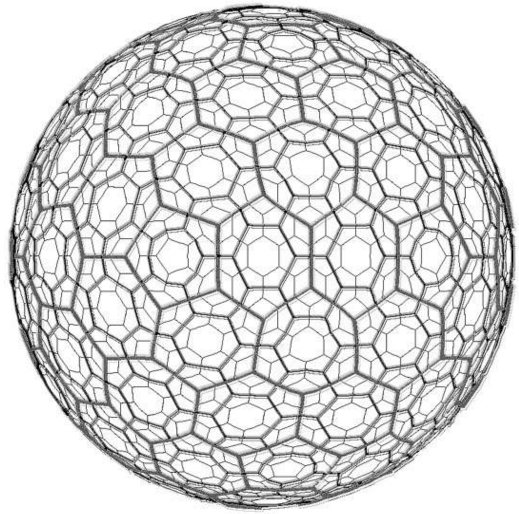

DGGRID version 6.2b

User Documentation for
Discrete Global Grid Generation Software

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TERRA
COGNITA
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Terms of Use

DGGRID is provided purely as a research tool. While we believe it performs as described in this documentation, we do not guarantee or warranty **DGGRID** for any specific use or purpose. Users of **DGGRID** must agree to take full responsibility for any damages that may occur through such use and agree not to hold the creators of **DGGRID** liable for any such damages.

DGGRID is fully in the public domain and may be used for any purpose with no restrictions. We do, however, ask that you acknowledge your use of **DGGRID** as applicable.

Credits

DGGRID was entirely written in C++ by Kevin Sahr with the following exceptions:

- **DGGRID** uses a (slightly modified) version of Alan Murta's General Polygon Clipping (GPC) library. See http://www.cs.man.ac.uk/aig/staff/alan/software/ for more details.

- Lian Song wrote the original versions of some of the spherical trigonometry routines and the original implementation of the ISEA projection.

- The gnomonic projection code is adapted from Gerald Evanden's PROJ.4 library. See http://everest.hunter.cuny.edu/mp/software.html for more details.

- **DGGRID** uses George Marsaglia's multiply-with-carry "Mother-of-all-RNGs" pseudo-random number generation function.

- Jesse Williamson ported the code to gcc 4.x and added the KML output support.

- The Fuller projection code was written in **R** by Denis White and then ported to C++ by James Scharmann.

- Matthew Gregory added the GeoJSON output support.

The **DGGRID** specifications were developed by (in alphabetical order): A. Ross Kiester, Tony Olsen, Barbara Rosenbaum, Kevin Sahr, Ann Whelan, and Denis White.

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www.discreteglobalgrids.org

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1. Introduction

DGGRID is a command-line application designed to generate and manipulate icosahedral discrete global grids (DGGs) [Sahr et al., 2003]. A single execution of **DGGRID** can perform one of five distinct operations:

1. *Grid Generation*. Generate the cells of a DGG, either covering the complete surface of the earth or covering only a specific set of regions on the earth's surface.

2. *Address Conversion*. Transform a file of locations from one address form (such as longitude/latitude) to another (such as DGG cell indexes).

3. *Point Value Binning*. Bin a set of floating-point values associated with point locations into the cells of a DGG, by assigning to each DGG cell the arithmetic mean of the values which are contained in that cell.

4. *Presence/Absence Binning*. Given a set of input files, each containing point locations associated with a particular class, **DGGRID** outputs, for each cell of a DGG, a vector indicating whether or not each class is present in that cell.

5. *Output Grid Statistics*. Output a table of grid characteristics for the specified DGG.

DGGRID is designed to be run from the Unix command line. **DGGRID** requires a single command line argument, the name of a "metafile," which is a text file that describes the actions that **DGGRID** is to perform in that run. Thus **DGGRID** is executed by typing at the command line:

```
dggrid metaFileName.meta
```

The metafile consists of a series of key-value pairs that tell **DGGRID** how to proceed. The format of this metafile is described in the next section. The rest of the sections in this documentation give more detail on setting up metafile parameters to control the execution of **DGGRID**.

2. Metafile Format

Metafiles are text files in which each line is either a comment, a blank line, or a key-value pair that designates the value of a parameter for **DGGRID**. Blank lines are ignored by **DGGRID**. Lines beginning with '#' are comments and are also ignored by **DGGRID**.

A parameter is specified by a single line of the form:

parameterName value

Parameter names are not case sensitive. A parameter can be of one of five types. The five parameter types, with a description of their legal values, are:

1. **boolean**. Legal values are **TRUE** and **FALSE** (case sensitive).
2. **integer**. Any integer is a legal value.
3. **double**. Any real number, specified in decimal form, is a legal value.
4. **string**. The remainder of the line following the parameter name is interpreted as the value. 5. **choice**. Legal values consist of one of a finite set of keywords specific to that parameter. The values of choice parameters are not case sensitive but by convention are usually written in all capital letters.

Some parameters are only used for specific operations or when specific other parameter conditions prevail. All parameters have a default value which is used if no value is specified. Detailed information on each parameter is given in the following sections and in **Appendix A**. Repeating a parameter specification within the same metafile over-writes the previously specified value; the last value given for a particular parameter will be used.

Note that a number of parameters from previous versions of **DGGRID** are still active in the code but are not described in this documentation; that is because those parameters have not been fully integrated with the new features in this beta release. Those parameters will be fully restored in a future release.

See the example metafiles that come with the **DGGRID** source code distribution for examples of parameter specification.

3. General Parameters

In this section we describe the parameters which are used by every run of **DGGRID**.

As described in **Section 1**, each run of **DGGRID** consists of one of five distinct modes of operation. The operation is specified using the **choice** parameter `dggrid_operation`. The allowable values for this parameter are:

`GENERATE_GRID` - perform grid generation (see **Sections 5** and **6**)
`TRANSFORM_POINTS` - perform address conversion (see **Section 8**)
`BIN_POINT_VALS` - perform point value binning (see **Section 8**)
`BIN_POINT_PRESENCE` - perform presence/absence binning (see **Section 9**)
`OUTPUT_STATS` - output a table of grid characteristics (see **Section 10**)

All operation modes require the specification of a single DGG. The parameters for specifying a DGG are described in **Section 4**.

The **integer** parameter `precision` specifies the number of digits to the right of the decimal place **DGGRID** is to use when outputting floating point numbers.

The **integer** parameter `verbosity` is used to control the amount of debugging information which is printed by **DGGRID**. Valid values are from `0` to `3`. The default value, `0`, gives minimal output, which includes the value of all active parameter settings. It is not recommended that you increase this value.

4. Specifying the DGG

Background

As described in [Sahr et al., 2003], a DGG system can be specified by a set of independent design choices. The first design choice is the desired base polyhedron; **DGGRID** can generate DGGs that have an icosahedron as their base polyhedron. The remaining primary design choices are:

1. The orientation of the base polyhedron relative to the earth.
2. The hierarchical spatial partitioning method defined symmetrically on a face (or set of faces) of the base polyhedron. This usually includes specifying the cell topology and an *aperture*, which determines the area ratio between cells at sequential resolutions.
3. The transformation between each face and the corresponding spherical surface.
4. The resolution (or degree of recursive partitioning).

The current version of **DGGRID** supports DGGs that use either the Icosahedral Snyder Equal Area (ISEA) projection [Snyder, 1992] or the icosahedral projection of R. Buckminster Fuller [1975] (as developed analytically by Robert Gray [1995] and John Crider [2008]). **DGGRID** can generate grids with cells that are triangles, diamonds, or hexagons. Grids with a triangle or diamond topology must use an aperture of 4, while hexagon grids can use an aperture of 3, 4, or a mixed aperture sequence consisting of some number of aperture 4 resolutions followed by aperture 3 resolutions down to the desired resolution. **DGGRID** can also generate the **Superfund_500m** DGG (see **Appendix E**), which is a mixed aperture hexagonal grid that uses the Fuller projection and a condensed hierarchical indexing.

Detailed information about the parameters that specify each of the DGG design choices are given below, along with a discussion on specifying the spherical earth radius. **Appendix D** gives a table of DGGs which can be generated by **DGGRID**; the table lists the parameters for each DGG and the corresponding characteristics of each resulting grid.

Preset DGG Types

DGGRID provides a number of preset DGG types for your use. A preset type can be chosen by specifying one of the following values for the **choice** parameter `dggs_type`:

`CUSTOM` (default) - indicates that the grid parameters will be specified manually (see below)
`SUPERFUND` - the **Superfund_500m** grid (see **Appendix D**)
`ISEA4T` - ISEA projection with triangle cells and an aperture of 4
`ISEA4D` - ISEA projection with diamond cells and an aperture of 4
`ISEA3H` - ISEA projection with hexagon cells and an aperture of 3
`ISEA4H` - ISEA projection with hexagon cells and an aperture of 4
`ISEA43H` - ISEA projection with hexagon cells and a mixed sequence of aperture 4 resolutions followed by aperture 3 resolutions

`FULLER4T` - FULLER projection with triangle cells and an aperture of 4
`FULLER4D` - FULLER projection with diamond cells and an aperture of 4
`FULLER3H` - FULLER projection with hexagon cells and an aperture of 3
`FULLER4H` - FULLER projection with hexagon cells and an aperture of 4
`FULLER43H` - FULLER projection with hexagon cells and a mixed sequence of aperture 4 resolutions followed by aperture 3 resolutions

Each preset grid type sets appropriate values for all of the parameters that specify a DGG. The default values for each preset grid type are given in **Appendix B**. These default preset values can be overridden by explicitly setting the desired individual parameters in your metafile as described below. In particular, note that all preset grid types have a default resolution of `9`; a desired DGG resolution can be specified using the parameter `dggs_res_spec` (see below).

