FRACTAL ANALYSIS OF GLOBAL EARTHQUAKE DATA

A DISSERTATION

Submitted in partial fulfilment of the Requirements for the award of the degree

Of

INTEGRATED MASTER OF TECHNOLOGY
in
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By
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DECLARATION OF AUTHORSHIP

I hereby solemnly declare that the work presented in this dissertation thesis titled "Fractal Analysis of Global Earthquakes Data" submitted by me in partial fulfilment of the requirements for award of the degree '**Integrated Master of Technology**' in '**Geophysical Technology**' to the **Department of Earth Sciences, IIT Roorkee**, is an authentic record of my own work carried out during the period May 2018 to April 2019, under the supervision of **Dr. Kamal**, Department of Earth Sciences, Indian Institute of Technology, Roorkee. The matter embodied in this dissertation has not been submitted by me for the award of any other degree in any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Any accomplishment in life merits a support structure which requires the efforts and support of many people. This bears a deeper meaning when it comes to the case of students, lacking expertise, insight and the knack of going about doing things. This dissertation is no different from what is mentioned above.

This dissertation is a culmination of support of many individuals, and this is a humble effort to pen my gratitude to them.

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ABSTRACT

This report presents a method to find a correlation, if any, of the earthquake occurrence in three different zones of the convergent plate boundaries in Pacific Plate region using the Iterated Function Systems (IFS).

The earthquake data of last 48 years was acquired and the area of study was divided into four zones based on their tectonic similarity.

The seismic events are arranged chronologically and are flagged according to the zone in which they occurred which resulted into a one dimensional time array for earthquakes according to their zones

This one dimensional time array for different zones was then read as 1-bit, 4-bit and 8-bit fractal addresses by running a script written in Matlab. The images obtained depicted the correlation or non-correlation between different zones.

The results are based on the past pattern of earthquakes in the study area and we can only determine the probability of the zone wise order occurrence in the future by comparing the visual results of chronological zone wise earthquake mapping

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INTRODUCTION

4.1 INTRODUCTION TO EARTHQUAKE

An earthquake is a sudden agitation of earth surface, which is caused due to an abrupt discharge of energy in Earth's lithosphere. Earth's lithosphere is separated into various tectonic plates, which are under slow yet continuous motion. At the point when two rocks or tectonic plates are scouring against one another, they don't simply slide easily, but stick a bit. Built up potential energy due to such motion is eventually released as seismic waves, causing earthquakes. Most recorded earthquakes are caused by the same mechanism. Intensity of such agitations felt on Earth's surface depends on multiple factors, such as, depth of hypocentre, energy released, epicentre distance, rock properties.

Large earthquakes incurs huge loss of life and assets, driving scientists worldwide to develop an earthquake prediction system, yet no success has been achieved to predict exact time and location of an earthquake. Researchers do have a thought of where is a high possibility for a seismic tremor to happen, however the specific date of event still remains a riddle. Be that as it may, the shot of event or likelihood of a seismic tremor can be assessed, in light of past records. Earthquake forecast will likewise help with expectation of occasions that pursues a quakes, for example, a Tsunami is trailed by an offshore tremor.

In past years, earthquake cautioning frameworks have been set up, that can give warning on a territorial dimension in regards to a seismic tremor in advancement, yet before the ground development starts, that may enable individuals to look for safe house before any significant obliteration happens.

In this report, we are attempting to take the idea of anticipating earthquake forward.

4.2 PACIFIC PLATE

The pacific plate is the largest tectonic plate that is almost completely submerged under water. The pacific plate has a total area around 103 million square kilometres.

It is a complex plate sharing boundaries with multiple plates with much of its boundary being divergent plate boundary, yet most of the earthquakes around Pacific plate occurs at convergent plate boundary. Most of its convergent plate boundary is shared with North American plate, Philippine plate and Indo-Australian plate.

A large portion of Ring of Fire is in basin of Pacific Ocean. This portion is marked by high numbers of volcanic eruptions and earthquakes.

The pacific plate has a drift towards northwest at a speed of 7-11 centimetres/year. The variation in the speed of different plates is the major reason for the build-up of strain in the lithosphere, which causes earthquakes. For example, earthquakes on San Andreas Fault happens due to release of strain built up due to the grinding of North American plate with Pacific Plate, in California.

