Cell Tower Population Estimation Through the Use of Voronoi Tessellations

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Abstract

This paper describes a system by which human populations can be easily estimated by utilizing surrounding cell towers. The system is designed with the objective that result data could be used to improve human mobility models. The project was conducted as a two credit-hour independent study for the computer science PhD student, Thyago Mota, to assist with his mobility model research at the Colorado School of Mines. The population estimation system operates by partitioning a geographic area into various segments, surrounding a provided set of cell tower coordinates, using a Voronoi tessellation. This generated tessellation is used in conjunction with NASA's large Gridded Population of the World (GPW) dataset, which provides population estimates for the world on an approximate five kilometer square grid, to generate a per cell tower population estimate. The system relies on efficient programing due to the large size of the datasets being utilized. To accomplish the system's objectives, a solution was implemented as a collection of programs written in JavaScript, Ruby, and Python. Results and potential improvements to the system are also discussed.

1 Introduction

The development of human mobility models has been an area of intense research over the past several years. Human mobility models have a wide variety of applications, including improved automation, occupancy prediction, and improved public transportation network design. Recently, cell tower log data has been utilized to gain new insight into human mobility models with high temporal accuracy. Such models could be improved by having set estimates of populations surrounding each cell tower.

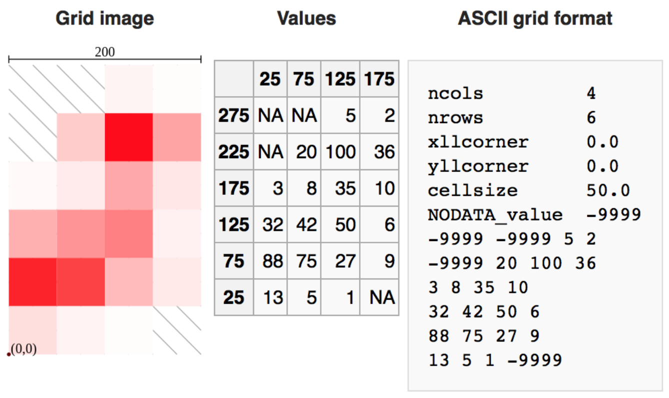
This project aims to accurately estimate cell tower surrounding populations using cell tower locations as inputs and NASA's Gridded Population of the World dataset. A Voronoi tessellation is run on the input location data to segment a geographic area into various polygons, each of which has a cell tower at its center. A Voronoi tessellation is a good representation of the distribution of people per cell tower, since each edge within a polygon is inherently an orthogonal bisector of the line between two cell towers.

Overall, the system appears to function adequately. However, there are several improvements that can be introduced into the system to enhance performance, due to the highly parallel nature of the estimation problem. Future research in this area will involve comparison of this system's results with population estimates gathered from call log data and population estimates from Twitter to evaluate each method's efficacy.

2 Related Work

[1] describes a framework for estimating wireless subscriber populations within cellular carriers using a pattern regularity-based system. Such a system provides data that can help to improve urban mobility models. The researchers were able to test the system on CDMA EV-DO cellular data usage data and resulted in high-accuracy subscriber estimations.

[2] discusses research on urban mobility models using population estimates that are calculated from call log data. The researchers claim that better understanding of urban



	25	75	125	175
275	NA	NA	5	2
225	NA	20	100	36
175	3	8	35	10
125	32	42	50	6
75	88	75	27	9
25	13	5	1	NA

```
ncols         4
nrows         6
xllcorner     0.0
yllcorner     0.0
cellsize      50.0
NODATA_value  -9999
-9999 -9999 5 2
-9999 20 100 36
3 8 35 10
32 42 50 6
88 75 27 9
13 5 1 -9999
```

Figure 1: Esri ASCII Raster Format – from [4]

mobility models would improve city planning and public space management. Identifying call patterns and general activity patterns with high temporal and spacial resolution would permit dynamic population estimation at any given point in time. The produced estimates were found to concur with actual, measured populations.

2.1 Gridded Population of the World

The NASA Socioeconomic Data and Applications Center (SEDAC) has developed a global population distribution dataset, named Gridded Population of the World version 3 (GPW) [3]. GPW provides a representation of the world's population count, set on 2.5 arc-minute square grid (translating to an approximately five kilometer square grid at the equator). GPW data is provided as an Esri raster file, detailed in Figure 1. This dataset was generated using a proportional allocation gridding algorithm to assign cell values within the grid. The 2010 GPW dataset has been utilized in this project as a granular population data source.