Manually Setting DGG Parameters

The following parameters are used to describe a specific DGG instance.

1. Specifying the orientation: The orientation of a DGG base icosahedron relative to the earth can be specified explicitly, randomly determined, or set so that a specified point is maximally distant from icosahedron vertices, by setting the **choice** parameter `dggs_orient_specify_type` to `SPECIFIED`, `RANDOM`, or `REGION_CENTER` respectively.

If `dggs_orient_specify_type` is set to `SPECIFIED` the DGG orientation is determined by the location of a single icosahedron vertex and the azimuth from that vertex to an adjacent vertex. The **double** parameters `dggs_vert0_lon` and `dggs_vert0_lat` are used to specify the location of the vertex, and the **double** parameter `dggs_vert0_azimuth` to specify the azimuth to an adjacent vertex; all or these parameters are in decimal degrees. Note that the default DGG placement, which is symmetrical about the equator and has only a single icosahedron vertex falling on land, is specified by:

```
dggs_vert0_lon 11.25
dggs_vert0_lat 58.28252559
dggs_vert0_azimuth 0.0
```

If `dggs_orient_specify_type` is set to `RANDOM` the orientation of the DGG is randomly determined. All parameter values (including the randomly generated values for a vertex location and azimuth used to orient the grid) will be output for your information to the file specified by the **string** parameter `dggs_orient_output_file_name`. Some control over the random specification of the grid orientation is afforded by the **choice** parameter `rng_type` and the **integer** parameter `dggs_orient_rand_seed`. The **choice** parameter `rng_type` indicates which pseudo-random number generator to use. A value of `RAND` indicates that the C standard library `rand/srand` functions should be used. A value of `MOTHER` (the default) indicates that George Marsaglia's "Mother-of-all-RNGs" function should be used. The seed value for

DGGRID to use to initialize the pseudo-random number sequence can be set using the **integer** parameter `dggs_orient_rand_seed`.

If the current operation involves only a small region on the earth's surface it is often convenient to orient the grid so that no icosahedron vertices occur in the region of interest. Such an orientation can be specified by setting `dggs_orient_specify_type` to `REGION_CENTER` and then specifying the center point of the region using the **double** parameters `region_center_lon` and `region_center_lat` (both in decimal degrees).

All operations require that at least one DGG be specified. A single DGG may be used by setting the **integer** parameter `dggs_num_placements` to 1 (the default). Alternatively, you may perform the desired operation on multiple DGGs by setting `dggs_num_placements` to the desired number. If the grid orientation is randomly chosen, this will perform the desired operation on multiple randomly oriented grids. The parameters for each grid will be output to a separate file based on the value of `dggs_orient_output_file_name`, with an additional suffix indicating the grid number (0001 to 000*n* where *n* equals the value of `dggs_num_placements`). This suffix will also be used to designate the corresponding output files (as specified in the particular operation being performed). Note that if `dggs_orient_specify_type` is set to any value other than `RANDOM` all of the grids generated will have exactly the same orientation.

2. Specifying the hierarchical spatial partitioning method: The hierarchical partitioning method used to generate the DGG is specified by choosing a grid topology and aperture (defined as the ratio of areas between cells in a given DGG resolution and the next finer resolution). The topology is specified using the **choice** parameter `dggs_topology` with one of the values: `HEXAGON` (default), `TRIANGLE`, or `DIAMOND`.

DGGRID can create grids that are produced using a single aperture, as well as hexagon grids produced using a mixed aperture of some number of aperture 4 resolutions followed by aperture 3 resolutions. The type of aperture is specified using the **choice** parameter `dggs_aperture_type` with a value of either `PURE` (default) or `MIXED43`. If a PURE aperture type is specified then the desired aperture is specified with the **integer** parameter `dggs_aperture`. The valid values for aperture are dependent on the chosen topology. **DGGRID** can create `HEXAGON` DGGs with an aperture of 3 or 4, and `DIAMOND` and `TRIANGLE` DGGs with an aperture of 4.

If a `MIXED43` aperture type is specified then the parameter `dggs_aperture` is ignored. Instead, the **integer** parameter `dggs_num_aperture_4_res` (default 0) specifies the number of resolutions which use aperture 4; the remaining grid resolutions up to the desired grid resolution (see the next subsection) are generated using aperture 3. Note that the parameter `dggs_num_aperture_4_res` is ignored with `PURE` aperture grids. Only `HEXAGON` topology grids may use the `MIXED43` aperture type.

3. Specifying the projection: The regular polygon boundaries and points associated with DGG cells are initially created on the planar faces of an icosahedron; they must then be inversely projected to the sphere. The desired projection to use for this is specified by the **choice** parameter `dggs_proj`. The valid values are `ISEA`, which specifies the Icosahedral Snyder Equal Area projection [Snyder, 1992], or `FULLER`, which specifies the icosahedral Dymaxion projection of R. Buckminster Fuller [1975] (as developed analytically by Robert Gray [1995] and John Crider [2008]). The ISEA projection creates equal area cells on the sphere at the expense of relatively high shape distortion, while the Fuller projection strikes a balance between area and shape distortion. See Gregory et al. [2008] for a more detailed discussion of these trade-offs.

4. Specifying the resolution: The desired DGG resolution can be specified using one of three methods chosen using the **choice** parameter `dggs_res_specify_type` with one of the following values:

`SPECIFIED` (default) - the desired resolution is explicitly specified by setting the value of the integer parameter `dggs_res_spec` (default 9).
`CELL_AREA` - the desired resolution is set to the DGG resolution whose cell area is closest to the area specified by the **double** parameter `dggs_res_specify_area` (in square kilometers).
`INTERCELL_DISTANCE` - the desired resolution is set to the DGG resolution whose intercell distance is closest to the distance specified by the **double** parameter `dggs_res_specify_intercell_distance` (in kilometers).

If `CELL_AREA` or `INTERCELL_DISTANCE` is specified, then the desired area or intercell distance (as applicable) is rounded up or down to the nearest grid resolution based on the value of the **boolean** parameter `dggs_res_specify_rnd_down`; a value of `TRUE` indicates round down, a value of `FALSE` indicates round up. The chosen resolution is always output by **DGGRID** for your information. The calculation of cell areas and intercell distances uses the value specified for the earth radius (see **Subsection 5** below).

If the `dggs_type` is specified to be `SUPERFUND` then the only supported value for `dggs_res_specify_type` is `SPECIFIED`, and the maximum resolution is 9.

DGGRID will attempt to generate grids up to a maximum resolution of **35** (except in the case of `SUPERFUND` grids, which have a maximum resolution of 9). However, the maximum resolution which can be successfully generated by **DGGRID** is a function of the specified grid topology, projection, the size of data types on the machine on which **DGGRID** is compiled and executed, and the location of the generated grid region relative to the faces of the underlying icosahedron. When generating very high resolution grids the user should be aware that even if **DGGRID** reports success the indexes and output cell geometries should be checked by the user to make sure that they are not degenerate.

5. Specifying the earth radius: The **choice** parameter `proj_datum` specifies a datum that **DGGRID** will use to determine the spherical radius of the earth. The legal values for this parameter are given below, along with the earth radius that they indicate:

`WGS84_AUTHALIC_SPHERE` (default): 6371.007180918475 km

`WGS84_MEAN_SPHERE`: 6371.0087714 km
`CUSTOM_SPHERE`: the earth radius (in kilometers) will be read from the double parameter `proj_datum_radius`

Note that the earth radius is *not* used in the process of generating grid geometries in geodetic coordinates; such generation is performed on a unit sphere. The radius is only used in determining the grid resolution (when `dggs_res_specify_type` is not `SPECIFIED`) and in generating grid statistics in kilometers.

5. Controlling Grid Generation

Specifying the value `GENERATE_GRID` for the **choice** parameter `dggrid_operation` will tell **DGGRID** to create all, or some portion of, the specified DGG (see the previous section). The **choice** parameter `clip_subset_type` controls the amount of the grid that will be generated. Setting the parameter `clip_subset_type` to `WHOLE_EARTH` will generate the entire earth at the specified resolution.

To generate just a portion of the earth you must specify one or more files containing polygons which **DGGRID** will use to determine the portion of the grid to generate. **DGGRID** supports two clipping file formats: ARC/INFO Generate files and ESRI Shapefiles. To specify a clipping file format, set the parameter `clip_subset_type` to `AIGEN` for ARC/INFO Generate files or to `SHAPEFILE` for ESRI Shapefiles.

The ARC/INFO Generate file format is a text file format that provides a way to create clipping regions manually, using just a text editor. For reference, the ARC/INFO Generate polygon file format consists of a text file containing a series of polygons. Each polygon is described by an entry of the form (assuming *n* vertices, in clockwise order):

```
integerPolygonID centerPtLon centerPtLat
vert1Lon vert1Lat
vert2Lon vert2Lat
    ...
vertnLon vertnLat
vert1Lon vert1Lat
END
```

The *centerPtLon* and *centerPtLat* values in the first line of the polygon description can be omitted when creating **DGGRID** clipping files.

To indicate the end of the file the last polygon is followed by an extra:

```
END
```

For example, the following ARC/INFO Generate file would specify a single triangular clipping polygon in southern Oregon:

```
1
-122.7083 42.1947
-121.5000 42.5000
-122.5688 42.4300
-122.7083 42.1947
END
END
```

Though both the ARC/INFO Generate and ESRI Shapefile formats support holes, **DGGRID** does not. Therefore holes in the clipping files will be interpreted by **DGGRID** as regular polygons.