4.3 RESEARCH OBJECTIVES

1. Generate Fractal images of earthquake data for area of interest.
2. Infer correlation between different earthquake zones.
3. Validate probability technique for establishing correlation between occurrence earthquakes.

LITERATURE REVIEW

5.1 FRACTALS

Fractals are geometrical figures that recurrent their structure at each scale, a feature that is also known as self-similarity. This means that a small portion of a fractal will show same statistical character as the whole figure. They can be used in displaying figures, in which comparative examples repeat at continuously smaller levels or scales, and in portraying incompletely arbitrary or tumultuous phenomena, for example, crystal structure and formations in galaxy. One good example of fractals in nature is a snowflake *(figure 1).* Repetitive structures can be observed on the dendrites or arms of a snowflake crystal. Such fractals can also be observed in structure of tree *(figure 2),* where branch shows self-similarity with the entire structure of the tree.

Figure 1*: Fractal structure of a snowflake*

*(*Figure source: *https://sites.google.com/a/stjoebruins.com/fractals-are-in-nature/snowflakes)*

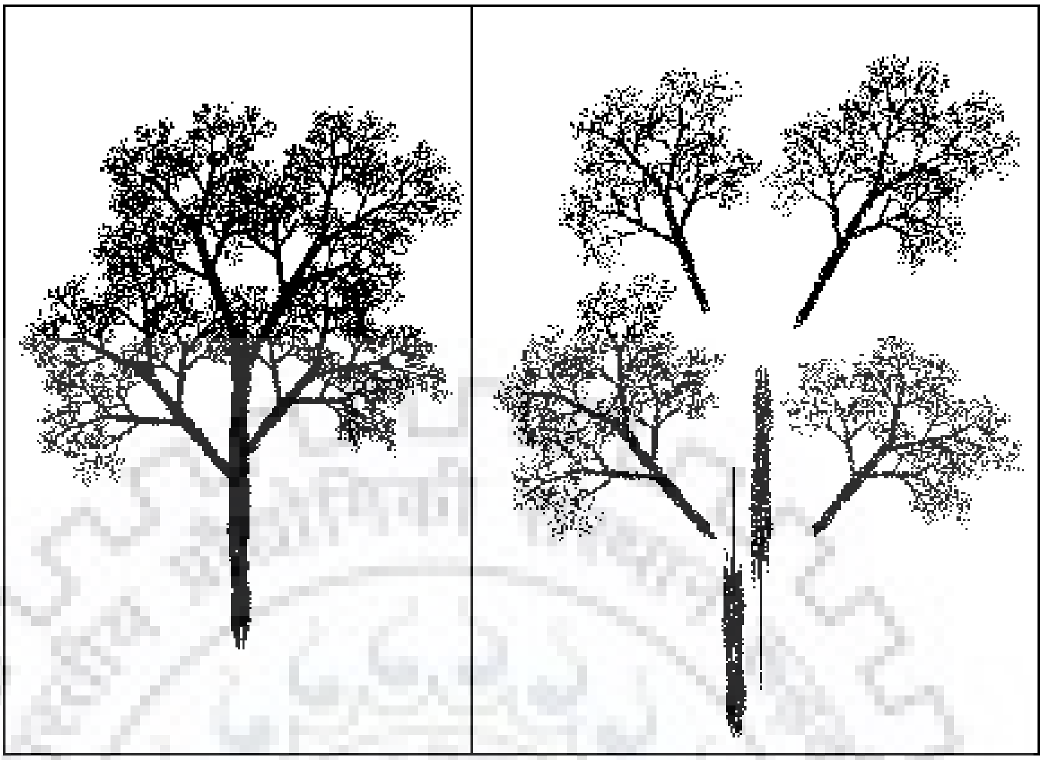


Figure 2: *Fractal structures in tree branch*

(Figure source: *https://users.math.yale.edu/public_html/People/frame/Fractals/IntroToFrac/InvProb/TreeIFS/TreeIFS.html)*

Self-similarity is of subsequent types:

- **Exact self-similarity**: the structure at different level or scales, looks the same.
- **Quasi self-similarity**: the structure or pattern shows some resemblance at different scales.
- **Statistical self-similarity**: in this case, the structures shows some stochastic redundancy of the patter so that if we move crosswise over scales the numerical and statistical proportions of fractals are protected.
- **Qualitative self-similarity**: in this case, self-similarity is followed in a time series.
- **Multifractal Scaling**: this type of self-similarity show resemblance of structure multiple dimensional or scaling rule.

