent dip, and (4) export planar (and linear) orientations for further analysis with other software. The fundamentals of these tools are not new (e.g., Fernandes, 2005; Kneissl and others, 2010; Jones and others, 2016; Gallo and others, 2018; Adams and Parks, 2020; Carli Dudas, Oregon DOGAMI, personal communication 2019). The contributions of this report are their packaging within an ArcMap interface that facilitates work with the GeMS geologic map schema recently developed by the U.S. Geological Survey (USGS) National Cooperative Geologic Mapping Program (NCGMP) (USGS NCGMP, 2020) and the discussion of quality metrics for planar orientations derived from numerous XYZ positions.

These tools are essential to new geologic mapping by the author and are here documented to provide background for forthcoming reports.

The code package for this report includes the following files:

BeddingTracesToS&D.py Script for tool **Bedding traces to S&D**

DownPlungeProjection.py Script for tool **Down-plunge projection**

ExtrapolatePlane.py Script for tool **Extrapolate Planes**

OpenStereoExport.py Script for tool **OpenStereo export**

PlanarOrientationTools.tbx ArcMap (version 10.5+) toolbox file

PrepOrientationPoints.py Script for tool **Prep OrientationPoints**

ProjectedBedding.lyr ArcMap .lyr file for symbolizing extrapolated planes

StereonetExport.py Script for tool **Stereonet export**

Scripts are written in Python 2.7 for use with ArcMap v10.x. Dependencies include the arcpy, math, and numpy modules, all of which are included in the standard ArcMap Python installation. The scripts, and this report, are not subject to US copyright and may be freely revised and redistributed. Attribution is appreciated.

Individual tools are described below. Eigenvector analysis and the fit parameters reported by the **Bedding traces to S&D** tool are discussed at the end of this document.

Current versions of the scripts are available at <https://github.com/rhaugerud/PlanarOrientationsTools>.

# Installation

Unzip the code package in a convenient location that probably should not be in your working data folders. Open ArcMap and click on the Arc Toolbox icon  to open the Arc Toolbox window. Right-click on an empty area of the window and select “Add Toolbox…”. Navigate to the unzipped code package and select PlanarOrientationTools.tbx. Note that Python scripts (\*.py files) and projectedBedding.lyr need to be in the same folder as the toolbox (.tbx) file; do not move them! Once you have added the toolbox, you may wish to right-click again on an empty area of the Arc Toolbox window and select “Save Settings > To Default”, to keep the toolbox loaded for future use. Alternatively you could open the ArcCatalog window within ArcMap, navigate to the location where you unzipped the files, and launch the toolbox from there.

# Bedding traces to S&D

The script tool **Bedding traces to S&D** uses eigenvector analysis to fit planes to clouds of 3-D points obtained by intersecting digitized 2-D bedding traces with a digital elevation model. Inputs are (1) a digital elevation model, (2) grid declination, (3) an ArcMap feature layer of lines with selected bedding traces, (4) an output point feature layer “OrientationPoints”, (5) a scratch workspace, (6) a DataSourceID string with which output values are labeled, and (7) a choice to stack lines (or not) as discussed under *Stack Lines?*, below.

The tool is designed to be run repetitively, selecting (or digitizing) one or a few bedding traces, analyzing them to obtain the strike and dip of the best-fit plane, and repeating.

From the ArcMap Item Description:

#### *Summary*

*Calculates bedding orientation (strike and dip) from collection of 3-D points defined by overlay of bedding traces on topography.*

*Designed to be used interactively:*

* *Fill in the parameters at left [in the tool dialog box]*
* *Start editing the bedding trace feature layer, select one or more bedding-trace arcs, and tap "OK" at the bottom of this window.*
* *Script will run, calculate a strike and dip, if fit is good enough add the result to OrientationPoints and refresh the map so the result is visible, and write results to a log file.*
* *You will see a red error message. This is OK if it follows a "DONE!" statement.*
* *Close the script output window, select another arc or set of arcs, or digitize an arc, and repeat.*
* *Tap "Cancel" to exit.*

*If a single feature is selected, calculated S&D will be placed at the point on the input feature closest to the mean of all input points. If multiple features are selected, calculated S&D will be placed at the mean of individual feature means. ObjectID(s) of source feature(s) are written to the Notes field of the calculated OrientationPoints feature.*