If `clip_subset_type` is set to `AIGEN` or `SHAPEFILE` then the string parameter `clip_region_files` should be set to a space-delimited list of file names containing polygons to use for clipping. These polygons must be specified using geodetic (latitude/longitude) coordinates. Limitations in **DGGRID** require that each clipping polygon be no more than approximately 60° of great circle arc in extant in any direction. The exact limitation is determined by the relationship between each polygon and the underlying icosahedron; **DGGRID** will let you know if a polygon is too large for the grid generation you are attempting. In that event you must break the polygon into smaller polygons before using it in a clipping file.

Intersections between the clipping polygons and the DGG cells are performed in the specified DGG projection space, with the great circle arcs between adjacent vertices in the original clipping polygons transformed into straight lines on the projection plane. If adjacent vertices in the original clipping polygons are too far apart this may result in an inaccurate representation of the region boundary in the clipping space. This effect can be minimized by introducing additional points into the great circle arcs before projection. Setting the double parameter `geodetic_densify` to some arc length (in decimal degrees) will cause **DGGRID** to introduce extra points into each edge arc so that no two vertices are more than the specified distance apart. Setting `geodetic_densify` to `0.0` (the default) indicates that no such densification is to be performed.

Note that a single execution of **DGGRID** can take several hours, depending on the resolution of the grid being generated and the number and complexity of the clipping polygons. You can control the frequency of feedback during grid generation by setting the integer parameter `update_frequency`. The value of this parameter specifies the number of cells that will be tested for inclusion before outputting a status update. The default value is `100000`.

6. Specifying Generated Grid Output

The grid cells generated by a **DGGRID** run with the value `GENERATE_GRID` specified for the **choice** parameter `dggrid_operation` can be output as cell boundaries, cell center points, or both. All DGG output from **DGGRID** is given in geodetic (longitude/latitude) coordinates in decimal degrees.

The **choice** parameters `cell_output_type` and `point_output_type` specify the desired output file format for cell boundaries and cell points respectively. Each of these parameters may have the following values:

> `NONE` - indicates that no output of that type will be performed
> `AIGEN` - indicates that the cell/point output should be in ARC/INFO Generate file format
> `SHAPEFILE` - indicates that the cell/point output should be in ESRI Shapefile format.
> `KML` - indicates that the cell/point output should be in KML (Google Earth) format

The file name prefix to use for the boundary or point output file is specified using the **string** parameter `cell_output_file_name` or `point_output_file_name` respectively. **DGGRID** will add the appropriate file suffix to the specified prefix name, depending on the chosen file format.

DGG output files created by **DGGRID** can be quite large, depending on the size of the region being generated and the resolution of the grid. The generated cell boundaries and/or points can be output across multiple files by setting the **integer** parameter `max_cells_per_output_file` to the maximum number of cells to output to a single file. Setting the parameter to 0 (the default) will cause **DGGRID** to output all cells to a single file, no matter how large. If `max_cells_per_output_file` is greater than 0, output files are distinguished by appending a "_1", "_2", etc. to each output file name.

Since cell boundaries are only true regular polygons in the chosen projection space it may be desirable to introduce additional points into the cell edges to better preserve the boundary shape after inverse projection to longitude/latitude coordinates. The number of additional points to introduce into each edge is specified by the **integer** parameter `densification`. A value of 0 (the default) indicates that no densification should be performed.

A unique integer cell identifier is output along with each cell boundary or point. The integer identifier type is specified using the **choice** parameter `output_cell_label_type`, which can have one of three values:

`GLOBAL_SEQUENCE` (default when `dggs_type` is not `SUPERFUND`) - the identifier is the appropriate value in a linear sequence 1 to *n*, where *n* is the total number of cells in the whole earth DGG

`ENUMERATION` - the generated cells are numbered from 1 to *n*, where *n* is the total number of cells generated

`SUPERFUND` (preset default when `dggs_type` is `SUPERFUND`) - the identifier is a condensed Superfund_500m index (see **Appendix D**). This value must be (and can only be) used when `dggs_type` is `SUPERFUND`.

When output is to an ESRI Shapefile the cell identifier is stored in a `global_id` field. The ESRI Shapefile format limits integer fields to 32-bit integer size, which is not sufficient for storing the identifiers associated with high resolution DGGs. Therefore **DGGRID** creates the Shapefile field **`global_id`** as a fixed width string with a width specified by the **integer** parameter `shapefile_id_field_length` (default `11`).

The color and width of KML output cell boundaries can be controlled using the **string** parameter `kml_default_color` (default `ffffffff` or opaque white) and the **integer** parameter `kml_default_width` (default 4) respectively. KML color values are expressed in 8 digit hexadecimal notation of the form *aabbggrr*, with two hexadecimal digits (`00` to `ff`) each for the alpha, blue, green, and red components.

7. Outputting Grid Statistics

Specifying the value `OUTPUT_STATS` for the **choice** parameter `dggrid_operation` causes **DGGRID** to output a table of grid characteristics for the specified DGG (see **Section 4**). The output table will consist of all grid resolutions from 0 up to and including the specified DGG resolution. The values output for each resolution are the number of cells, the area of a hexagonal cell in square kilometers, the intercell distance in kilometers, and the characteristic length scale (CLS). The CLS is the diameter of a spherical cap of the same area as a hexagonal cell of the specified resolution; this metric was suggested by Ralph Kahn. The calculation of cell areas and intercell distances uses the specified earth radius (see **Section 5.5**). Area and distance values are calculated in the projection plane; the actual values for individual cells will vary based on the characteristics of the chosen projection.

The **integer** parameter `precision` (default 7) specifies the number of digits to the right of the decimal point to output for each floating point value.

8. Performing Address Conversions

Setting the **choice** parameter `dggrid_operation` to `TRANSFORM_POINTS` tells **DGGRID** to perform address conversion. **DGGRID** reads the input file specified in the string parameter `input_file_name`. It interprets each line of the file as consisting of an address followed by optional arbitrary text. The components of the address (if any) must be delimited by the character indicated within double quotes in the **string** parameter `input_delimiter`, and if there is text following the address it must also be separated from the address by that character. The address must be a valid address under the address form indicated in the **choice** parameter `input_address_type` (see **Appendix C**). Addresses of types other than `GEO` are interpreted as addresses in a DGG specified as per **Section 4**.

Each input address is transformed to an address of the form indicated by the **choice** parameter `output_address_type`. For all values of `output_address_type` except for `AIGEN` (see below) each transformed address is output using the value of `output_delimiter` to separate any address components. The addresses are output to the file specified in the **string** parameter `output_file_name`. If there was additional text on the input line following the address, then an output delimiter followed by that text is appended to the output line.

If `output_address_type` is `AIGEN` then the output will be in ARC/INFO Generate file format. For each input address, the output will consist of the cell polygon of the DGG cell corresponding to the input address. Any additional text on the input lines following the addresses will be ignored.

The `TRANSFORM_POINTS` operation can be used to determine the DGG cells that correspond to a set of input geodetic coordinates by using an `input_address_type` of `GEO` and an `output_address_type` corresponding to the desired DGG indexing (e.g., `SEQNUM`). Note that **DGGRID** cannot be used to transform between two different DGGs in a single run, since only one DGG can be defined per run. However, this can be accomplished in two steps by first using **DGGRID** to transform cell addresses in the input DGG into `GEO` addresses, and then using a second run of **DGGRID** to transform those GEO addresses into the desired output DGG.

9. Binning Point Values

Setting the choice parameter `dggrid_operation` to `BIN_POINT_VALS` tells **DGGRID** to bin a set of floating-point data values associated with geodetic coordinates into the cells of a DGG(s) specified as per **Section 4**. The binning is performed by assigning to each DGG cell the arithmetic mean of the values which are contained in that cell.

DGGRID reads each of the input files specified in the string parameter `input_files`. Each line in each file should consist of a longitude, a latitude (both in decimal degrees), and a floating-point value. These three values must be delimited by the character indicated within double quotes in the string parameter `input_delimiter`. **DGGRID** then bins these values into the cells of the specified DGG(s).

DGGRID outputs the cell address and value associated with each cell, one cell per line, into the file specified in the string parameter `output_file`. The cell addresses are output in the form indicated by the choice parameter `output_address_type` (see **Appendix C**), using the character specified by parameter `output_delimiter` to separate any address components and to separate the address from the associated value. By setting the choice parameter `cell_output_control` you can limit **DGGRID** to only outputting those cells which contain values (`OUTPUT_OCCUPIED`) or have **DGGRID** output all cells (`OUTPUT_ALL`), in which case cells in which no values occurred will be output with a value of 0.0.

If the data to be binned covers a substantial portion of the earth's surface, then the choice parameter `bin_coverage` should be set to `GLOBAL`. If the data covers only a relatively small portion of the earth's surface then `bin_coverage` should be set to `PARTIAL`. This allows **DGGRID** to make trade-offs between speed and memory usage. `GLOBAL` data sets are binned more quickly, but may fail at higher DGG resolutions due to memory restrictions. `PARTIAL` data sets are binned more slowly, but can often be binned at higher resolutions (depending on the actual extent of the data set).

10. Presence/Absence Binning.

Setting the choice parameter `dggrid_operation` to `BIN_POINT_PRESENCE` tells **DGGRID** to perform presence/absence binning into the DGG(s) specified as per **Section 4**.