5.2 INTRODUCTION TO CHAOS

The word ‘Chaos’ originates from a Greek word ‘Khaos’ which means unpredictability. In science field, chaos can explained as dynamic behaviour which is most regularly portrayed by sensitivity to the initial condition. It is most commonly referred as a synonym to randomness, which is not true at all. Instead it can be understood as opposite of stability. In a chaotic system, even the slightest changes in the initial conditions can show an immense impact on final results. Thus, understanding of a chaotic system, such as our universe itself, is dependent upon the precision of our knowledge. The butterfly effect depicts how the slightest of variation in even a single condition of a deterministic nonlinear framework can provide us with an extensive contrasts in a later state, for example a butterfly fluttering its wings in South America can cause a hurricane in Texas.

Smallest of contrast in the beginning conditions, for example, smallest of adjustments made in numerical calculations, can cause the results to be highly diverging for a chaotic system. This can cause predictions for long-term to be incomprehensible all in all. This happens despite the fact that these frameworks are deterministic, which implies that there is no random component included. Such deterministic systems imply that their future conduct is completely dictated by their underlying conditions.

One good example of chaotic system is our own universe. Several failed attempts has been made to recreate the structure of the universe from the start in a computer simulation. Even the slightest of mistakes in initial conditions or in numerical calculations will draw us to unexpected results. The very life to initiate on earth requires many numerical values related to physical properties as such precision which is still impossible to attain for physicists.

So, chaos can be summed up in one line, at the point when the present decides the future, yet the estimated present does not provide estimation of what's to come

5.3 CHAOS GAME THEORY

Chaos systems can be simply understood as systems that initially looks predictable but after some time, starts to appear the opposite. One of the most popular example of chaos system is the double pendulum. It is simply made by attaching one more pendulum to the end of a pendulum. Motion of single pendulum can be easily understood, yet the motion of a double pendulum is highly chaotic and very tough to predict. Even the slightest change in initial condition of motion can have huge impact on following motion.

Although their does not exist a particular definition for chaos, a widely accepted definition is provided by Robert L. Devaney, which states that, to consider a dynamic system to be chaotic, following properties must be met:

1. Sensitivity to the initial conditions.
2. It must show topological transitivity or mixing: system should develop over time so that any particular region of its phase space in the end, covers with some other given region.
3. It should have dense periodic orbits: this means that in a chaotic system, each point in the space is drawn closer arbitrarily by periodic orbits.

One of the first analyst in the field of chaos theory was a meteorologist by the name Edward Lorenz. He utilized a set of equations and conditions to hypothesis a model of weather. Studying such framework, he found that a particle follows an exceptionally confusing direction under the impact of atmospheric powers. He additionally derived that such directions dependably end up in a similar structure of an attractor. This structure is called Lorenz attractor. Lorenz attractor shows a similarity with the shape of a butterfly. This experiment very well conclude that how in a chaotic system, smallest change in the starting condition can bear unpredictable and exceptional results.

Chaos manages the portrayal of complex structures and curves called fractals.

5.4 DYNAMIC SYSTEMS

Dynamic of a system can be defined as how the situation changes through the span of time.

The physical setting of a dynamic system is how a situation shifts or advances from a point of time to another. The manner in which such advances or variations take place with time, are governed by a lot of standards and physical settings. The present estimation of the factors of such framework is its present state. No information about the system’s history is required to anticipate its future states, an instantaneous depiction is adequate. A few examples of such systems are Pendulum and Mathematical model of human system.

In a dynamic system, changes in dynamic quantities can be determined for a brief span, by consolidating the numerical amounts in a formula. For long timeframes, the advancement in this system for longer timeframes can determined by iteration. For contemplating the conduct of a non-linear dynamic systems, chaos theory is referred, because of its sensitivity to the initial condition. It endeavours to find structures or patterns in systems which may appear random at first.

5.5 CHAOS GAME

"In mathematics, the term chaos game originally referred to a method of creating a fractal, using a polygon and an initial point selected at random inside it."[Barnsley, Michael (1993). Fractals Everywhere. Morgan Kaufmann. ISBN 978-0-12-079061-6.]