*A log file is written within folder of GDB that hosts source for OrientationPoints feature layer.*

|  |  |  |
| --- | --- | --- |
| ***Parameter*** | ***Explanation*** | ***Data Type*** |
| *DEM* | *DEM for the area of interest. Lidar is best, but not required. Z units must equal XY units.*  *Input bedding traces are densified to 3 x dem.cellSize.* | *Raster Layer* |
| *Grid\_declination* | *Difference, in degrees clockwise, between true North (the reference direction for OrientationPoints) and grid north (the reference direction for the DEM. With common large-scale map projections at low to moderate latitudes, the absolute value of grid\_declination is usually less than a few degrees.*  *If you adjust the Rotation value in the General tab of the Data Frame Properties window to square the (rectangular) DEM with the ArcMap window, the Rotation value is the grid declination.* | *Double* |
| *Bedding\_trace\_feature\_layer* | *Line feature layer in map document that contains bedding traces. Probably the GeologicLines layer if the map document is built on a GeMS database. Source should be in same projection (e.g., in same feature dataset) as the source for OrientationPoints.*  ***Select with the drop-down arrow****, which gives you a feature layer. Do not select with the folder icon, which will lead you to a feature class. If you do not see a drop-down arrow, save your map document and restart ArcMap.*  *We use a feature layer from the map document so that only selected lines are passed to the script.* | *Feature Layer* |
| *OrientationPoints* | *Point feature layer to which calculated strikes and dips are written. Source should be in same projection (e.g., in same feature dataset) as the source for Bedding\_trace\_feature\_layer.*  *Assumed to have fields Type, Azimuth, Inclination, OrientationSourceID, LocationSourceID, OrientationConfidenceDegrees, and Notes--all of which are in a GeMS OrientationPoints feature class. Azimuth and Inclination are type FLOAT. Remainder are TEXT (or STRING). This feature class must also have fields Oblateness, Scatter, and Spread. All are type FLOAT. The names are case sensitive.*  *If any of these fields are not present, exit your edit session, add the fields, and resume. Or exit your edit session and run script* ***Prepare OrientationPoints****.*   * *Oblateness: ln(ev2/ev3)--the natural logarithm of intermediate eigenvalue / small eigenvalue* * *Scatter: sqrt(ev3/n)--roughly, the standard deviation of points from the best-fit plane* * *Spread: sqrt(ev2/n)--roughly, the spread of points within the plane at right angles to the direction of maximum point cloud orientation* | *Feature Layer* |
| *scratch\_folder* | *A folder within which scratch geodatabase xxx\_S&D.gdb is created, if it does not already exist. Folder must be writable.* | *Folder* |
| *DataSourceID* | *Value written to OrientationSourceID and LocationSourceID for newly-calculated features.* | *String* |
| *Stack\_lines\_* | *Input to this script may be*   1. *A single line that follows one bedding plane.* ***Stack Lines?*** *checked or unchecked makes no difference* 2. *Multiple line segments along a single bedding plane.* ***Stack Lines?*** *should be* ***UNCHECKED*** 3. *Multiple line segments on different, presumed parallel, bedding planes.* ***Stack lines?*** *should be* ***CHECKED****.*   *If multiple input lines are stacked (option 2), each line is translated so that its XYZ centroid is at (0,0,0). If you wish to stack lines that include multiple line segments along a single bedding plane (options 2 and 3), merge segments along each single bedding plane into a multi-part feature.*  *Default is checked.* | *Boolean* |
| *Type (Optional)* | *String value written to Type field of OrientationPoints. If empty, Type will be set to <Null>* | *String* |
| *Symbol (Optional)* | *String value written to Symbol field of OrientationPoints, if field is present. If field is present and this string is empty, Symbol will be set to <Null>* | *String* |

When digitizing bedding traces from a topographic image, I recommend the use of a vertical hillshade (slopeshade) image (Figure 1B) calculated with the ArcGIS Hillshade command, setting illumination source at 90° above the horizon and up to 10x vertical exaggeration. With a default ordinary shaded-relief image calculated with oblique illumination, the visibility of features is strongly dependent on their orientation relative to the illumination direction and there may be slight shifts in the apparent XY position of slope breaks. Vertical illumination of a vertically exaggerated DEM obviates these problems and makes subtle features more evident.