The input to this operation is a set of files, with each file containing a set of locations associated with one specific class of objects. The names of the input files are specified as a space-delimited list of file names in the string `parameter input_files`. The locations in the files must be specified as longitude/latitude in decimal degrees, one per line, with the components separated by the character indicated within double quotes in the string parameter `input_delimiter`. Each location can be followed, on the same line, by arbitrary text which is ignored by **DGGRID**.

DGGRID determines which classes occur in which cells in the specified DGG(s). **DGGRID** outputs the results for each cell, one cell per line, into the file specified in the string parameter `output_file`. The output for each cell consists of a cell address and a presence/absence vector, separated by the character specified (inside double quotes) in the string parameter `output_delimiter`. The cell addresses are output in the form indicated by the choice parameter `output_address_type` (see **Appendix C**), using the value of `output_delimiter` to separate any address components. The presence/absence vector consists of a string of 0's and 1's. The length of the string corresponds to the number of input files (and therefore to the number of classes). Each character in the string indicates whether the corresponding class is present (indicated by a 1) or not present (indicated by a 0) in the cell specified on that line. The first character in the string corresponds to the class represented by the first file listed in `input_files`, the second character corresponds to the second file listed in `input_files`, and so forth. Additionally, if the boolean parameter `output_count` is set to `TRUE` the number of classes present in a each cell is output in between the address and the presence/absence vector.

By setting the choice parameter `cell_output_control` you can limit **DGGRID** to only out-putting those cells which contain at least one class of object (`OUTPUT_OCCUPIED`) or have **DGGRID** output all cells (`OUTPUT_ALL`), in which case cells containing no input-specified locations would have presence/absence vectors consisting entirely of 0's.

If the in put locations cover a substantial portion of the earth's surface, then the choice parameter `bin_coverage` should be set to `GLOBAL`. If the locations covers only a relatively small portion of the earth's surface then `bin_coverage` should be set to `PARTIAL`. This allows **DGGRID** to make trade-offs between speed and memory usage. `GLOBAL` location sets are processed more quickly, but may fail at higher DGG resolutions due to memory restrictions. `PARTIAL` location sets are processed more slowly, but can often use higher resolution DGGs (depending on the actual extent of the input locations).

Appendix A. DGGRID Metafile Parameter

Parameter Name (Type)	Description	Allowed Values (v)	Default	Notes	Used When
bin_coverage (**choice**)	are values distributed over most of the globe or only a relatively small portion?	GLOBAL PARTIAL	GLOBAL	allows **DGGRID** to determine how to trade-off speed vs. memory usage	dggrid_operation is BIN_POINT_VALS or BIN_POINT_PRESENCE
cell_output_file_name (**string**)	cell boundary output file name prefix	any	"cells"		cell_output_type is AIGEN, SHAPEFILE, or KML
cell_output_control (**choice**)	designates which cells to output	OUTPUT_ALL OUTPUT_OCCUPIED	OUTPUT_ALL	OUTPUT_ALL - output all cells, even if no input values were associated with them OUTPUT_OCCUPIED - output only cells with associated input values	dggrid_operation is BIN_POINT_VALS or BIN_POINT_PRESENCE
cell_output_type (**choice**)	cell boundary output file format	NONE AIGEN SHAPEFILE KML GEOJSON	AIGEN		dggrid_operation is GENERATE_GRID
clip_region_files (**string**)	space delimited list of files that specify grid clipping	any	"test.gen"		dggrid_operation is GENERATE_GRID
clip_subset_type (**choice**)	specifies how portion of DGG to generate will be determined	WHOLE_EARTH AIGEN SHAPEFILE	WHOLE_EARTH		dggrid_operation is GENERATE_GRID
clip_type (**choice**)	method for determining whether a cell is included by a clipping polygon	POLY_INTERSECT	POLY_INTERSECT		dggrid_operation is GENERATE_GRID
densification (**integer**)	number of points-per-edge densification to use when generating cell boundaries	$0 \leq v \leq 500$	0	v of 0 indicates no densification	dggrid_operation is GENERATE_GRID
dggrid_operation (**choice**)	specifies the operation to be performed by this run of **DGGRID**	GENERATE_GRID BIN_POINT_VALS BIN_POINT_PRESENCE TRANSFORM_POINTS OUTPUT_STATS	GENERATE_GRID		always

Parameter Name (Type)	Description	Allowed Values (v)	Default	Notes	Used When
dggs_aperture (**integer**)	desired DGGS aperture	3, 4	4		dggs_aperture_type is PURE
dggs_aperture_type (**choice**)	is the aperture sequence constant or mixed?	PURE MIXED43	PURE		dggs_topology is HEXAGON
dggs_num_aperture_4_res (**integer**)	number of aperture 4 resolutions in a mixed aperture sequence	$0 \leq v \leq 35$	0		dggs_aperture_type is MIXED43
dggs_num_placements (**integer**)	number of grid placements to use	$1 \leq v$	1	if dggs_orient_specify_type is not RANDOM all placements will be the same	dggrid_operation is GENERATE_GRID
dggs_orient_output_file_name (**string**)	name of file for output of multiple DGGS placement parameter values	any	"grid.meta"		dggs_num_placements > 1
dggs_orient_rand_seed (**integer**)	seed for orientation random number generator	$0 \leq v$	77316727		dggs_orient_specify_type is RANDOM
dggs_orient_specify_type (**choice**)	how is the DGG orientation specified?	RANDOM SPECIFIED REGION_CENTER	SPECIFIED		dggrid_operation is GENERATE_GRID
dggs_proj (**choice**)	projection used by the DGGS	ISEA FULLER	ISEA		all operations
dggs_res_spec (**integer**)	specified DGG resolution	$0 \leq v \leq 35$	9	if dggs_type is SUPERFUND then $0 \leq v \leq 9$	dggs_res_specify_type is SPECIFIED
dggs_res_specify_area (**double**)	desired cell area	$1.0 \leq v$	100		dggs_res_specify_type is CELL_AREA
dggs_res_specify_intercell_distance (**double**)	desired intercell distance	$1.0 \leq v$	100		dggs_res_specify_type is INTERCELL_DISTANCE

Parameter Name (Type)	Description	Allowed Values (v)	Default	Notes	Used When
dggs_res_specify_ rnd_down (**boolean**)	should the desired cell area or intercell distance be rounded down (or up) to the nearest DGGS resolution?	TRUE FALSE	TRUE		dggs_res_specify_ type is CELL_AREA or INTERCELL_DISTANCE
dggs_res_specify_type (**choice**)	how is the DGGS resolution specified?	SPECIFIED CELL_AREA INTERCELL_DISTANCE	SPECIFIED		dggrid_operation is GENERATE_GRID
dggs_topology (**choice**)	desired cell shape	HEXAGON TRIANGLE DIAMOND	HEXAGON		all operations
dggs_type (**choice**)	specify a preset DGG type	CUSTOM SUPERFUND ISEA3H ISEA4H ISEA43H ISEA4T ISEA4D FULLER3H FULLER4H FULLER43H FULLER4T FULLER4D	CUSTOM	see Appendix **B** for preset parameter value details	all operations
dggs_vert0_azimuth (**double**)	azimuth from icosahedron vertex 0 to vertex 1 (degrees)	$0.0 \leq v \leq 360.0$	0		dggs_orient_ specify_type is SPECIFIED
dggs_vert0_lat (**double**)	latitude of icosahedron vertex 0 (degrees)	$-90.0 \leq v \leq 90.0$	58.28252559		dggs_orient_ specify_type is SPECIFIED
dggs_vert0_lon (**double**)	longitude of icosahedron vertex 0 (degrees)	$-180.0 \leq v \leq 180.0$	11.25		dggs_orient_ specify_type is SPECIFIED
geodetic_densify (**double**)	maximum degrees of arc for a clipping polygon line segment	$0.0 \leq v \leq 360.0$	0	0.0 indicates no densification	dggrid_operation is GENERATE_GRID
input_address_type (**choice**)	cell address form in input file(s)	GEO Q2DI SEQNUM Q2DD PROJTRI VERTEX2DD	GEO	see **Appendix C**	dggrid_operation is TRANSFORM_POINTS, BIN_POINT_VALS, or BIN_POINT_PRESENCE
input_delimiter (**string**)	character that delimits address components and additional data in the input files	*v* is any single character in double quotes	" " (a single space)		dggrid_operation is TRANSFORM_POINTS, BIN_POINT_VALS, or BIN_POINT_PRESENCE
input_file_name (**string**)	name of file containing input addresses	*fileName*	valsin.txt		dggrid_operation is TRANSFORM_POINTS