Creating fractals by iterative method can be simply explained through following steps:

- Select a triangle of any shape.
- Colour code the vertices of triangle with different colours, let us say, red, blue and green.
- Generate a system that provides with a single colour at one turn and has equal probability on selecting the colour, for example, colour a die's two faces with singular colour.
- Choose one vertex as the initial point.
- Roll the die.
- For every colour obtained after rolling the die, move the point to halfway towards that colour vertex.
- Use this new point as the initial point to repeat the process.
- Toss out initial couple of points.

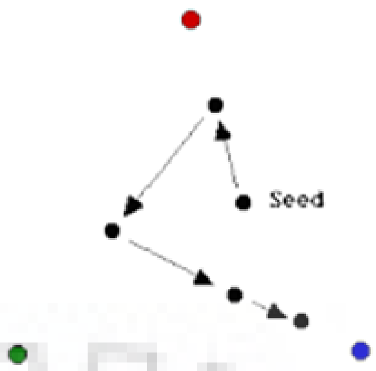


Figure 3: *Playing Chaos Game*

(Figure source: *www.lifenscience.com/bioinformatics/chaos-game-representation)*

The ultimate goal is to repeat this process for an infinite number. Pattern appeared from this process may appear like random at first, but repeating it for sufficient will eventually show some sort of pattern. The resulting pattern observed is well known as the "Sierpinski Triangle". But formation of a fractal requires the repetition of this iterative process for a large number of times, choosing the vertex arbitrarily on every turn. Although this process does not guarantees generation of a fractal structure.

One process to have surety of attaining self-similarity is by fabricating a structure by applying same similar procedure or repetition at smaller scales. The initial shape used is called initiator while the similar, yet scaled copies of initiator are called generators.

5.6 SIERPINSKI TRIANGLE

Another way to form a Sierpinski Triangle or Sierpinski gasket is by forming a triangle as generator and join the mid points each sides to generate a similar triangle with half the scales of the original. Remove the area of this smaller triangle. Repeating this process further and further as shown in the figure (figure 4) will show the evolution of Sierpinski Triangle.