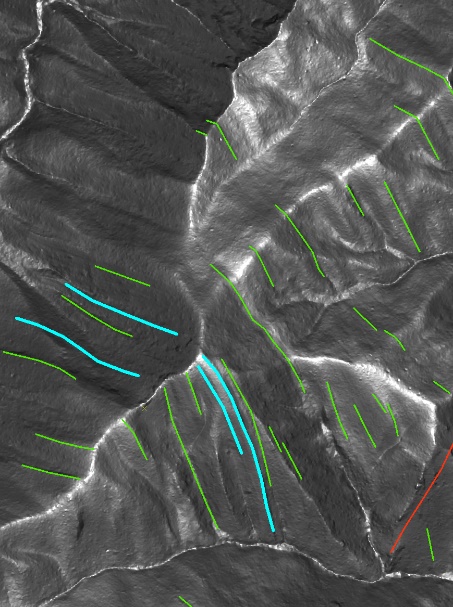
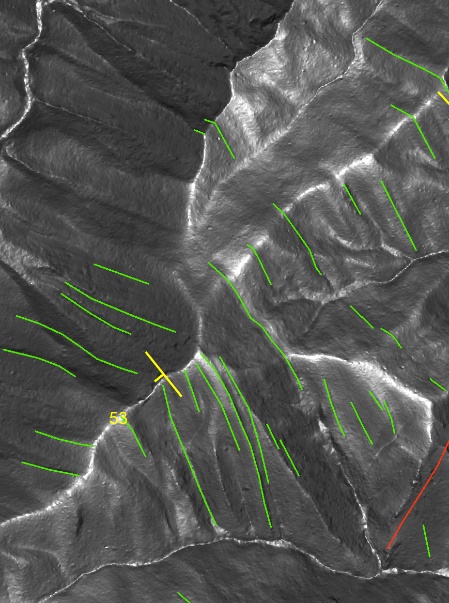
  

Figure 1. (A) NE-illuminated hillshade image of 1-m lidar DEM. View is 650 m wide. Area, on east slope of North Cascade Range in Washington state, is underlain by inclined Eocene fluvial strata. (B) Vertical hillshade (aka “slopeshade”), 6X exaggeration, of same area. Green lines are bedding traces interpreted from this image. Blue lines are a subset of these traces selected for input to **Bedding traces to S&D**. Red line marks trace of basaltic dike. (C) Same as B, with strike and dip (in yellow) calculated by **Bedding traces to S&D** with option to stack lines.

The tool was developed for use with 1- to 2-m resolution (XY) lidar DEMs (for example, Fig. 1) that provide both evidence for the XY locations of bedding traces and Z values (elevations) for these traces. In principle the tool should be usable with other data sources, particularly XY locations determined from widely available 1- to 2-m resolution aerial photographs and 10-m resolution DEMs derived from 1:24,000-scale contours. However, my experiments with such inputs have been discouraging. Failure to produce useful results could reflect mis-registration of aerial photography relative to the 10-m DEMs, or simply a low signal-to-noise ratio in the areas of my experiments, where local relief of 10 to 200 m is only 3 to 60 times the nominal 1/3-contour-interval accuracy of the DEMs.

Use the tool in an ArcMap map document that includes the following layers. Note that layer names are NOT significant; those given here are for likely feature classes in a GeMS-style (USGS NCGMP, 2020) database. Other layers may also be present.

* OrientationPoints point layer in which calculated attitudes will be stored
* GeologicLines line layer that contains bedding traces
* myDEM\_v6 raster image created from DEM with Hillshade command (optional)
* myDEM raster DEM (optional)

OrientationPoints (or its equivalent) is expected to contain a number of fields, some standard in a GeMS OrientationPoints feature class and others not. Ensure that the necessary fields are present by processing it with **Prep OrientationPoints**, described below. OrientationPoints and GeologicLines are expected to have the same projection, datum, and units, which is ensured if they are contained within the same Arc feature dataset. New features added to OrientationPoints will have Type=bedding. To immediately see familiarly symbolized results, go to the Layer Properties for OrientationPoints and set all features to draw with a simple bedding symbol. Or draw by categories, such that if value field Type=bedding, a simple bedding symbol is employed. In either case, tap the **Advanced**  dropdown, select **Rotation…**, set **Rotate Points by Angle in this field:** to Azimuth, and ensure that **Rotation Style:** is set to **Geographic**.

This tool may be used while working in a GeMS-style geologic map database. However, the source for the input bedding trace feature layer could be a shapefile so long as it has the same projection, datum, and units as the output point feature class. The output point feature class (in GeMS, likely the OrientationPoints feature class) is expected to have long field names that are not supported by the shapefile format.

## Stack Lines?

Strata are commonly parallel over an appreciable extent and thus combined analysis of the traces of multiple strata may be useful to better determine their common strike and dip. To do this, check the **Stack Lines?** box. All traces are then translated so that the centroid of each trace is at (0,0,0), and then eigenvectors and eigenvalues are calculated.

In other instances, discontinuous separate traces of a single stratum are reasonably analyzed—without stacking—to determine strike and drip. The **Stack Lines?** box should be unchecked.

Discontinuous traces of a single stratum and traces of other parallel strata may be analyzed jointly by combining each set of discontinuous traces into a multi-part feature (while editing in ArcMap, select traces to be combined, open the Editor dropdown menu, and select Merge… ), and then selecting all traces, checking the **Stack Lines?** box, and running the script.