Parameter Name (Type)	Description	Allowed Values (v)	Default	Notes	Used When
input_files (**string**)	name(s) of files containing lon/lat locations with associated values	*fileName1 fileName2 ... fileNameN*	vals.txt		dggrid_operation is BIN_POINT_VALS or BIN_POINT_PRESENCE
kml_default_color (**string**)	color of cell boundaries in KML output	any valid KML color	ffffffff		cell_output_type is KML
kml_default_width (**integer**)	width of cell boundaries in KML output	$1 \leq v \leq 100$	4		cell_output_type is KML
kml_description (**string**)	description tag value in KML output file		Generated by DGGRID 6.2		cell_output_type is KML
kml_name (**string**)	name tag value in KML output file		the output file name		cell_output_type is KML
max_cells_per_output_file (**integer**)	maximum number of cells output to a single output file	$0 \leq v$	0	0 indicates no maximum	dggrid_operation is GENERATE_GRID
output_address_type (**choice**)	address form to use in output	GEO Q2DI SEQNUM INTERLEAVE PLANE Q2DD PROJTRI VERTEX2DD AIGEN	SEQNUM	see **Appendix C**	dggrid_operation is TRANSFORM_POINTS, BIN_POINT_VALS, or BIN_POINT_PRESENCE
output_cell_label_type (**choice**)	output form for generated cell indexes	GLOBAL_SEQUENCE ENUMERATION SUPERFUND	GLOBAL_SEQUENCE		dggrid_operation is GENERATE_GRID
output_count (**boolean**)	output the count of classes which are present between the cell address and the presence vector	TRUE FALSE	TRUE		dggrid_operation is BIN_POINT_PRESENCE
output_delimiter (**string**)	character that delimits address components and additional data in the output file	v is any single character in double quotes	" " (a single space)		dggrid_operation is TRANSFORM_POINTS, BIN_POINT_VALS, or BIN_POINT_PRESENCE
output_file_name (**string**)	name of file to use for output		valsout.txt		dggrid_operation is TRANSFORM_POINTS, BIN_POINT_VALS, or BIN_POINT_PRESENCE
point_output_file_name (**string**)	cell point output file name prefix	any	"centers"		point_output_type is AIGEN, SHAPEFILE, KML, or TEXT
point_output_type (**choice**)	cell point output file format	NONE AIGEN KML SHAPEFILE TEXT GEOJSON	NONE		dggrid_operation is GENERATE_GRID

Parameter Name (Type)	Description	Allowed Values (v)	Default	Notes	Used When
precision (**integer**)	number of digits to right of decimal point when outputting floating point numbers	$0 \leq v \leq 30$	7		all operations
proj_datum (**choice**)	desired earth radius datum	WGS84_AUTHALIC_SPHERE WGS84_MEAN_SPHERE CUSTOM_SPHERE	WGS84_AUTHALIC_SPHERE		all operations
proj_datum_radius (**double**)	desired earth radius	$1.0 \leq v \leq 10{,}000.0$	6371.00718091847		proj_datum is CUSTOM_SPHERE
randpts_concatenate_output (**boolean**)	put random points for multiple DGG placements in a single file?	TRUE FALSE	TRUE		randpts_output_type is AIGEN, KML, SHAPEFILE, or TEXT
randpts_num_per_cell (**integer**)	number of random points to generate per cell	$0 \leq v$	0		randpts_output_type is AIGEN, KML, SHAPEFILE, or TEXT
randpts_output_file_name (**string**)	random points-in-cell output file name prefix	any	“randPts”		randpts_output_type is AIGEN, KML, SHAPEFILE, or TEXT and randpts_num_per_cell > 0
randpts_output_type (**choice**)	random points-in-cell output file format	NONE AIGEN KML SHAPEFILE TEXT GEOJSON	NONE		dggrid_operation is GENERATE_GRID
randpts_seed (**integer**)	seed for cell points random number generator	$0 \leq v$	77316727		randpts_output_type is RANDOM
region_center_lat (**double**)	latitude of study region (degrees)	$-90.0 \leq v \leq 90.0$	0		dggs_orient_specify_type is REGION_CENTER
region_center_lon (**double**)	longitude of study region (degrees)	$-180.0 \leq v \leq 180.0$	0		dggs_orient_specify_type is REGION_CENTER
rng_type (**choice**)	specifies the random number generator to use	RAND MOTHER	RAND	RAND: C standard library rand MOTHER: George Marsaglia's multiply-with-carry “Mother” function	

Parameter Name (Type)	Description	Allowed Values (v)	Default	Notes	Used When
`shapefile_id_field_length` (**integer**)	number of digits in Shapefile output cell index strings	$1 \leq v \leq 50$	`11`		`cell_output_type`, `point_output_type`, or `randpts_output_type` is `SHAPEFILE`
`update_frequency` (**integer**)	number of cell inclusion tests to perform between outputting status updates	$0 \leq v$	`100000`		`dggrid_operation` is `GENERATE_GRID`
`verbosity` (**integer**)	amount of debugging output to display	$0 \leq v \leq 3$	`0`		all operations

Appendix B. Default Values for Preset DGG Types

All preset grid types share the following default parameter values:

```
dggs_orient_specify_type:  SPECIFIED
dggs_num_placements:       1
dggs_vert0_lon:            11.25
dggs_vert0_lat:            58.28252559
dggs_vert0_azimuth:        0.0
dggs_res_specify_type:     SPECIFIED
```

The table below gives the values of other parameters that are set by each preset DGG type. In addition to the listed parameters, the preset type `SUPERFUND` also sets the value of the parameter `output_cell_label_type` to `SUPERFUND`. Note that any preset parameter value can be overridden by explicitly specifying a different value for that parameter in the metafile anywhere after the `dggs_type` parameter value has been specified.

dggs_type	dggs_topology	dggs_proj	dggs_res_spec	dggs_aperture_type	dggs_aperture	dggs_num_aperture_4_res
CUSTOM	HEXAGON	ISEA	9	PURE	4	N/A
SUPERFUND	HEXAGON	FULLER	9	MIXED43	N/A	2
ISEA3H	HEXAGON	ISEA	9	PURE	3	N/A
ISEA4H	HEXAGON	ISEA	9	PURE	4	N/A
ISEA43H	HEXAGON	ISEA	9	MIXED43	N/A	0
ISEA4T	TRIANGLE	ISEA	9	PURE	4	N/A
ISEA4D	DIAMOND	ISEA	9	PURE	4	N/A
FULLER3H	HEXAGON	FULLER	9	PURE	3	N/A
FULLER4H	HEXAGON	FULLER	9	PURE	4	N/A
FULLER43H	HEXAGON	FULLER	9	MIXED43	N/A	0
FULLER4T	TRIANGLE	FULLER	9	PURE	4	N/A
FULLER4D	DIAMOND	FULLER	9	PURE	4	N/A

Appendix C. DGG Address Forms

In **DGGRID** geographic coordinates are always expressed as:

longitude latitude

in decimal degrees. The parameters `input_address_type` and `output_address_type` refer to this address form as `GEO`.

DGGRID supports a number of address forms for specifying a particular cell in a DGG. These address forms are listed below according to their designation in the `input_address_type` and `output_address_type` parameters:

`Q2DI` - quad number and (i, j) coordinates on that quad
`SEQNUM` - linear address (1 to size-of-DGG)
`INTERLEAVE` - digit-interleaved form of Q2DI (not supported for input_address_type)
`PLANE` - (x, y) coordinates on unfolded ISEA plane (not supported for input_address_type)
`Q2DD` - quad number and (x, y) coordinates on that quad
`PROJTRI` - triangle number and (x, y) coordinates within that triangle on the ISEA plane
`VERTEX2DD` - vertex number, triangle number, and (x, y) coordinates on ISEA plane

Appendix D. Characteristics of ISEA Hexagonal DGGs

This appendix gives a table of characteristics for hexagonal DGGs based on the ISEA projection which can be generated using **DGGRID.** For footnotes refer to the **Notes** following all tables. All measurements assume an earth radius of 6,371.007180918475 km (WGS84 authalic sphere radius).

Aperture 3 (ISEA3H)

res	Number of Cells*	Hex Area** (km^2)	Internode Spacing (km)			
			min	max	mean	std.dev.
1	32	17,002,187.39080	4,156.18000	4,649.10000	4,320.49000	233.01400
2	92	5,667,395.79693	2,324.81000	2,692.72000	2,539.69000	139.33400
3	272	1,889,131.93231	1,363.56000	1,652.27000	1,480.02000	89.39030
4	812	629,710.64410	756.96100	914.27200	855.41900	52.14810
5	2,432	209,903.54803	453.74800	559.23900	494.95900	29.81910
6	7,292	69,967.84934	248.80400	310.69300	285.65200	17.84470
7	21,872	23,322.61645	151.22100	187.55000	165.05800	9.98178
8	65,612	7,774.20548	82.31100	104.47000	95.26360	6.00035
9	196,832	2,591.40183	50.40600	63.00970	55.02260	3.33072
10	590,492	863.80061	27.33230	35.01970	31.75960	2.00618
11	1,771,472	287.93354	16.80190	21.09020	18.34100	1.11045
12	5,314,412	95.97785	9.09368	11.70610	10.58710	0.66942
13	15,943,232	31.99262	5.60065	7.04462	6.11367	0.37016
14	47,829,692	10.66421	3.02847	3.90742	3.52911	0.22322
15	143,489,072	3.55473	1.86688	2.35058	2.03789	0.12339
16	430,467,212	1.18491	1.00904	1.30335	1.17638	0.07442
17	1,291,401,632	0.39497	0.62229	0.78391	0.67930	0.04113
18	3,874,204,892	0.13166	0.33628	0.43459	0.39213	0.02481
19	11,622,614,672	0.04389	0.20743	0.26137	0.22643	0.01371
20	34,867,844,012	0.01463	0.11208	0.14489	0.13071	0.00827