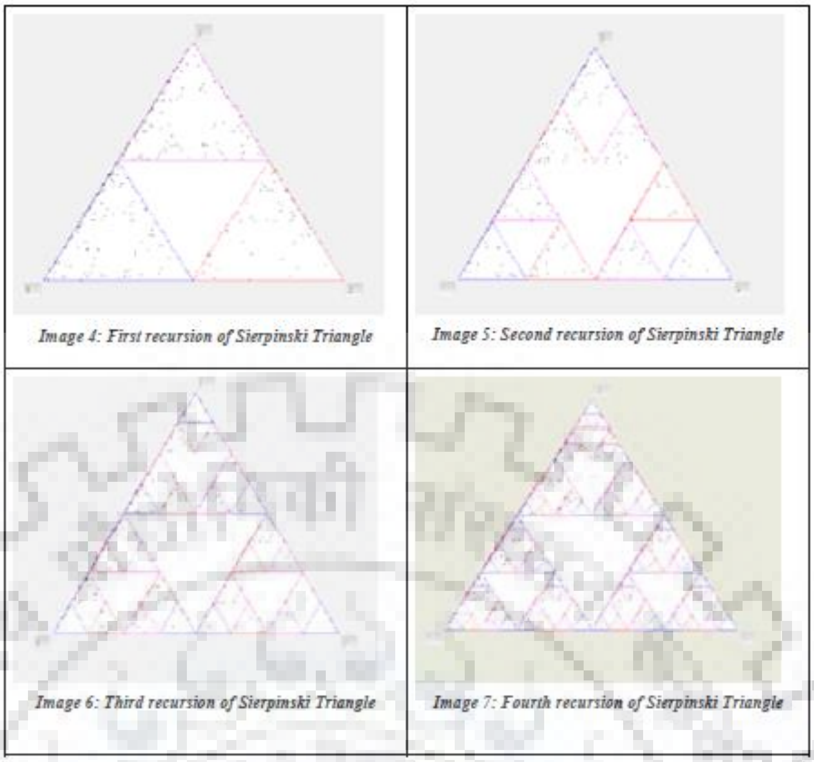


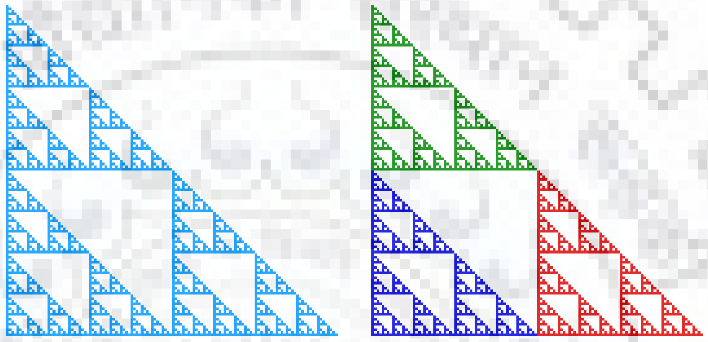
Figure 4: *Recursion of Sierpinski Triangle*

(Figure Source: *http://www.lifenscience.com/bioinformatics/chaos-game-representation)*

5.7 ITERATED FUNCTION SYSTEMS

Iterated Function System or IFS was introduced for the formation of fractals, so that fractal possess self-similarity. It was first introduced in 1981.

In IFS, fractals are generated by repeating the shape of an initial structure at different scales. This can be achieved by transformation achieved through a function. Such transformations consist of scaling, reflection, rotation and translation. The same order is widely used as the convention. Sierpinski Gasket can be formed as shown in Figure 5.



r	s	θ	φ	e	f
0.5	0.5	0	0	0.0	0.0
0.5	0.5	0	0	0.5	0.0
0.5	0.5	0	0	0.0	0.5

Figure 5: *Translations to Sierpinski Gasket*

(Figure source: *https://users.math.yale.edu/public_html/People/frame/Fractals/IntroToFrac/IFS/GasketInvar.html)*

To find the translations applied to a single structure, select a point, for example, lower left corner, and calculate the movement of a single structure. Here, r (x-directional scaling), s (y-directional scaling), θ (reflection), φ (rotational), e (x-directional translation), f (y-directional translation) are transformations applied to three similar structure (blue, red and green) to create a scaled up Sierpinski Triangle. This generates a right isosceles Sierpinski gasket.

AREA OF STUDY

Area selected for this study is along the tectonic plate boundary of Pacific plate.

Earthquake events along only the convergent plate boundaries are used to show some correlation in the occurrence of these events. These convergent boundaries are shared by Pacific plate with Eurasian plate, Philippine plate and Indo-Australian plate. These convergent plate boundary areas are subdivided into multiple zones, as shown in Table 1. For Zone-2, data for latitude (20°-37°) and longitude (130°-135°) has been removed to discard the earthquakes caused due to Eurasian and Philippine plate boundaries. All of these zones constitute of earthquake caused mainly due to convergence of oceanic tectonic plates.

ZONES	1	2	3	4
LATITUDE (NORTH-SOUTH)	60°-38°	37°-0°	0°-(-15°)	0°-(-15°)
LONGITUDE (WEST-EAST)	150°-(-150°)	130°-150°	135°-155°	155°-173°
TECTONIC PLATE 1	Pacific plate	Pacific plate	Pacific plate	Pacific plate
TECTONIC PLATE 2	North American plate	Philippine plate	Indo-Australian plate	Indo-Australian plate
NAME	North American	Philippine	Indo-Australian 1	Indo-Australian 2