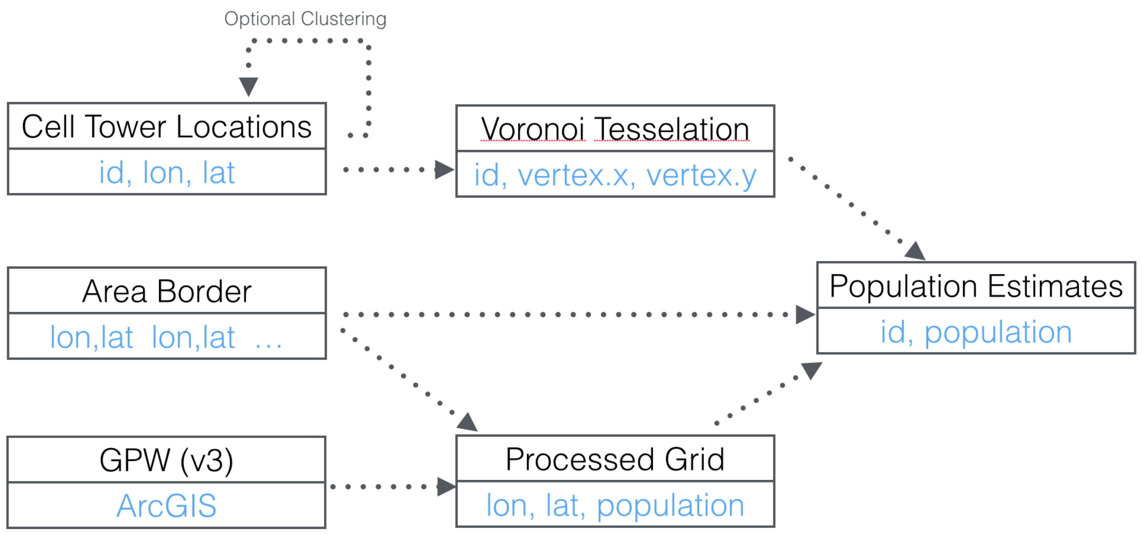


Figure 2: High-Level System Overview

3 Project Overview and Methods

The project described in this paper has been broken into various pieces to improve manageability. Figure 2 shows the overall architecture and flow of data within the system. The system relies on three main components:

1. GPW Processing Scripts,
2. Voronoi Tessellation, and
3. Population Estimator.

3.1 Datasets

Two empirical datasets were chosen for this project: An Ivory Coast dataset consisting of 1238 cell tower locations, and an Abidjan dataset consisting of 383 cell tower locations, a small subset of the Ivory Coast dataset that focusses around its largest city, Abidjan.

The Ivory Coast was chosen due to the free availability of cell tower information, which is inaccessible within the United States.

3.2 Gridded Population of the World Processing

Substantial processing is performed on the GPW data prior to use within the estimation program using a Python script with the `shapely` module. The Esri grid format metadata (Figure 1) is first read from the GPW datafile, in conjunction with an outline geometry file. Data is extracted from the GPW file and output to a CSV file in longitude, latitude, population format. This processing removes unnecessary, outlying data points from the GPW data, ultimately reducing the 1.3GB Ivory Coast GPW raster file to an easily parsable, 780MB CSV file.

3.3 Voronoi Tessellation

A Voronoi tessellation is a method of dividing an n-dimensional space, such as a plane, into various regions, such as polygons, around a set of center-points. Every point in each region is closest to that region's corresponding center-point. The Voronoi tessellation for a set of points is inverse to the Delaunay triangulation for that same set of points. For this project we shall consider a two-dimensional Voronoi tessellation. Using a Voronoi tessellation is logical since each polygon's corresponding cell tower is the cell tower with the strongest signal within that polygon, assuming homogeneous cell towers.

The JavaScript Topology Suite (JSTS) [5] was selected for this project due to its ease of use, ability to process large sets of points, and integration with OpenLayers [6]. JSTS is a JavaScript implementation of the widely used Java Topology Suite (JTS).

The Voronoi tessellation component of the system is written in JavaScript and utilizes JSTS to calculate the Voronoi polygons for a set of cell tower coordinates which are then overlaid on a Google map using OpenLayers. The Voronoi tessellations for both datasets (Figure 3 and Figure 4) are calculated in under one second. The resultant tessellation is