ObjectID (OID) values of input features are written to the Notes field of OrientationPoints. If the Stack Lines? option was selected, the OID list has a “stacked” suffix. OID lists longer than 254 characters are clipped to 254 characters.

# Prep OrientationPoints

**Prep OrientationPoints** checks for, and adds as necessary, fields that **Bedding traces to S&D** expects in its output feature class.

From the ArcMap Item Description:

***Summary***

*Adds, as necessary, fields to a point feature class to be used as source for an OrientationPoints layer in script Bedding traces to S&D.*

* *Type (string)*
* *Azimuth (float)*
* *Inclination (float)*
* *OrientationConfidenceDegrees (float)*
* *OrientationSourceID (string)*
* *Notes (string)*
* *Oblateness (float)*
* *Scatter (float)*
* *Spread (float)*

*Except for Oblateness, Scatter, and Spread these fields are already present in a GeMS OrientationPoints feature class*.

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| --- | --- | --- |
| ***Parameter*** | ***Explanation*** | ***Data Type*** |
| *OrientationPoints* | ***Dialog Reference***  *Should be a point feature class. Should have the same projection (e.g., be in the same feature dataset) as a line feature class that contains bedding traces.*  *Must not editable! If this layer is editable, stop editing.* | *Feature Class* |

# Extrapolate Planes

**Extrapolate Plane** predicts bedding traces from planar orientations at points. It is, in a sense, the inverse of **Bedding traces to S&D**.

From the ArcMap Item Description:

***Summary***

*Calculates intersections of planes with topography. Takes as input a DEM and a point feature class of strike and dip data (e.g., GeMS feature class OrientationPoints) with a selection. For each selected point, extrapolates the plane defined by the point location, strike (Azimuth), and dip (Inclination) over a distance Radius and finds the intersection of this plane with topography (the DEM). If dip = 90, a value of 89.99 is substituted.*

*To use:*

* *Set parameters*
* *Start edit session, editing OrientationPoints*
* *Select 1 or more features in OrientationPoints. These should represent planar orientations. The number of selected points must be 5 or fewer*
* *Click OK to extrapolate planes and add results to current map document*
* *You will see a red error message. This is OK if it follows a "DONE!" statement*
* *Repeat as needed*
* *Click Cancel (or upper-right X) to exit*

*Output--a raster for each input point--is written to Output Geodatabase. Scratch feature classes and scratch rasters are created in Output Geodatabase and deleted.*

*This tool was inspired by similar scripts by Drew Adams and Heather Parks (Adams and Parks, 2020) and Carli Duda (Oregon DOGAMI, personal communication, 2019).*

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| --- | --- | --- |
| ***Parameter*** | ***Explanation*** | ***Data Type*** |
| *DEM* | *Raster elevation dataset. Should overlap selected points in OrientationPoints feature class.*  *XY and Z units for this DEM should be the same.* | *Raster Dataset* |
| *grid\_declination* | *Difference, in degrees clockwise, between true North (the reference direction for OrientationPoints) and grid North (the reference direction for the DEM).*  *Can usually be assumed to be 0.0 (the default), but for the most precise work it may be appropriate to enter a non-zero value. With common large-scale map projections at low to moderate latitudes, the absolute value of grid\_declination is usually less than a few degrees.*  *If, in ArcMap, the Data Frame projection is that of the DEM, the grid declination is the Rotation value in the General tab of the Data Frame Properties window that is required to square a geographic rectangle (e.g., a quadrangle map) with the ArcMap window.* | *Double* |
| *OrientationPoints* | *Layer, in the map document, that references a point feature class that contains structural (orientation) data. Select a small number (1-5) of point features before running this script; intersections of planes with topography will be calculated for selected features only. If no features are selected, intersections will be calculated for all features. Selected points should correspond to planar orientations.*  *Script will abort if you attempt to calculate intersections for more than 5 point features.*  *Note that the referenced feature class need not be a GeMS OrientationPoints feature class. But it must have azimuth (strike) and inclination (dip) fields with the appropriate conventions: azimuth (strike) is measured in degrees clockwise from geographic north, range 0--360, and the azimuth direction is chosen so that the dip direction is to the right when facing the azimuth direction. Inclination (dip) is measured in degrees down from horizontal, range 0--90.*  ***Select with the dropdown arrow, not the folder icon.*** *If a dropdown arrow is not visible, save your work, exit ArcMap, and restart.* | *Feature Layer* |
| *Azimuth\_field* | *Field within OrientationPoints feature class that contains strike (azimuth) data. Values are measured in degrees clockwise from North (0) to E (90), S (180), W (270) and N (360). Dip direction is by convention 90 degrees clockwise from azimuth (the "Righthand Rule").* | *Field* |
| *Inclination\_field* | *Field within OrientationPoints feature class that contains dip (inclination) data. Values are measured in degrees down from horizontal and may range from 0 to 90.* | *Field* |
| *Radius* | *Distance, in map units, over which planes are extrapolated.* | *Double* |
| *Output\_Geodatabase* | *A file geodatabase, existing or created via the selection dialog.*  *Recommend that this not be the geologic-map database* | *Workspace* |