Aperture 4 (ISEA4H)

res	Number of Cells*	Hex Area** (km^2)	Internode Spacing (km)			
			min	max	mean	std.dev.
1	42	12,751,640.54310	3,526.83000	4,003.02000	3,764.92000	238.59500
2	162	3,187,910.13578	1,730.20000	2,017.48000	1,913.88000	116.98200
3	642	796,977.53394	853.05600	1,024.99000	961.97800	58.98050
4	2,562	199,244.38349	422.25300	520.74600	481.77100	29.93870
5	10,242	49,811.09587	209.61200	262.55900	241.04700	15.09590
6	40,962	12,452.77397	104.30400	131.99100	120.56000	7.58663
7	163,842	3,113.19349	51.98740	66.29560	60.28930	3.80352
8	655,362	778.29837	25.94120	33.24750	30.14700	1.90448
9	2,621,442	194.57459	12.95380	16.65580	15.07410	0.95293
10	10,485,762	48.64365	6.47162	8.33821	7.53719	0.47664
11	41,943,042	12.16091	3.23413	4.17238	3.76863	0.23837
12	167,772,162	3.04023	1.61654	2.08723	1.88432	0.11919
13	671,088,642	0.76006	0.80810	1.04394	0.94217	0.05960
14	2,684,354,562	0.19001	0.40400	0.52208	0.47108	0.02980
15	10,737,418,242	0.04750	0.20198	0.26107	0.23554	0.01490
16	42,949,672,962	0.01188	0.10099	0.13055	0.11777	0.00745

Mixed Aperture 4 and 3 (ISEA43H)

# Ap 4 Res***	Res	Number of Cells*	Hex Area** (km²)	Internode Spacing (km)			
				min	max	mean	std.dev.
1	2	122	4,250,546.84770	2,050.27000	2,445.80000	2,210.50000	134.60200
1	3	362	1,416,848.94923	1,143.10000	1,360.38000	1,280.77000	76.55180
2	3	482	1,062,636.71193	1,021.81000	1,246.71000	1,111.74000	66.88040
1	4	1,082	472,282.98308	680.80200	835.86200	742.02700	44.62200
2	4	1,442	354,212.23731	565.39700	690.57000	642.04700	39.50560
3	4	1,922	265,659.17798	510.49600	628.59000	556.76100	33.52270
1	5	3,242	157,427.66103	374.89400	463.73500	428.31100	26.59520
2	5	4,322	118,070.74577	340.28000	420.15500	371.29600	22.39940
3	5	5,762	88,553.05933	280.26400	349.09400	321.32800	20.04290
4	5	7,682	66,414.79450	255.19700	315.51700	278.50600	16.82030
1	6	9,722	52,475.88701	226.83800	280.57700	247.56900	14.95740
2	6	12,962	39,356.91526	186.14700	233.60700	214.27900	13.42690
3	6	17,282	29,517.68644	170.12500	210.75100	185.68800	11.22680
4	6	23,042	22,138.26483	139.31500	175.54900	160.73100	10.09490
1	7	29,162	17,491.96234	123.74300	156.19900	142.87800	8.98060
5	6	30,722	16,603.69862	127.59200	158.48900	139.27000	8.42455
2	7	38,882	13,118.97175	113.41500	141.01800	123.79700	7.48970
3	7	51,842	9,839.22881	92.65450	117.43200	107.16800	6.74663
4	7	69,122	7,379.42161	85.06050	105.99400	92.84930	5.61894
1	8	87,482	5,830.65411	75.60920	94.29160	82.53310	4.99505
5	7	92,162	5,534.56621	69.39600	88.24730	80.38160	5.06634
2	8	116,642	4,372.99058	61.65500	78.49940	71.45200	4.50532
6	7	122,882	4,150.92466	63.79510	79.64280	69.63760	4.21501
3	8	155,522	3,279.74294	56.70670	70.84140	61.90030	3.74689
4	8	207,362	2,459.80720	46.19200	58.96580	53.59140	3.38187
1	9	262,442	1,943.55137	41.04410	52.44340	47.63750	3.00696
5	8	276,482	1,844.85540	42.53000	53.20880	46.42540	2.81045
2	9	349,922	1,457.66353	37.80440	47.32180	41.26710	2.49825
6	8	368,642	1,383.64155	34.61350	44.28150	40.19490	2.53804
3	9	466,562	1,093.24765	30.75780	39.38000	35.72920	2.25652
7	8	491,522	1,037.73116	31.89750	39.95570	34.81920	2.10797
4	9	622,082	819.93573	28.35330	35.53200	30.95040	1.87379
1	10	787,322	647.85046	25.20290	31.59700	27.51150	1.66561
5	9	829,442	614.95180	23.05280	29.56480	26.79750	1.69313
2	10	1,049,762	485.88784	20.48640	26.28940	23.82020	1.50522
6	9	1,105,922	461.21385	21.26500	26.67450	23.21280	1.40539
3	10	1,399,682	364.41588	18.90220	23.71890	20.63360	1.24924
7	9	1,474,562	345.91039	17.27980	22.19230	20.09850	1.27026
4	10	1,866,242	273.31191	15.35680	19.73240	17.86540	1.12925

# Ap 4 Res***	Res	Number of Cells*	Hex Area** (km^2)	Internode Spacing (km) min	max	mean	std.dev.
8	**9**	1,966,082	259.43279	15.94870	20.02190	17.40960	1.05406
1	**11**	2,361,962	215.95015	13.64790	17.54480	15.88050	1.00387
5	**10**	2,488,322	204.98393	14.17660	17.80240	15.47520	0.93695
2	**11**	3,149,282	161.96261	12.60150	15.82860	13.75580	0.83285
6	**10**	3,317,762	153.73795	11.51260	14.80890	13.39920	0.84712
3	**11**	4,199,042	121.47196	10.23190	13.16650	11.91050	0.75305
7	**10**	4,423,682	115.30346	10.63250	13.36000	11.60640	0.70272
4	**11**	5,598,722	91.10397	9.45109	11.87820	10.31680	0.62464
8	**10**	5,898,242	86.47760	8.63138	11.11270	10.04950	0.63545
1	**12**	7,085,882	71.98338	8.40097	10.56060	9.17051	0.55524
5	**11**	7,464,962	68.32798	7.67135	9.87982	8.93293	0.56487
9	**10**	7,864,322	64.85820	7.97436	10.02520	8.70482	0.52704
2	**12**	9,447,842	53.98754	6.81818	8.78363	7.94040	0.50213
6	**11**	9,953,282	51.24598	7.08832	8.91291	7.73762	0.46848
3	**12**	12,597,122	40.49065	6.30073	7.92394	6.87788	0.41643
7	**11**	13,271,042	38.43449	5.75194	7.41293	6.69974	0.42370
4	**12**	16,796,162	30.36799	5.11234	6.59024	5.95533	0.37664
8	**11**	17,694,722	28.82587	5.31624	6.68732	5.80321	0.35136
1	**13**	21,257,642	23.99446	4.54389	5.85880	5.29364	0.33480
5	**12**	22,394,882	22.77599	4.72555	5.94513	5.15841	0.31232
9	**11**	23,592,962	21.61940	4.31298	5.56160	5.02482	0.31780
2	**13**	28,343,522	17.99585	4.20049	5.28525	4.58526	0.27762
6	**12**	29,859,842	17.08199	3.83345	4.94425	4.46652	0.28250
10	**11**	31,457,282	16.21455	3.98718	5.01714	4.35241	0.26352
3	**13**	37,791,362	13.49688	3.40726	4.39539	3.97024	0.25112
7	**12**	39,813,122	12.81150	3.54416	4.46020	3.86881	0.23424
4	**13**	50,388,482	10.12266	3.15036	3.96505	3.43894	0.20822
8	**12**	53,084,162	9.60862	2.87459	3.70916	3.34990	0.21189
1	**14**	63,772,922	7.99815	2.80032	3.52485	3.05684	0.18508
5	**13**	67,184,642	7.59200	2.55504	3.29734	2.97769	0.18835
9	**12**	70,778,882	7.20647	2.65812	3.34599	2.90161	0.17568
2	**14**	85,030,562	5.99862	2.27101	2.93122	2.64684	0.16742
6	**13**	89,579,522	5.69400	2.36277	2.97448	2.57921	0.15616
10	**12**	94,371,842	5.40485	2.15564	2.78247	2.51243	0.15892
3	**14**	113,374,082	4.49896	2.10024	2.64420	2.29263	0.13881
7	**13**	119,439,362	4.27050	1.91602	2.47350	2.23327	0.14127
11	**12**	125,829,122	4.05364	1.99359	2.51002	2.17621	0.13176
4	**14**	151,165,442	3.37422	1.70305	2.19883	1.98513	0.12557
8	**13**	159,252,482	3.20287	1.77208	2.23129	1.93441	0.11712
1	**15**	191,318,762	2.66605	1.51376	1.95464	1.76456	0.11162