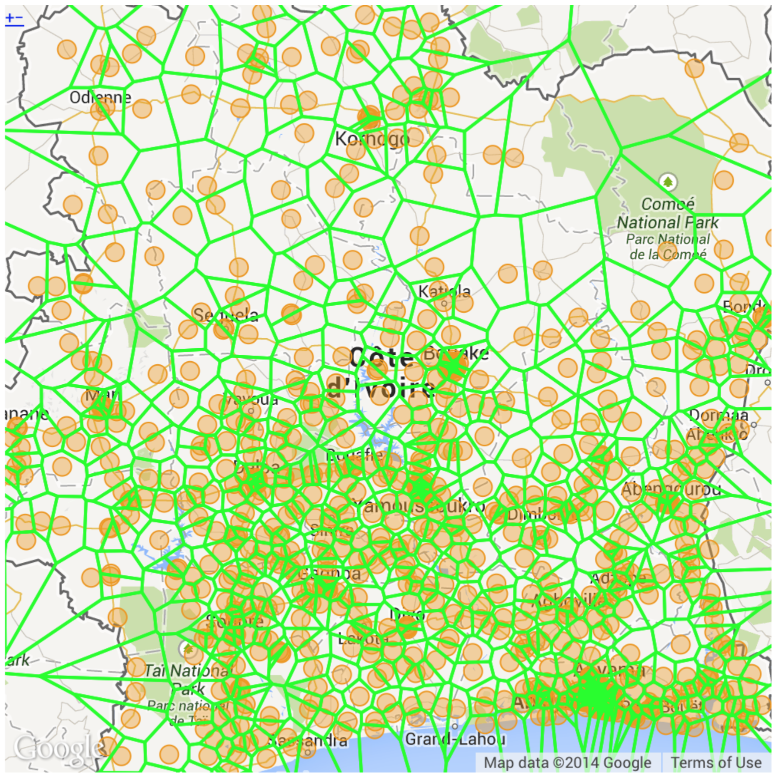


Figure 3: Voronoi Tessellation for Ivory Coast Dataset

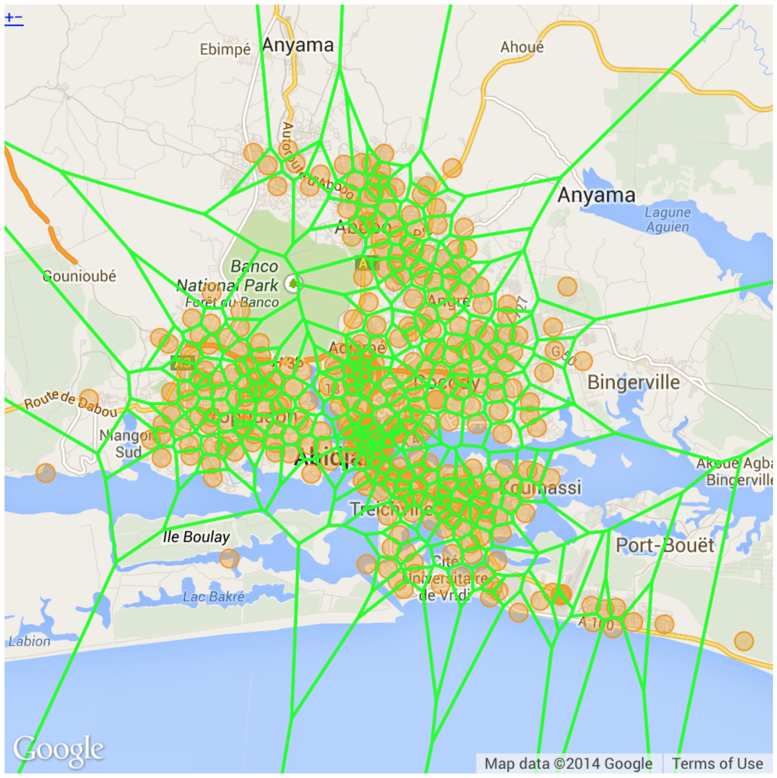


Figure 4: Voronoi Tessellation for Abidjan Dataset

output as a plain-text list of identifiers and polygons, each in Well Known Text (WKT) format. This output is then converted into an easily parsable CSV file using regular expressions in a Ruby script.

3.4 Population Estimation

Population estimation is implemented using a Python script with the `shapely` module. The processed GPW CSV file is read into memory along with the Voronoi polygon CSV file and the outline geometry file. A hash-table mapping from cell tower identifier to estimated population is created where all values map to zero. The program then iterates over each GPW population datapoint together with each Voronoi polygon and adds the GPW population to the current cell tower's entry within the hash-table if the GPW population datapoint's latitude and longitude are contained within the Voronoi polygon. Estimates are then output from the hash-table into a CSV file.

4 Results and Future Research

The system can run on empirical datasets with results that concur with measured data. The Voronoi tessellation component can be clearly observed to produce correct Voronoi polygons for a set of cell tower coordinate inputs. Upon running the Abidjan dataset through the system, the aggregate population sum was found to be 3,812,122 people (using 2010 GPW data). The population of Abidjan in 2006 was 3,796,677 people [7]. The actual and estimated populations are nearly identical, taking population growth and potentially different borders into account.

There is substantial future research that can be performed to add features and improve the performance of this system. Currently, all population estimation tasks are performed on one single thread. Due to the easily parallelizable nature of the estimation algorithm, the population estimation program could be modified to take advantage of the several processor cores available on the host machine to significantly reduce run times.

There is room for future research to determine the validity and usefulness of the generated population estimates. Other population estimation methods, including those produced from analyzing call log data and geotagged tweets from Twitter, can be compared with the method presented in this paper to evaluate each method's effectiveness and applicability to human mobility models.