For each orientation point, the script:

* Calculates several points on the specified plane
* Uses the ArcGIS TREND function to create a raster, in the area of interest, of the plane that passes through the calculated points
* Subtracts this raster from a DEM
* Classifies the resultant raster DEM-R to obtain OutcropRaster

If abs(DEM-R) > specified value: *plane is above or below DEM*

OutcropRaster = 0

else: *plane is at surface*

OutcropRaster = 1

* Inserts OutcropRaster into the map document, symbolized so that pixels with OutcropRaster = 0 are transparent

# Down-plunge projection

Script tool **Down-plunge projection** takes a GeMS-style geologic map database, a cross-section line, and the plunge of a projection axis at right angles to the cross-section line as input and creates a new feature dataset with projected features; if there is an OrientationPoints feature class, the script calculates apparent dips for all orientation points.

The resulting feature classes do not constitute an acceptable geologic cross-section. However, they do provide a useful framework for interpreting and drafting such a cross-section.

Thoms (2005; see also <https://github.com/ethoms-usgs/Cross-Section>) presents similar code that assumes the projection axis has zero plunge. A more evolved version of the zero-plunge code is part of the GeMS toolkit (<https://github.com/usgs/gems-tools-arcmap>).

From the ArcMap Item Description:

***Summary***

*Generates backdrop feature classes useful in constructing a geologic cross section. Inputs include a GeMS-style geodatabase, a cross-section line (feature class, feature layer, or selection), and a DEM.*

*The cross-section line should be straight, with no bends in section. Projection is down-plunge; if horizontal projection is desired, enter a plunge of 0.*

*Final output is written to feature dataset* ***CrossSectionXXX*** *within the GeMS-style geodatabase, where XXX is Output\_name\_token. This feature dataset will be created if it does not exist.*

*All feature classes in the GeologicMap feature dataset are projected into the cross section feature dataset, with the exception of feature classes whose names begin with errors\_ and ed\_.*

*GeologicMap/OrientationPoints gets special treatment. Four new attributes are added to the projected equivalent:*

* *DistanceFromSection (float)--map distance from section line*
* *MapAzimuth (float)--set equal to Azimuth of unprojected points. Field Azimuth now contains azimuth in section plane of projected planar orientation*
* *Obliquity (float)--angle between section line and MapAzimuth. Measured clockwise; 90 = strike at right angles to section line, dip to right*
* *ApparentDip (float)*

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| --- | --- | --- |
| ***Parameter*** | ***Explanation*** | ***Data Type*** |
| *GeMS\_style\_geodatabase* | *A GeMS-style geodatabase with GeologicMap feature dataset* | *Workspace* |
| *DEM* | *Digital elevation model that encompasses section line and buffered selection polygon.*  *Z units should be equal to XY units of GeologicMap feature dataset.* | *Raster Dataset* |
| *DEM\_sample\_distance* | *Spacing of projected points along lines and polygon boundaries. Value is a multiplier for the DEM cell size. That is, with a 6-ft DEM and DEM\_sample\_distance of 2.5, DEM Z value will be sampled every 15 ft along lines and polygon boundaries prior to projection.* | *Double* |
| *Section\_line* | *Feature class, feature layer, or selection that contains ONLY ONE element. Section line should be straight.* | *Feature Layer* |
| *Output\_name\_token* | *Short text token used to name output feature dataset and feature classes.*  *The output feature dataset will be named CrossSection****Output\_name\_token****. If this feature dataset does not exist it will be created.*  *Output feature classes will be named CS****Output\_name\_token****Input\_featureclass\_name. Suggested values are A, B, C, ...* | *String* |
| *Plunge* | *Angle below horizon of projection axis. In degrees. Value should be >= 0.0, < 90.0* | *Double* |
| *Selection\_distance* | *Distance, in GeologicMap XY units, within which point features are projected onto the cross section plane. Section line is buffered by this distance to create a clip polygon, which is then used to clip input feature classes. Note that this results in extra data (context!) beyond the end of the section lines.* | *Double* |
| *Force\_exit* | *If checked, use sys.exit() to force an exit with error. Allows re-run of tool without re-entry of all parameters.*  *Default is false (unchecked).* | *Boolean* |

# OpenStereo Export

**OpenStereo Export** exports azimuth and inclination values to text files formatted for input to the program OpenStereo (Grohmann and Campanha, 2010; see <http://sites.igc.usp.br/openstereo/>).