Table 1*: Area of study*

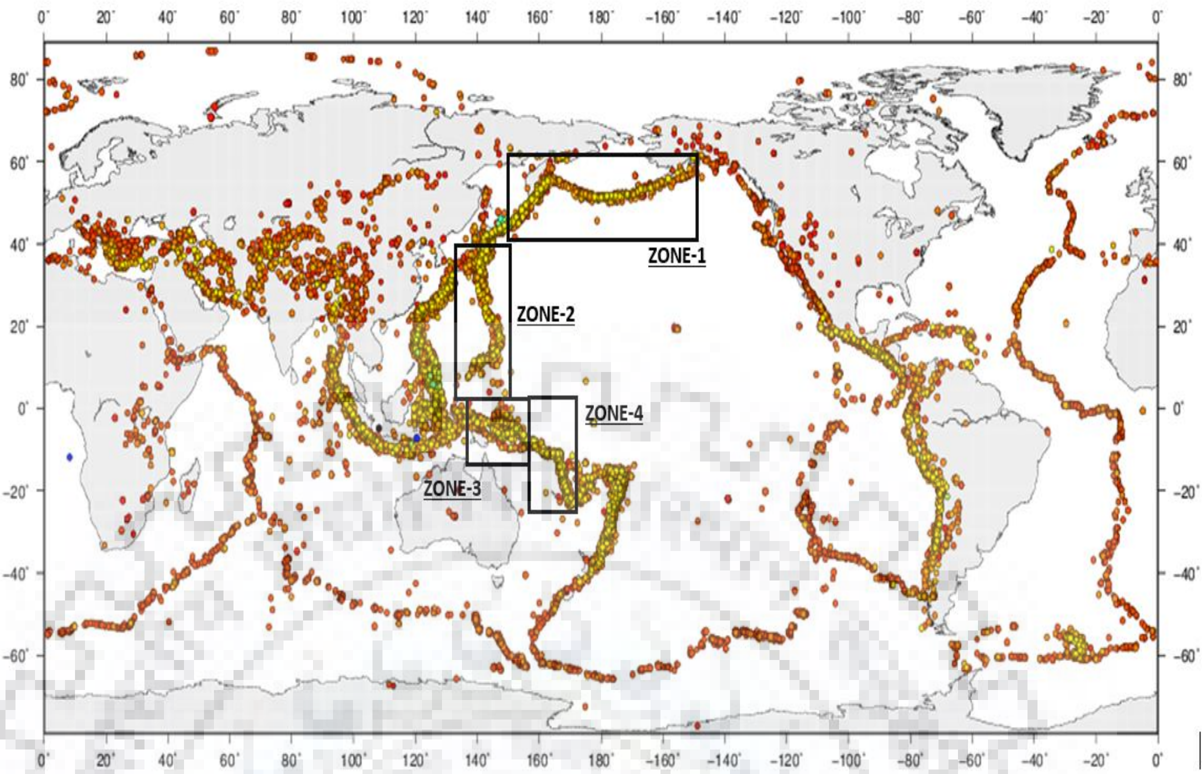


Figure 6: *Area of study*

(Figure source: *http://www.isc.ac.uk/iscbulletin/search/catalogue*)

DATA SET

The earthquake data for the above mentioned zones has been selected for a time span of 48 year, from 1st January 1970 to 31st December 2017 and data is collected for the earthquake with magnitude over 3.5 (MS). Data was obtained from:
http://www.isc.ac.uk/iscbulletin/search/catalogue/

The total number of earthquake data used for this report is 49,102. Number of data points in each zone are:

Zone-1: 12291

Zone-2: 11977

Zone-3: 11949

Zone-4: 12885

These zones are selected based on the basis of geological and seismic conditions of the locations. Along with that, a conscious effort is made to keep the number of earthquakes in all zones almost equal. High difference in the number of data points in different conditions will cause the fractal figures to be dominated by zones with high data points only.

Each event in data set is numbered according to the zone in which that earthquake happened. The data set is then chronologically arranged to generate an array of coarse grain data made up of 1s, 2s, 3s and 4s. So, the data set is arranged as oldest to newest from top to bottom. A small portion of this data is shown in table 2, with coarse grain data shown under the heading "Grading".