5 Summary

In the hopes of facilitating the improvement of human mobility models, a system has been developed for Colorado School of Mines PhD student, Thyago Mota, that is capable of estimating human populations in surrounding cell towers. This system applies a Voronoi tessellation on a set of cell tower coordinate points to segment a local polygon for each datapoint. These Voronoi polygons are then used in conjunction with a Gridded Population of the World dataset and an outline geometry of the region of interest to generate a population estimate for each cell tower.

The system has been applied to an Ivory Coast dataset and an Abidjan dataset, and successfully generates estimates that, when aggregated, appear to be correct. Further research in this area will involve the analysis and comparison of these estimates with additional population estimation methods, including the use of call log data and geotagged Twitter messages.

References

[1] S. Motahari, K. Jintaseranee, P. Reuther, Hui Zang, "Regularity-based wireless subscriber population estimation," *Global Communications Conference (GLOBECOM), 2012 IEEE* , vol., no., pp.5177,5182, 3-7 Dec. 2012

[2] The University of Tokyo, “A Study on Urban Mobility and Dynamic Population Estimation by Using Aggregate Mobile Phone Sources,” *Center for Spatial Information Science* [Online]. Available: `http://www.csis.u-tokyo.ac.jp/dp/115.pdf`

[3] NASA Socioeconomic Data and Applications Center (SEDAC), “Gridded Population of the World (GPW) v3,” [Online]. Available: `http://sedac.ciesin.columbia.edu/data/collection/gpw-v3`

[4] Wikipedia, “Esri grid,” [Online]. Available: `https://en.wikipedia.org/wiki/Esri_grid`

[5] Bjrn Harrtell, “JavaScript Topology Suite (JSTS),” *GitHub* [Online]. `https://github.com/bjornharrtell/jsts`

[6] “OpenLayers,” [Online]. `http://openlayers.org`

[7] Princeton Universite, “Abidjan,” [Online]. Available: `http://www.princeton.edu/~achaney/tmve/wiki100k/docs/Abidjan.html`

Appendix 1 — Code Listings

Code relevant to this project has been appended in the following subsections. This code, along with input data, documentation, and a README, is available as a public repository on GitHub at `https://github.com/sgonzalez/cell-tower-population`.