From the ArcMap Item Description:

***Summary***

*Exports strike and dip from an ArcGIS point feature layer to a text file formatted for OpenStereo input.*

*OpenStereo is open-source, multiplatform software for structural geology analysis using stereonets. (c) 2009-2011 by Carlos H. Grohmann and Ginaldo A.C. Campanha.* [*http://sites.igc.usp.br/openstereo/*](http://sites.igc.usp.br/openstereo/)

|  |  |  |
| --- | --- | --- |
| ***Parameter*** | ***Explanation*** | ***Data Type*** |
| *OrientationPoints\_layer* | *Feature layer of point structural data.*  *If a selection exists in this layer, only the selected points will be exported. If no selection exists, all points will be exported.*  ***Select with the dropdown arrow, not the folder icon.*** *If a dropdown arrow is not visible, save your work, exit ArcMap, and restart.* | *Feature Layer* |
| *eAzimuth\_field* | *Field that stores the azimuth (strike, trend) of structural orientations. In GeMS, the Azimuth field.* | *Field* |
| *Inclination\_field* | *Field that stores the inclination (dip, plunge) of structural orientations. In GeMS, the Inclination field.* | *Field* |
| *Output\_location* | *Folder within which file Output Name (next field) is written.* | *Folder* |
| *Output\_name* | *Name of output file. Suggest it end with suffix " .txt "* | *String* |
| *Comment\_line (Optional)* | *Script writes 3 comment lines.*   1. *Script name, date, time* 2. *Full pathname to data source for OrientationPoints layer* 3. *Any comment entered here.* | *String* |

# Stereonet Export

**Stereonet Export** exports azimuth and inclination values to text files formatted for input to the program Stereonet 10 (by Richard Allmendinger, <http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html>)

From the ArcMap Item Description:

***Summary***

*Exports strike and dip from an ArcGIS point feature layer to a text file formatted for Stereonet input.*

*Stereonet is multiplatform software for structural geology analysis using stereonets, (c) 2011-2018 by Richard W. Allmendinger.* [*http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html*](http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html)

*Output includes 2 standard comment lines, a free-form comment line, and 1 line per feature giving*

*Azimuth, Inclination, Longitude, Latitude, Type*

*Longitude and latitude are WGS 84 datum.*

|  |  |  |
| --- | --- | --- |
| ***Parameter*** | ***Explanation*** | ***Data Type*** |
| *OrientationPoints\_layer* | *Feature layer of point structural data.*  *If a selection exists in this layer, only the selected points will be exported. If no selection exists, all points will be exported.*  ***Select with the dropdown arrow, not the folder icon.*** *If a dropdown arrow is not visible, save your work, exit ArcMap, and restart.* | *Feature Layer* |
| *Type\_field* | *Field that stores the Type (e.g., bedding, joint, minor fold) of structural orientations. In GeMS, the Type field.* | *Field* |
| *Azimuth\_field* | *Field that stores the azimuth (strike, trend) of structural orientations. In GeMS, the Azimuth field.* | *Field* |
| *Inclination\_field* | *Field that stores the inclination (dip, plunge) of structural orientations. In GeMS, the Inclination field.* | *Field* |
| *Output\_location* | *Folder within which file Output Name (next field) is written. Script will also create file geodatabase xxxxScratch.gdb in this folder and then delete it.* | *Folder* |
| *Output\_name* | *Name of output file. Suggest it end with suffix " .txt "* | *String* |
| *Comment\_line (Optional)* | *Script writes 3 comment lines:*   1. *Script name, date, and time* 2. *Full pathname to data source for OrientationPoints layer* 3. *Any comment entered here* | *String* |

# Discussion

## Eigenvector (Principal Component, Moment of Inertia) analysis

Eigenvector (or moment of inertia) analysis can be used to fit a plane to a 3-D cloud of points (Fernandez, 2005; Jones and others, 2016). Eigenvectors **ν1** and **ν2** lie in the best-fit plane, whereas **ν3** is perpendicular to it. Corresponding eigenvalues (**λ1**, **λ2**, **λ3**) correspond to the sum of variances in each direction and have units of length2. For a cloud of **n** 3-D points, sqrt(**λ1**/**n**), sqrt(**λ2**/**n**), and sqrt(**λ3**/**n**) may be thought of as the standard deviations in each direction or, approximately, the lengths of the semi-axes of the best-fit ellipsoid.