# Ap 4 Res***	Res	Number of Cells*	Hex Area** (km²)	Internode Spacing (km)			
				min	max	mean	std.dev.
5	**14**	201,553,922	2.53067	1.57518	1.98351	1.71947	0.10411
9	**13**	212,336,642	2.40216	1.43686	1.85544	1.67496	0.10595
2	**15**	255,091,682	1.99954	1.40016	1.76323	1.52842	0.09254
6	**14**	268,738,562	1.89800	1.27716	1.64937	1.48885	0.09418
10	**13**	283,115,522	1.80162	1.32906	1.67373	1.45080	0.08784
3	**15**	340,122,242	1.49965	1.13521	1.46619	1.32342	0.08372
7	**14**	358,318,082	1.42350	1.18139	1.48785	1.28960	0.07808
11	**13**	377,487,362	1.35121	1.07755	1.39177	1.25622	0.07947
4	**15**	453,496,322	1.12474	1.05012	1.32260	1.14631	0.06941
8	**14**	477,757,442	1.06762	0.95779	1.23719	1.11664	0.07064
12	**13**	503,316,482	1.01341	0.99679	1.25547	1.08810	0.06588
1	**16**	573,956,282	0.88868	0.93344	1.17570	1.01895	0.06169
5	**15**	604,661,762	0.84356	0.85134	1.09977	0.99257	0.06279
9	**14**	637,009,922	0.80072	0.88604	1.11602	0.96720	0.05856
2	**16**	765,275,042	0.66651	0.75673	0.97762	0.88228	0.05581
6	**15**	806,215,682	0.63267	0.78759	0.99206	0.85974	0.05205
10	**14**	849,346,562	0.60054	0.71829	0.92799	0.83748	0.05298
3	**16**	1,020,366,722	0.49988	0.70008	0.88187	0.76421	0.04627
7	**15**	1,074,954,242	0.47450	0.63847	0.82491	0.74443	0.04709
11	**14**	1,132,462,082	0.45040	0.66453	0.83710	0.72540	0.04392
4	**16**	1,360,488,962	0.37491	0.56751	0.73328	0.66171	0.04186
8	**15**	1,433,272,322	0.35587	0.59069	0.74412	0.64480	0.03904
12	**14**	1,509,949,442	0.33780	0.53869	0.69605	0.62811	0.03973
1	**17**	1,721,868,842	0.29623	0.50445	0.65182	0.58819	0.03721
5	**16**	1,813,985,282	0.28119	0.52506	0.66146	0.57316	0.03470
9	**15**	1,911,029,762	0.26691	0.47883	0.61873	0.55832	0.03532
13	**14**	2,013,265,922	0.25335	0.49840	0.62788	0.54405	0.03294
2	**17**	2,295,825,122	0.22217	0.46672	0.58798	0.50947	0.03085
6	**16**	2,418,647,042	0.21089	0.42562	0.55000	0.49628	0.03140
10	**15**	2,548,039,682	0.20018	0.44302	0.55813	0.48360	0.02928
3	**17**	3,061,100,162	0.16663	0.37832	0.48890	0.44114	0.02791
7	**16**	3,224,862,722	0.15817	0.39380	0.49613	0.42987	0.02603
11	**15**	3,397,386,242	0.15013	0.35910	0.46408	0.41874	0.02649
4	**17**	4,081,466,882	0.12497	0.35004	0.44101	0.38210	0.02314
8	**16**	4,299,816,962	0.11862	0.31920	0.41252	0.37221	0.02355
12	**15**	4,529,848,322	0.11260	0.33226	0.41862	0.36270	0.02196
1	**18**	5,165,606,522	0.09874	0.31115	0.39202	0.33965	0.02056
5	**17**	5,441,955,842	0.09373	0.28373	0.36670	0.33086	0.02093
13	**15**	6,039,797,762	0.08445	0.26932	0.34808	0.31405	0.01987
2	**18**	6,887,475,362	0.07406	0.25220	0.32596	0.29409	0.01860

Notes

*   At every resolution 12 of the cells are pentagons and the remainder are hexagons.
**   The 12 pentagons at each resolution have an area exactly 5/6 the area of a hexagon.
*** Specified in a metafile using parameter `dggs_num_aperture_4_res`.

Appendix E. The Superfund_500m DGG

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Introduction

The **Superfund_500m** grid was commissioned by the US Environmental Protection agency for use in developing its Superfund Emergency Response Atlas. The grid is a hierarchically indexed icosahedral hexagonal discrete global grid (DGG) (Sahr et al. 2003) consisting of approximately 22 hectare hexagons, with approximately 500 meter distance between hexagon centers. This cell size is generated geometrically by creating a mixed aperture sequence of two aperture 4 subdivisions followed by 15 aperture 3 subdivisions.

It is not possible to create a network of equal area, equal shape, and equally spaced grid cells greater than twenty in number on the surface of a sphere. Thus one or more, often two or all three, of these characteristics are distorted to varying degrees across the surface. The approach used here starts with the twenty triangular faces of the icosahedron, creates a regular, equal area, equal shape, and equally spaced network of hexagons of the desired size on one or more of the planar triangles and then projects these cells to the surface of the globe. The distortion characteristics of this approach have been investigated by Kimerling et al. (1999) and Gregory et al. (2008).

Grid characteristics for the 10 addressable **Superfund_500m** resolutions are given in Table 1.

Grid Construction

The cells are generated as regular hexagons (and pentagons) on the surface of an icosahedron, oriented relative to the globe so as to be symmetrical about the equator. The cells are projected to longitude and latitude on a sphere with the authalic WGS84 radius (NAD 83 datum) using the inverse icosahedral projection of R. Buckminster Fuller (1975) as developed analytically by Robert Gray (1995) and John Crider (2008).

The **Superfund_500m** cell identifiers are an instance of Central Place Indexing (CPI). CPI (Sahr, 2011; Sahr & White, in preparation) is a class of hierarchical indexing systems for pure and mixed aperture hexagonal DGGs, where the linear index assigned to each cell is constructed as a path address (Sahr 2008) on a multi-resolution discrete global grid system with the specified aperture sequence. A CPI addressing system was used in the initial design for a sampling system for the EPA’s Environmental Monitoring and Assessment Program (White et al. 1992).

Table 1. Superfund_500m DGG Resolutions (see notes after table).

Resolution	# Cells[1]	Hex Area[2] (sq. km)	Intercell Distance[3] (km)	CLS[4] (km)
0	42	12,751,640.5431	3,526.8262	4,046.3596
1	162	3,187,910.1358	1,763.4131	2,016.7939
2	1,442	354,212.2373	587.8044	671.6409
3	12,962	39,356.9153	195.9348	223.8573
4	116,642	4,372.9906	65.3116	74.6182
5	1,049,762	485.8878	21.7705	24.8727
6	9,447,842	53.9875	7.2568	8.2909
7	85,030,562	5.9986	2.4189	2.7636
8	765,275,042	0.6665	0.8063	0.9212
9	2,295,825,122	0.2222	0.4655	0.5319

Table 1 Notes:
[1]At every resolution 12 of the cells are pentagons and the remainder are hexagons.
[2]The 12 pentagons have an area exactly 5/6 the area of a hexagon.
[3]Measured in the plane of the Fuller projection space.
[4]Characteristic Length Scale (CLS): the diameter of a spherical cap of the same area as a cell of the specified resolution. This metric was suggested by Ralph Kahn.

The **Superfund_500m** CPI system was designed to meet two design goals. First, the CPI approach allows the grid to have an intercell spacing of approximately 500 meters, which cannot be achieved with sufficient accuracy using a pure aperture grid system. Second, in order to take advantage of the pre-existing discrete global grid software tool **DGGRID** the cells needed to be hierarchically indexed in such a manner that the Christaller sets of each base cell are each restricted to a single **ij** coordinate system whose axes form two of the edges of a spherical quadrilateral formed by a pair of adjacent icosahedral faces.

These design goals were met by constructing a grid with base cells of valence 5 (i.e., with pentagonal voronoi areas) centered on each of the 12 vertices of an icosahedron and then applying the following aperture sequence:

$4, 4, 3^{ccw}, 3^{cw}, 3^{ccw}, 3^{cw}, 3^{ccw}, 3^{cw}, 3^{ccw}, 3^{cw}, 3^{ccw}, 3^{cw}, 3^{ccw}, 3^{cw}, 3^{ccw}, 3^{cw}, 3^{ccw}$

To assign a unique hierarchical index to each cell, as well as to achieve the remaining grid design goals, the generator types ***A-K*** were defined with the following generator string representations:

A: ***A***123456
B: ***C***123***CCC***
C: ***D***123***EED***
D: ***F***123***IK***6
E: ***J***123***GH***6
F: ***D***123***EE***6
G: ***DD***234***E***6

H: ***EE***2***D***456
I: ***E***1***DD***456
J: ***E***1***D***345***E***
K: ***D***123***E***5***D***

Two of the base cells on opposing sides of the icosahedron are assigned generator type ***A***, while the remaining 10 base cells (centered on the remaining 10 icosahedral vertices) are assigned generator type ***B***. Figures 1-3 illustrate the resolution 17 regions corresponding to the resolution 1 grid cells, numbered 10-51 (to avoid leading zeros in indexes). The resolution 0 base tiles centered on the resolution 1 cells labeled 10 and 51 are the two base cells that were assigned generator type ***A***, which generates a single pentagonal cell at all resolutions.

Index Form

The base tiles of the **Superfund_500m** CPI indexes correspond to resolution 1 DGG cells, as illustrated in Figure 1. Base tiles 11-50 each have four hierarchical children at the aperture 4 resolution 2, which are assigned the additional digits 1-4. These resolution 2 cells each have three children at resolution 3, which are assigned the additional digits 1-3; this assignment continues recursively through the aperture 3 resolutions 3-17. The special base tiles 10 and 51 have a single hierarchical child at all resolutions, which is assigned the additional digit 1 at each resolution. In order to reduce the length of indexes, a first order compression is performed by grouping the aperture 3 resolution 3-16 digits into pairs and replacing each pair of digits with a digit value of 1-9.

The assignment of digits has been chosen so that all indexes form integers with the same number of digits, and so that possibly troublesome leading zeros can be avoided, even if redundant leading digits are removed from indexes when working in regions where this is possible.

Thus the full resolution 17 **Superfund_500m** CPI indexes are condensed into indexes with 11 digits, resulting in 10 addressable grid resolutions (see Table 1).

A **Superfund_500m** index at full resolution (resolution 9) has the 11-digit form:

BB499999993

where:

- *BB* is the 2-digit resolution 1 base tile cell with values 10-51,
- *4* is the resolution 2 aperture 4 digit with values 1-4,
- each *9* represent two successive combined aperture 3 digits for resolutions 3-16, with values 1-9 each, and
- the final 3 represents the extra aperture 3 at resolution 17, with values 1-3

Note that the resolution 9 footprint of base tiles 11-50 form approximate spherical diamonds on the surface of the globe, as illustrated in Figure 1. Figures 2 and 3 illustrate the resolution 9 indexing footprints of base tiles adjacent to base tiles 10 and 15 respectively. The hierarchical children at each aperture 3 resolution form a compact triangle; Figure 4 illustrates the pattern formed at resolution 9.