Voronoi Tessellation *(abridged)*

Input data has been removed from this code listing for brevity.

```
<!DOCTYPE html PUBLIC "-//W3C//DTD␣XHTML␣1.0␣Strict//EN" "http://www.w3.org
   /TR/xhtml1/DTD/xhtml1-strict.dtd">
<html>

<!-- HEAD -->
<head>
```

```
        <title>Voronoi Tesselation Example</title>
        <meta http-equiv="Content-Type" content="text/html;␣charset=utf-8"/
           >
    <meta name="Author" content="Thyago␣Mota"/>
</head>

<script src="http://maps.google.com/maps/api/js?sensor=false"></script>
<script type="text/javascript" src="OpenLayers.js"></script>
<script type="text/javascript" src="javascript.util.js"></script>
<script type="text/javascript" src="jsts.js"></script>
<script type="text/javascript" src="attache.array.min.js"></script>
<script type="text/javascript">
        var map, baseLayer, sitesLayer, tilesLayer;

        function init() {
                // 0. the parser object converts objects from JSTS to
                   OpenLayers
                var parser = new jsts.io.OpenLayersParser();

                // 1. these objects will be necessary to convert from one
                   projection to another
                var epsg4326   = new OpenLayers.Projection('EPSG:4326');
                var epsg900913 = new OpenLayers.Projection('EPSG:900913');

                // 2. define the points in JSTS
                var jstsPoints = [
//// INSERTION POINT ////

//// END POINT ////

                        /*new jsts.geom.Coordinate(-105.210492, 39.750589),
                        new jsts.geom.Coordinate(-105.222601, 39.751347),
                        new jsts.geom.Coordinate(-105.153801, 39.736102),
                        new jsts.geom.Coordinate(-105.223925, 39.742108)*/
                ];

                // 3. calculate the voronoi tesselation
                var geometryFactory = new jsts.geom.GeometryFactory();
                var jstsMultipoints = geometryFactory.createMultiPoint(
                   jstsPoints);
                var voronoiBuilder  = new jsts.triangulate.
                   VoronoiDiagramBuilder();
                voronoiBuilder.setSites(jstsMultipoints);
                var voronoi         = voronoiBuilder.getDiagram(
                   geometryFactory);

                // 4. create an openlayers map
                map = new OpenLayers.Map('map', {projection: "EPSG:900913"
                   });
```

```
            // 5. base layer is a google map
            baseLayer = new OpenLayers.Layer.Google('Google Map Layer',
                 {layers: 'basic'});

            // 6. have a layer with the sites
            sitesLayer = new OpenLayers.Layer.Vector('sites layer');
            var features1 = new Array(jstsPoints.length);
            var point;
            for (var i in jstsPoints) {
                    point = new OpenLayers.Geometry.Point(jstsPoints[i
                        ].x, jstsPoints[i].y);
                    features1[i] = new OpenLayers.Feature.Vector(point.
                        transform(epsg4326, epsg900913), null);
            }
            sitesLayer.addFeatures(features1);

            // 7. have another layer with the tiles
            tilesLayer = new OpenLayers.Layer.Vector('tiles layer');
            var geometries = parser.write(voronoi).components;
            var features2 = new Array(geometries.length);
            for (var i in geometries) {
                    features2[i] = new OpenLayers.Feature.Vector(
                        geometries[i].transform(epsg4326, epsg900913),
                        null, {fillOpacity:0,strokeColor:'#00FF00'});
            }
            tilesLayer.addFeatures(features2);

            // 8. add the layers to the map
            map.addLayers([baseLayer, sitesLayer, tilesLayer]);

            // 9. do the zoom
            map.zoomToExtent(tilesLayer.getDataExtent());



            var button = document.getElementById('exportButton');
        button.addEventListener('click', exportToCsv);

        function exportToCsv() {
            var myCsv = "";

//              myCsv += voronoi;
            // var pointIndex = 1;
            // var voronoiResult = voronoiBuilder.getDiagram(geomFact);
            // var parser = new jsts.io.OpenLayersParser();
            // input = parser.write(input);
            // voronoiResult = parser.write(voronoiResult);
            // vertices = voronoiResult.getVertices();
                    /*var str = '';
                    for (i in vertices) {
```

```
                                point = vertices[i];
                                point = point.transform(epsg900913,epsg4326
                                   );
                                str = str + point.x + ',' + point.y + ' ';
                                str += '\n'
                        }*/
            var gs = parser.write(voronoi).components;
            var pointIndex = 1;
            for (var i in gs) {
                var verts = gs[i]/*.transform(epsg900913, epsg4326)/*.
                    transform(epsg4326, epsg900913)*/.getVertices();
                myCsv += pointIndex;
                myCsv += "␣";
                myCsv += verts;
                myCsv += "\n";
                /*for (var loc in verts) {
                    myCsv += loc instanceof OpenLayers.Geometry;
                    myCsv += "␣␣␣␣␣";
                    myCsv += pointIndex;
                    myCsv += ",␣";
                    myCsv += loc.latitude;
                    myCsv += ",␣";
                    myCsv += loc.longitude;
                    myCsv += "\n";
                }*/
                pointIndex ++;
                // features2[i] = new OpenLayers.Feature.Vector(geometries[
                    i].transform(epsg4326, epsg900913), null, {fillOpacity
                    :0,strokeColor:'#00FF00'});
            }
//            var vtcs = voronoi.getCoordinates();
//              var str = '';
//              var p;
//              for (i in vtcs) {
//                      p = vtcs[i];
//                // p = p.transform(epsg900913,epsg4326);
//                      str = str + p.x + ',' + p.y + '\n';
//              }
//            myCsv += str;
            // var resultString = '';
            // var index = 0;
            // for (i in voronoi.getVertices()) {
            //     resultString += index;
            //     index++;
            // }
            // myCsv += voronoi.getCoordinates();

                /*for (var pt in jstsPoints) {
                    for (var i in g) {
```

```
                                f[i] = new OpenLayers.Feature.Vector(g[i].
                                    transform(epsg4326, epsg900913), null, {
                                    fillOpacity:0,strokeColor:'#00FF00'});
                                myCsv += f[i];

                                myCsv += pointIndex;
                            myCsv += ",␣";
                            myCsv += pt.latitude;
                            myCsv += ",␣";
                            myCsv += pt.longitude;
                            myCsv += "\n";
                        }
                    pointIndex++;
                }*/

            window.open('data:text/csv;charset=utf-8,' + escape(myCsv));
        }
        }
</script>

<!-- BODY -->
<body onload="init()">
        <div id="map" style="width:␣500px;␣height:␣500px;"></div>
        <P>
        <!--<textarea id="text" rows="20" cols="50"></textarea>-->
        <button id="exportButton">Export Geometries to CSV</button>
</body>

</html>
```