Fitting a plane to a cloud of points is a more general version of the 3-point problem—graphically or analytically translating (X1, Y1, Z1), (X2, Y2, Z2), and (X3, Y3, Z3) into strike and dip, or contours—that is part of the education of many geologists. With additional observations the problem is overdetermined, an error minimization approach is appropriate, and the answer is more robust. Ordinary least-squares regression, as embodied in the ArcMap TREND tool, provides a ready technique (e.g., Kneissl and others, 2010) that works well for planes that are nearly horizontal, but is inappropriate for resolving steeper surfaces as it assumes all error in point positions is along the Z direction. Total least squares regression—formally equivalent to principal component analysis and moment of inertia (eigenvector) analysis—provides a more appropriate solution for such fitting (Jones and others, 2016).

## What is a good fit?

Woodcock (1977) introduced the use of eigenvalues to describe rock fabrics. From his perspective, eigenvalues (and their associated eigenvectors) were a method for summarizing and analyzing orientation data that is analogous to a stereoplot. He used ratios of eigenvalues and functions of those ratios to describe fabric shape and intensity. Notably,

**C = ln (λ1/λ3)**

“is a measure of the strength of the preferred orientation” (Woodcock, 1977, p. 1232). Fernandez (2005) renamed Woodcock’s (1977) parameter **C** to **M**

**M = ln (λ1/λ3)**

and stated that it was a measure of the degree of fit—the larger M, the more coplanar the points in the cloud, “and thus the smaller the distance between the nodes and the best-fit plane.” Fernandez further noted that a large value of M was not a guarantee of a well-defined best-fit plane, as collections of nearly collinear points have low M and are equally well fit by an infinity of planes. He suggested that the parameter **K**, defined by Woodcock (1977) as

**K = ln (λ1/λ2) / ln (λ2/λ3)**

is useful to identify such collinear point clouds. Fernandez proposed

**M > 4**

**K < 0.8**

as criteria for reliable orientation values obtained by moment-of-inertia (eigenvector) analysis.

Jones and others (2016) observed that parameters M and K are scale-independent and thus inadequate for assessing the fit of planes to measured XYZ positions with real, scale-dependent, uncertainties in position. They proposed two scale-dependent tests:

Test for collinearity: Reject fits where **λ2** < **ρ2**, where **ρ** is proportional to the spatial precision of the data

Test for planarity #1: Reject fits where **λ3 > Tv**, where **Tv** is a user-defined threshold for variance. In effect, reject fits if the mean of the squared residuals is too high

and they offered an alternate, scale-independent test for planarity:

Test for planarity #2: Reject fits where **λ2/λ3 < C**, where lower values of **C** allow more curvature or irregularity of the surface being fit. Jones and others (2016) offer **C=10** as an example value

While their arguments are compelling, Jones and others (2016) offered no useful rules for obtaining **ρ**, **Tv**, and **C**. Their examples are from short-range laser scanner data with equidimensional precision of 2-6 mm. Such examples do not readily transfer to geologic interpretation of airborne lidar DEMs with likely X, Y, and Z errors that may range from 2 cm (Z) to >1 m (XY) and are strongly correlated by the local surface slope.

Gallo and others (2018) addressed the uncertainty in planar orientations inferred from eigenvector analysis of a 3-D point cloud. Monte Carlo analysis of many simulated datasets led them to observe that oblateness, defined as

**Ob = ln (λ2/λ3)**

of a point cloud is the strongest predictor of the confidence with which an orientation is inferred. If α**95** is the radius of the circle on the unit sphere that contains 95% of the poles to the calculated best-fit planes, they suggest that for **Ob** = 3, **α95** = 5°; for **Ob** = 1.5, **α95** = 10°. Generalization of their analysis (using their Figure 6, upper right graph) suggests the following formulas:

**Ob >= 1.5: α95 = 10(1.30103 – Ob\*0.200687)**

**Ob < 1.5: α95 = 10(2.2 – Ob\*0.8)**

This result is similar to the test for planarity #2 of Jones and others (2016), which rejects fits with **Ob < ln (10)**, equivalent to **α95 = 6.9°**.

Large oblateness indicates a confident fit of a plane to a point cloud but provides no guarantee that the point cloud corresponds to an outcrop trace of a planar feature. In general, the only guarantee is provided by the judgement of the observer. One can, however, ask that the dimensions of the point cloud be consistent with likely errors in the observations, particularly that **sqrt(λ3/n)** be smaller than likely measurement errors and **sqrt(λ2/n)** be larger than such errors.

Script BeddingTracesToS&D.py contains four tests for the reliability of a fitted plane. Cutoff values for **n**, **sqrt(λ2/n)**, **sqrt(λ3/n)**, and **Ob** are based on my experience analyzing traces of thick fluvial sandstone beds that are visible in 3-ft (XY) resolution airborne lidar DEMs of steep, lightly-wooded, non-glaciated terrain with hundreds of meters of local relief. Other strata, other sensing technology, and other terrain may dictate other cutoff values. These cutoff values may be changed on lines 16-19 of file BeddingTracesToS&D.py.