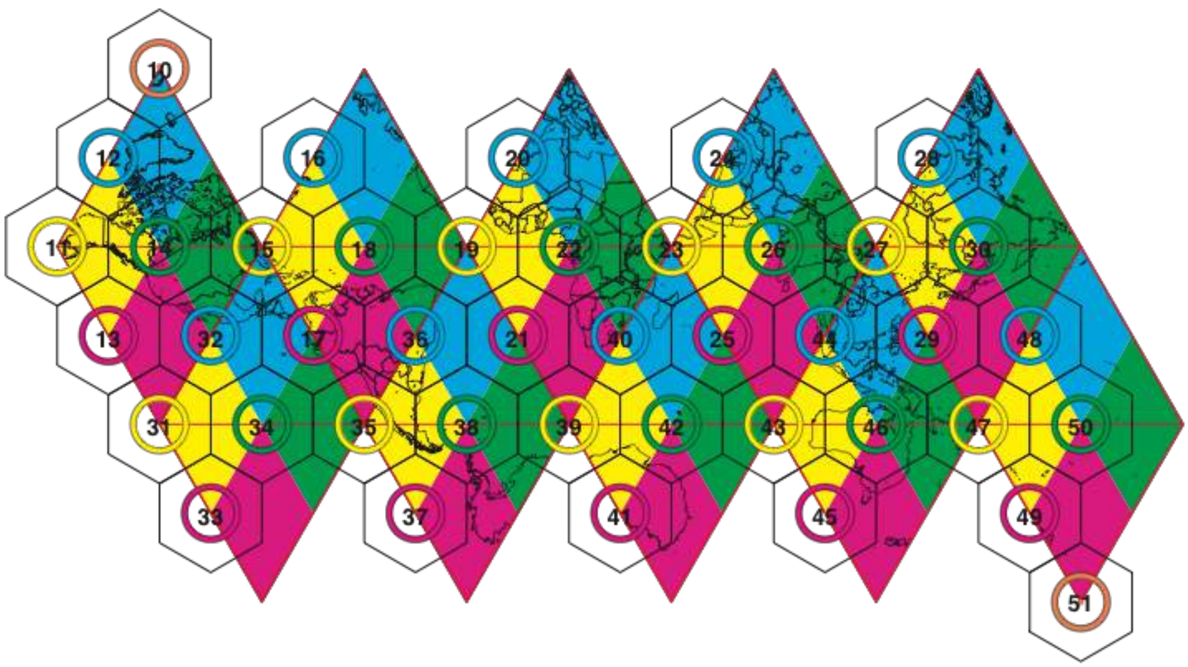

Figure 1. Superfund_500m base tiles on an unfolded icosahedron with corresponding resolution 9 indexing footprints. Cells within the footprint region of a base tile will have that base tile's index as the first two digits of the cell's index. Tiles 10 and 51 index only a single cell at all resolutions, centered on the corresponding base tile. Note that all tiles that are centered on a triangle vertex are actually pentagons on the sphere.

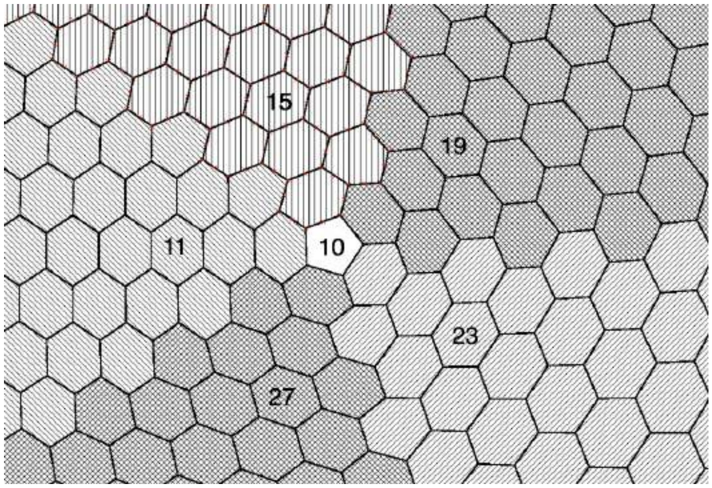

Figure 2. Region around base tile 10 at resolution 9.

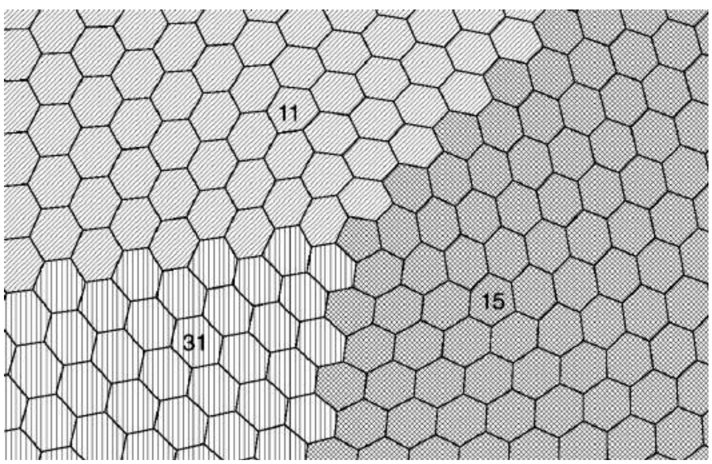

Figure 3. Region around base tile 15 at resolution 9.

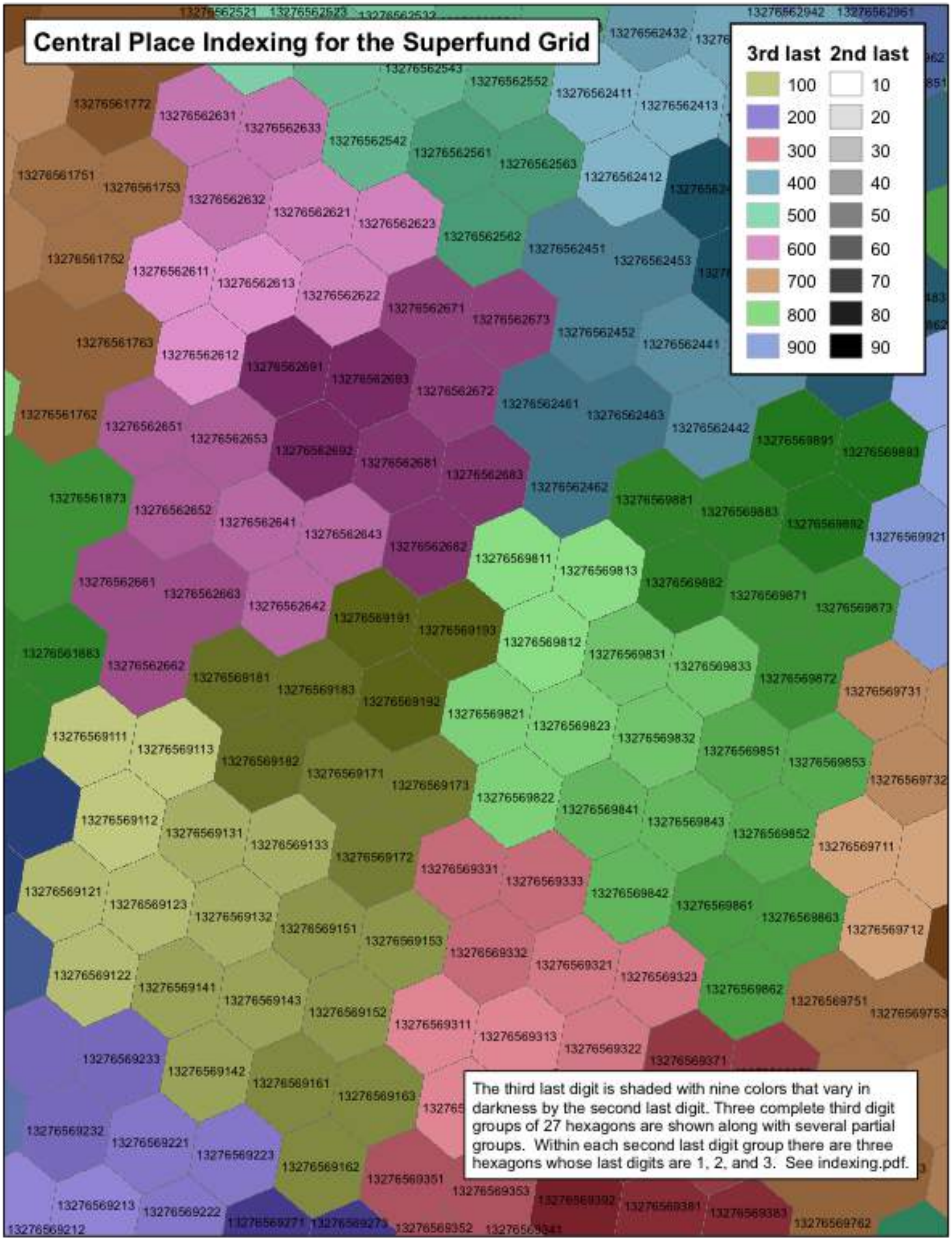

Figure 4. Superfund_500m resolution 9 tiling pattern.

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