Voronoi WKT to CSV Converter

```
#!/usr/bin/ruby

#########################
### Santiago Gonzalez ###
#########################

def process_line line, poly_out_file, pops_out_file
  split_line = line.split('␣', 2)
  polygon_id = split_line[0]
  points = split_line[1].scan(/POINT\((-?\d+\.\d+) (-?\d+\.\d+)\)/)

  points.each do |vertex|
    print polygon_id
    print ",␣"
    print vertex[0]
    print ",␣"
    print vertex[1]
    puts ""
    poly_out_file.write("#{polygon_id},␣#{vertex[0]},␣#{vertex[1]}\n")
  end

  puts ""
end


############################
## PROGRAM EXECUTION START

# take input file argument
if ARGV.length != 1
  puts "Usage:␣./polygon_processor.rb␣[results␣file]"
  exit 1
end
filename = ARGV[0]

# parse file line by line
File.open(filename, "r") do |file|
  File.open("OUTPUT/parsed_polygons.csv", 'w+') do |poly_out_file|
    File.open("OUTPUT/polygon_populations.csv", 'w') do |pops_out_file|
      file.each do |ln|
        process_line ln, poly_out_file, pops_out_file
      end
    end
  end
end

exit 0
```

Grid Converter

```
#
    --------------------------------------------------------------------------------
     #
# grid_converter.py - Converts a grid map with population to the following
    format #
# lon, lat, population
                                                                #
# Author: Thyago Mota
                                                                 #
# Date: 02/01/2014
                                                                    #
#
    --------------------------------------------------------------------------------
     #
```

```
import datetime, shapely, sys, math
from datetime import datetime, date, time
from shapely.geometry import Polygon, Point
from math import modf

def help():
        print('Use:␣' + sys.argv[0] + '␣input_file␣geometry_file␣
            output_file')

#
    ------------------------------------------------------------------------------
     #
# Some definitions
                                                                   #
#
    ------------------------------------------------------------------------------
     #
FEEDBACK_NUM_RECORDS = 100
NUM_ARGS             = 4
TOLERANCE            = 0.00001
ARCGIS_NO_DATA_VALUE = -3.40282346639e+038

#
    ------------------------------------------------------------------------------
     #
# Script begins
                                                                      #
#
    ------------------------------------------------------------------------------
     #
startTime = datetime.now()
print('Start␣time:␣' + str(startTime.hour) + ':' + str(startTime.minute) +
    ':' + str(startTime.second))

#
    ------------------------------------------------------------------------------
     #
# Command line validation
                                                             #
# Parameters (required): input_file output_file
                                              #
#
    ------------------------------------------------------------------------------
     #
if len(sys.argv) != NUM_ARGS:
        help()
        exit(1)

#
    ------------------------------------------------------------------------------
    #
# Opening of files
                                                                  #
#
   ------------------------------------------------------------------------------
    #
print('Trying␣to␣open␣the␣input␣and␣geometry␣files␣for␣reading')
try:
        input = open(sys.argv[1], 'rt')
except:
        print('Could␣not␣open␣file␣' + sys.argv[1])
        exit(2)
try:
        geometry = open(sys.argv[2], 'rt')
except:
        print('Could␣not␣open␣file␣' + sys.argv[2])
        input.close()
        exit(3)
try:
        output = open(sys.argv[3], 'wt')
except:
        print('Could␣not␣open␣file␣' + sys.argv[3])
        input.close()
        geometry.close()
        exit(4)
print('Success!')

#
   ------------------------------------------------------------------------------
    #
# Reading geometry file
                                                             #
#
   ------------------------------------------------------------------------------
    #
print('Reading␣geometry␣file')
geoData = []
for line in geometry:
        line = line.replace('\n', '')
        data = line.split('␣')
        for i in range(0, len(data)):
                d = data[i].split(',')
                geoData.append([float(d[0]), float(d[1])])
geometry.close()
print('Geometry␣file␣looking␣good␣:-)')
#print(geoData)

#
   ------------------------------------------------------------------------------
    #
```

```
# Creating a polygon based on geometry
                                                #
#
   ---------------------------------------------------------------------------------
    #
print('Creating␣a␣polygon␣based␣on␣geometry')
poly = Polygon(geoData)
print('That␣was␣easy!')

#
   ---------------------------------------------------------------------------------
    #
# Reading metadata
                                                                    #
#
   ---------------------------------------------------------------------------------
    #
print('Metadata:')
for i in range(0, 6):
        line = input.readline()
        line = line.replace('\n', '')
        line = "␣".join(line.split()) # eliminates duplicate whitespaces
        data = line.split('␣')
        #print(data[1])
        if i == 0:
                nCols = int(data[1])
        elif i == 1:
                nRows = int(data[1])
        elif i == 2:
                xllCorner = float(data[1])
        elif i == 3:
                yllCorner = float(data[1])
        elif i == 4:
                cellSize = float(data[1])
        else:
                noDataValue = float(data[1])
print('\tnCols:␣\t\t' + str(nCols))
print('\tRows:␣\t\t' + str(nRows))
print('\txllCorner:␣\t' + str(xllCorner))
print('\tyllCorner:␣\t' + str(yllCorner))
print('\tcellSize:␣\t' + str(cellSize))
print('\tnoDataValue:␣\t' + str(noDataValue))
print('Grid␣box:')
print('\t(' + str(xllCorner) + ',' + str(yllCorner) + ')')
print('\t(' + str(xllCorner + nCols * cellSize) + ',' + str(yllCorner) + ')
   ')
print('\t(' + str(xllCorner) + ',' + str(yllCorner + nRows * cellSize) + ')
   ')
print('\t(' + str(xllCorner + nCols * cellSize) + ',' + str(yllCorner +
   nRows * cellSize) + ')')
```

```
#
    -------------------------------------------------------------------------------
     #
# Reading the grid
                                                                   #
#
    -------------------------------------------------------------------------------
     #
grid = [ [ 0. for j in xrange(nCols) ] for i in xrange(nRows) ]
i = 0
totalUnbounded = 0
for line in input:
        line = line.replace('\n', '')
        if line[0] == '␣':
                line = line[1:]
        data = line.split('␣')
        for j in xrange(nCols):
                value = float(data[j])
                if value == ARCGIS_NO_DATA_VALUE or value == noDataValue or
                     value < 0:
                        continue
                grid[i][j] = value
                totalUnbounded = totalUnbounded + value
        i = i + 1
input.close()
print('Total␣unbounded:␣' + str(totalUnbounded))

#
    -------------------------------------------------------------------------------
     #
# Writing the new file
                                                               #
#
    -------------------------------------------------------------------------------
     #
print('Writing␣the␣new␣file')
totalBounded = 0
for i in xrange(nRows):
        #print('Line ' + str(i+1) + ' of ' + str(nRows))
        lat = yllCorner + (nRows - i) * cellSize + cellSize/2 # cellSize/2
            to have values centered instead of top-left
        for j in xrange(nCols):
                if grid[i][j] == 0:
                        continue
                lon = xllCorner + j * cellSize + cellSize/2 # cellSize/2 to
                     have values centered instead of top-left
                point = Point(lon, lat)
                if point.within(poly):
                        totalBounded = totalBounded + grid[i][j]
                        output.write(str.format('{0:.5f}', lon) + ',' + str
                            .format('{0:.5f}', lat) + ',' + str.format('
                            {0:.2f}', grid[i][j]) + '\n')
output.close()
print('Total␣bounded:␣' + str(totalBounded))

#
    ------------------------------------------------------------------------------
     #
# Script ends
                                                                        #
#
    ------------------------------------------------------------------------------
     #
endTime = datetime.now()
print('End␣time:␣' + str(endTime.hour) + ':' + str(endTime.minute) + ':' +
    str(endTime.second))
elapsedTime = endTime - startTime
print('Elapsed␣time:␣' + str(elapsedTime))
```