1. Reject fits where **n < 15**

Sample size should play a role. Note that since observed traces are uniformly densified to produce input points this is a proxy for trace length. Some traces are simply too short, given the observation scale, to produce a useful result.

If you get an error message that n is too small, consider whether there are nearby traces of coplanar beds that this trace could be stacked with.

1. Reject fits where **sqrt(λ3/n) > 3 \* DEM cell size**

Variance in the direction of least scatter should be no more than expected from the imprecision in point location (3 \* DEM cell size). Greater scatter likely indicates that the feature being observed is not planar, lack of care in digitizing bedding trace(s), or unusually large errors in the DEM. This is an instance of Jones and others’ (2016) first test for planarity.

If you get an error message that scatter is too large, you may wish to examine the digitized bedding trace to see if it’s location can be improved.

1. Reject fits with **sqrt(λ2/n) < 3 \* DEM cell size**

Variance in the intermediate direction should be significantly larger than the imprecision in point location (3 \* DEM cell size). Some nearly-colinear point clouds may have high oblateness (for example, a surface trace digitized as a straight line over subtle topography) but insufficient spread in the intermediate direction to provide a confident orientation. This is an instance of Jones and others’ (2016) test for collinearity. Note that this test implicitly establishes a minimum value for **λ1/n.**

If you get an error message that spread is too small, consider whether there are nearby, non-parallel, traces of coplanar beds that this trace could be stacked with.

1. Reject fits with **Ob < 1.2** (equivalent to rejecting fits with **λ2/λ3 < 3.32**)

**λ3** should be small relative to **λ2**. Large values of **λ3** may indicate a trace that is poorly observed or the trace of a surface that is not planar. This test is similar to, but more permissive than, Jones and others’ (2016) second test for planarity.

BeddingTracesToS&D.py assigns OrientationConfidenceDegrees (**α95**) on the basis of oblateness using the formulas above, which I extrapolated from the numerical experiments of Gallo and others (2018).

A few results that pass these tests are clearly unrealistic. All results should be approved by a knowledgeable observer! One could use the **Extrapolate Planes** tool to see if forward modeling of the bedding trace from the fitted strike and dip matches the observed bedding trace.

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# References Cited

Adams, D.B., and Parks, H.L., 2020, The surface trace tool—Modeling complex planar interactions using ArcGIS: U.S. Geological Survey Open-File Report 2019–1136, 14 p., https://doi.org/10.3133/ofr20191136.

Fernández, O., 2005, Obtaining a best fitting plane through 3D georeferenced data: Journal of Structural Geology, v. 27, p. 855–858, doi:10.1016/j.jsg.2004.12.004 .

Gallo, L. C., Cristallini, E. O., and Svarc, M., 2018, A nonparametric approach for assessing precision in georeferenced point clouds best fit planes: Toward more reliable thresholds: Journal of Geophysical Research: Solid Earth, v. 123. <https://doi.org/10.1029/2018JB016319>

Grohmann, C.H., and Campanha, G.A., 2010, OpenStereo: Open source, cross-platform software for structural geology analysis: AGU Fall Meeting Abstracts, <https://ui.adsabs.harvard.edu/abs/2010AGUFMIN31C..06G/abstract>

Jones, R.R., Pearce, M.A., Jacquemyn, C., and Watson, F.E., 2016, Robust best-fit planes from geospatial data: Geosphere, v. 12, no. 1, p. 196–202, doi:10.1130/GES01247.1.

Kneissl, T., van Gasselt, S., and Neukum, G., 2010, Measurement of strike and dip of geologic layers from remote sensing data – new software tool for ArcGIS: 41st Lunar and Planetary Science Conference, abstract 1630, <https://www.lpi.usra.edu/meetings/lpsc2010/pdf/1640.pdf> (February 9, 2020).

USGS NCGMP (U.S. Geological Survey National Cooperative Geologic Mapping Program), 2020, GeMS—a standard format for the digital publication of geologic maps: U.S. Geological Survey, Techniques and Methods Book 11, Chap. B10, 74 p., [https://doi.org//10.3133/tm](https://doi.org/x)11B10. *Draft version at* [*https://ngmdb.usgs.gov/Info/standards/GeMS/*](https://ngmdb.usgs.gov/Info/standards/GeMS/),

Woodcock, N.H., 1977, Specification of fabric shapes using an eigenvalue method: Geological Society of America Bulletin, v. 88, p. 1231–1236, <https://doi.org/10.1130/0016-7606(1977)88%3C1231:SOFSUA%3E2.0.CO;2>.