Clustering

```
#
    ------------------------------------------------------------------------------
     #
# clustering.py - Runs a clustering algorithm (DBSCAN) to identify cell
    towers    #
#                  in Abidjan area that are close to each other; assign a
    new      #
#                  coordinate to each cluster to be the centroid location
             #
# Author: Thyago Mota
                                                                #
# Date: 01/24/2014
                                                                   #
#
    ------------------------------------------------------------------------------
     #

import datetime, math
from datetime import datetime, date, time

#
    ------------------------------------------------------------------------------
     #
# Calculates the centroid of a set of points
                                          #
# points = [ (lon, lat), ... ]
                                                          #
```

```
#
    ------------------------------------------------------------------------------
     #
def centroid(points):
        sumLon = 0
        sumLat = 0
        total  = 0
        for point in points:
                sumLon = sumLon + point[0]
                sumLat = sumLat + point[1]
                total = total + 1
        return [ sumLon / total, sumLat / total ]

#
    ------------------------------------------------------------------------------
     #
# haversine function that calculates the distance (in km) between two
    points      #
#
    ------------------------------------------------------------------------------
     #
def haversine( XY ):
        p1 = [ x * ( math.pi / 180 ) for x in XY[0] ]
        p2 = [ x * ( math.pi / 180 ) for x in XY[1] ]
        d_lon = p1[0] - p2[0]
        d_lat = p1[1] - p2[1]
        h = (math.sin(d_lat/2))**2 + math.cos(p1[1]) * math.cos(p2[1]) * (
            math.sin(d_lon/2))**2
        return 6372.8 * 2 * math.atan2( math.sqrt(h), math.sqrt(1-h) )

#
    ------------------------------------------------------------------------------
     #
# neighboors function that identifies locations that are nearby
                      #
#
    ------------------------------------------------------------------------------
     #
def neighboors(tower, towers, eps):
        neighboors = []
        for candidate in towers:
                if candidate == tower:
                        continue
                d = haversine([towers[candidate], towers[tower]])
                if d <= eps:
                        neighboors.append(candidate)
        return neighboors

#
    ------------------------------------------------------------------------------
    #
# DBSCAN clustering algorithm
                                                         #
#
   ------------------------------------------------------------------------------
    #
def dbscan(towers, eps, min):
        clusters = []
        visited = {}
        for tower in towers:
                visited[tower] = False
        for tower in towers:
                if visited[tower]:
                        continue
                visited[tower] = True
                # print( 'Visiting ' + str( tower ) )
                n = neighboors(tower, towers, eps)
                # print( 'Neighboors of ' + str( tower ) + ': ' + str( n )
                    )
                if len(n) >= min:
                        newCluster = [tower]
                        # expand neighboor list
                        for other in n:
                                visited[other] = True
                                nn = neighboors(other, towers, eps)
                                # print( nn )
                                if len(nn) >= min:
                                        n = n + nn
                        n = list(set(n))
                        # print( 'Expanded neighboors of ' + str( tower ) +
                             ': ' + str( n ) )
                        # add neighboors IF they are not in a cluster
                        for other in n:
                                if other == tower:
                                        continue
                                found = False
                                for c in clusters:
                                        if other in c:
                                                found = True
                                                break
                                if not found:
                                        newCluster.append(other)
                                        visited[other] = True # no need to
                                            revisit a location that is
                                            already in a cluster
                        # print(newCluster)
                        clusters.append(newCluster)
        return clusters
```

```
#
    -------------------------------------------------------------------------------
     #
# Some definitions
                                                                   #
#
    -------------------------------------------------------------------------------
     #
DATA_FOLDER  = 'd:\\development\\research\\data\\'
D4D_FOLDER   = 'D4D\\'
TOWERS_FILE  = 'abidjan_towers.csv'
LOCAL_FOLDER = '..\\data\\'
OUTPUT_FILE  = 'clusters.csv'
# DBSCAN parameters
EPSILON      = 0.5 # km
MIN_POINTS   = 1

#
    -------------------------------------------------------------------------------
     #
# Script begins
                                                                      #
#
    -------------------------------------------------------------------------------
     #
startTime = datetime.now()
print('Start␣time:␣' + str(startTime.hour) + ':' + str(startTime.minute) +
    ':' + str(startTime.second))

#
    -------------------------------------------------------------------------------
     #
# Reading Abidjan cell towers
                                                        #
# towers[cellID] = (lon, lat)
                                                        #
#
    -------------------------------------------------------------------------------
     #
print('Reading␣Abidjan␣cell␣towers')
file = open(DATA_FOLDER + D4D_FOLDER + TOWERS_FILE, 'rt')
towers = {}
for line in file:
        line   = line.replace('\n', '')
        data   = line.split(',')
        tower  = int(data[0])
        lon    = float(data[1])
        lat    = float(data[2])
        towers[tower] = (lon, lat)
file.close()
```

```
print(str(len(towers)) + '␣towers␣read')

#
   ------------------------------------------------------------------------------
     #
# Running the clustering procedure
                                                   #
#
   ------------------------------------------------------------------------------
     #
clusters = dbscan(towers, EPSILON, MIN_POINTS)
# exclude clusters with just one tower
clusters = [cluster for cluster in clusters if len(cluster) > 1]
print(str(len(clusters)) + '␣clusters␣created')

#
   ------------------------------------------------------------------------------
     #
# Printing cluster information
                                                       #
#
   ------------------------------------------------------------------------------
     #
output = open(LOCAL_FOLDER + OUTPUT_FILE, 'wt')
seq = 0
total = 0
for cluster in clusters:
        points = []
        total = total + len(cluster)
        #print(cluster)
        for tower in cluster:
                points.append(towers[tower])
        center = centroid(points)
        output.write(str(seq) + ',' + str(center[0]) + ',' + str(center[1])
            )
        for tower in cluster:
                output.write(',' + str(tower))
        output.write('\n')
        seq = seq + 1
output.close()
print('Towers␣in␣cluster:␣' + str(total))
print('New␣number␣of␣venues:␣' + str(len(towers) - total + len(clusters)))

#
   ------------------------------------------------------------------------------
     #
# Script ends
                                                                          #
#
   ------------------------------------------------------------------------------
```

```
     #
endTime = datetime.now()
print('End␣time:␣' + str(endTime.hour) + ':' + str(endTime.minute) + ':' +
    str(endTime.second))
elapsedTime = endTime - startTime
print('Elapsed␣time:␣' + str(elapsedTime))
```

Population Estimator

```
#
    ------------------------------------------------------------------------------
     #
# population_estimator.py - Estimates populations using cell tower Voronoi
    polys  #
# cell_id, population
                                                                #
# Author: Santiago Gonzalez
                                                          #
# Date: April 2014
                                                                   #
#
    ------------------------------------------------------------------------------
     #

import datetime, shapely, sys, math
from datetime import datetime, date, time
from shapely.geometry import Polygon, Point
from collections import defaultdict
from math import modf

def help():
  print('Usage:␣' + sys.argv[0] + '␣polygon_file␣geometry_file␣
      grid_population_file␣output_file')

#
    ------------------------------------------------------------------------------
     #
# Some definitions
                                                                   #
#
    ------------------------------------------------------------------------------
     #
NUM_ARGS           = 5

#
    ------------------------------------------------------------------------------
     #
# Script begins
                                                                      #
```

```
# 
    ------------------------------------------------------------------------------
     #
startTime = datetime.now()
print('Start␣time:␣' + str(startTime.hour) + ':' + str(startTime.minute) +
    ':' + str(startTime.second))

# 
    ------------------------------------------------------------------------------
     #
# Command line validation
                                                            #
# Parameters (required): input_file output_file
                                      #
# 
    ------------------------------------------------------------------------------
     #
if len(sys.argv) != NUM_ARGS:
  help()
  exit(1)

# 
    ------------------------------------------------------------------------------
     #
# Opening of files
                                                                   #
# 
    ------------------------------------------------------------------------------
     #
print('Trying␣to␣open␣the␣polygon␣and␣geometry␣files␣for␣reading')
try:
  input = open(sys.argv[1], 'rt')
except:
  print('Could␣not␣open␣file␣' + sys.argv[1])
  exit(2)
try:
  geometry = open(sys.argv[2], 'rt')
except:
  print('Could␣not␣open␣file␣' + sys.argv[2])
  input.close()
  exit(3)
try:
  populations = open(sys.argv[3], 'rt')
except:
  print('Could␣not␣open␣file␣' + sys.argv[3])
  input.close()
  exit(4)
try:
  output = open(sys.argv[4], 'wt')
except:
  print('Could␣not␣open␣file␣' + sys.argv[3])
  input.close()
  geometry.close()
  exit(5)
print('Success!')

#
   --------------------------------------------------------------------------------
    #
# Reading geometry file
                                                                              #
#
   --------------------------------------------------------------------------------
    #
print('Reading␣geometry␣file')
geoData = []
for line in geometry:
  line = line.strip()
  data = line.split('␣')
  for i in range(0, len(data)):
    d = data[i].split(',')
    geoData.append([float(d[0]), float(d[1])])
geometry.close()
print('Geometry␣file␣looking␣good␣:-)')
#print(geoData)

#
   --------------------------------------------------------------------------------
    #
# Creating a polygon based on geometry
                                                               #
#
   --------------------------------------------------------------------------------
    #
print('Creating␣a␣polygon␣based␣on␣geometry')
poly = Polygon(geoData)
print('That␣was␣easy!')

#
   --------------------------------------------------------------------------------
    #
# Load populations into array
                                                                        #
#
   --------------------------------------------------------------------------------
    #
print('Reading␣gridded␣populations')
populationData = {} # map of x,y tuple to number
for line in populations:
  line = line.strip()
  data = line.split(',')
  populationData[(float(data[0]), float(data[1]))] = float(data[2])
populations.close();
print('Finished␣loading␣gridded␣populations')

#
   ------------------------------------------------------------------------------
    #
# Load polygons into array
                                                           #
#
   ------------------------------------------------------------------------------
    #
print('Reading␣polygons')
voronoiPolygons = {} # map of cell tower id to polygon
for line in input:
  line = line.strip()
  data = line.split(',')
  voronoiPolygons.setdefault(int(data[0]),[]).append([float(data[1]), float
      (data[2])])
for k in voronoiPolygons:
  poly = Polygon(voronoiPolygons[k])
  voronoiPolygons[k] = poly
print('Finished␣reading␣polygons')

#
   ------------------------------------------------------------------------------
    #
# Estimate populations
                                                               #
#
   ------------------------------------------------------------------------------
    #
print('Estimating...')
estimatedPopulations = defaultdict(int) # map of cell tower id to number,
   defaultdict ensures values default to 0
for coord in populationData:
    for towerid in voronoiPolygons: # if we aren't deleting used items as
        we go along, this for loop should be the innermost one, for
        efficiency
        popAtCoord = populationData[coord]
        point = Point(coord[0], coord[1])
        if point.within(voronoiPolygons[towerid]):
            estimatedPopulations[towerid] += popAtCoord
        #    del populationData[coord] # we can delete this popData entry
            since it will not appear again

#
   ------------------------------------------------------------------------------
    #
```

```
# Writing the new file
                                                              #
#
   ------------------------------------------------------------------------------
    #
print('Writing␣the␣new␣file')
for towerid in estimatedPopulations:
    output.write(str.format('{0:.0f}', towerid) + ',' + str.format('{0:.2f}
        ', estimatedPopulations[towerid]) + '\n')
output.close()
print('Finished!')

#
   ------------------------------------------------------------------------------
    #
# Script ends
                                                                       #
#
   ------------------------------------------------------------------------------
    #
endTime = datetime.now()
print('End␣time:␣' + str(endTime.hour) + ':' + str(endTime.minute) + ':' +
   str(endTime.second))
elapsedTime = endTime - startTime
print('Elapsed␣time:␣' + str(elapsedTime))
```