EVENTID	AUTHOR	DATE	LAT	LON	DEPTH	DEPFIX	AUTHOR	TYPE	MAG	GRADING
799571	ISC	01-01-1970	45.9834	154.3436	14.7		MOS	MS	5.1	1
799772	ISC	06-01-1970	-9.5873	151.4461	4.1		ISC	MS	6.2	3
799984	ISC	11-01-1970	-22.5602	171.5048	40.4		USCGS	MS	5.5	4
800041	ISC	13-01-1970	-14.6481	166.333	28	TRUE	USCGS	MS	4.7	4
800167	ISC	18-01-1970	21.4145	146.7342	35	TRUE	ISC	MS	5.6	2
800229	ISC	20-01-1970	53.6479	-163.604	30.3		MOS	MS	4.8	1
800290	ISC	22-01-1970	51.2546	177.2433	15.2		ISC	MS	5.5	1
800323	ISC	23-01-1970	53.6019	-163.707	29	TRUE	USCGS	MS	4.8	1
800401	ISC	26-01-1970	-12.6372	166.5284	42.7		ISC	MS	6.5	4
800433	ISC	27-01-1970	57.4996	163.8251	35	TRUE	MOS	MS	4.5	1
800427	ISC	27-01-1970	-10.8457	165.9457	50.8		USCGS	MS	5.5	4
798843	ISC	05-02-1970	46.9237	154.2239	29		ISC	MS	6.1	1
798861	ISC	06-02-1970	54.5393	163.4829	34.6		ISC	MS	5.9	1
798892	ISC	07-02-1970	47.1634	154.0727	18.6		ISC	MS	5.9	1
798901	ISC	07-02-1970	47.2959	153.766	10.2		ISC	MS	5.9	1
798917	ISC	07-02-1970	47.2445	153.8927	9.4		MOS	MS	5.2	1
799201	ISC	17-02-1970	-22.4299	170.4304	43.2		ISC	MS	5.5	4
799220	ISC	18-02-1970	52.2004	175.3327	42.4		MOS	MS	4.6	1
799250	ISC	19-02-1970	-4.5345	140.0937	27	TRUE	MOS	MS	5.2	3
799476	ISC	27-02-1970	50.0932	-179.76	9.6		ISC	MS	5.9	1
799495	ISC	27-02-1970	31.8312	141.7302	26	TRUE	MOS	MS	5.5	2
797450	ISC	02-03-1970	31.7017	141.8295	29	TRUE	MOS	MS	4.5	2

Table 2: Data Set

METHODOLOGY

8.1 FRACTAL ADDRESSES OF A SQUARE

For relating fractals, addresses are used as a fundamental tool. Utilizing these addresses, we are plotting multiple events that we have gathered to find some relationship between different zones.

For this report, we are plotting the events in two-dimensional plot, using the following transformations,

$$T_1(x, y) = (x/2, y/2)$$

$$T_2(x, y) = (x/2, y/2) + (1/2, 0)$$

$$T_3(x, y) = (x/2, y/2) + (0, 1/2)$$

$$T_4(x, y) = (x/2, y/2) + (1/2, 1/2)$$

T shows the translational transformation applied, as explained earlier.

This provides us with the square S, which is used for the plotting. That is,

$$S = T1(S) \cup T2(S) \cup T3(S) \cup T4(S),$$

Every 1/2x1/2 squares generated here is of length 1 and marked by address i.

By iterating this process of decomposition, every square can be divided further. For example,

$$T_1(S) = T_1T_1(S) \cup T_1T_2(S) \cup T_1T_3(S) \cup T_1T_4(S)$$

Addresses generated are read right to left here. The digit on the left will show the transformation that is applied as of late.

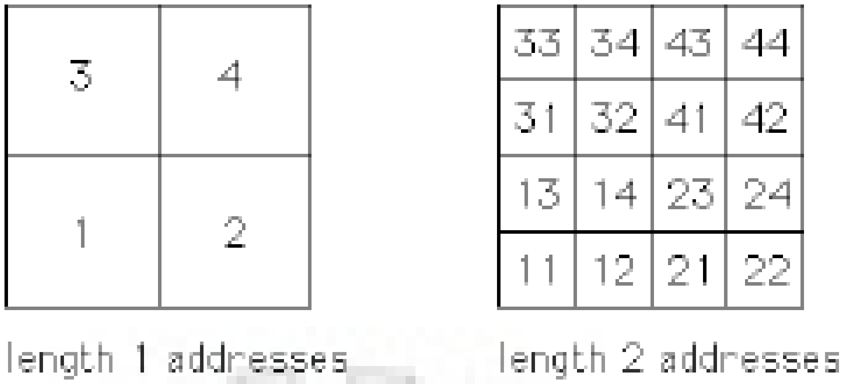


Figure 7: *1-bit and 2-bit fractal addresses*

LENGTH 1 ADDRESS: The Square is further divided into 4 sub-zones.

LENGTH 2 ADDRESS: Every new smaller zone is further divided into 4 sub-zones and the address for each subzone is more specific.

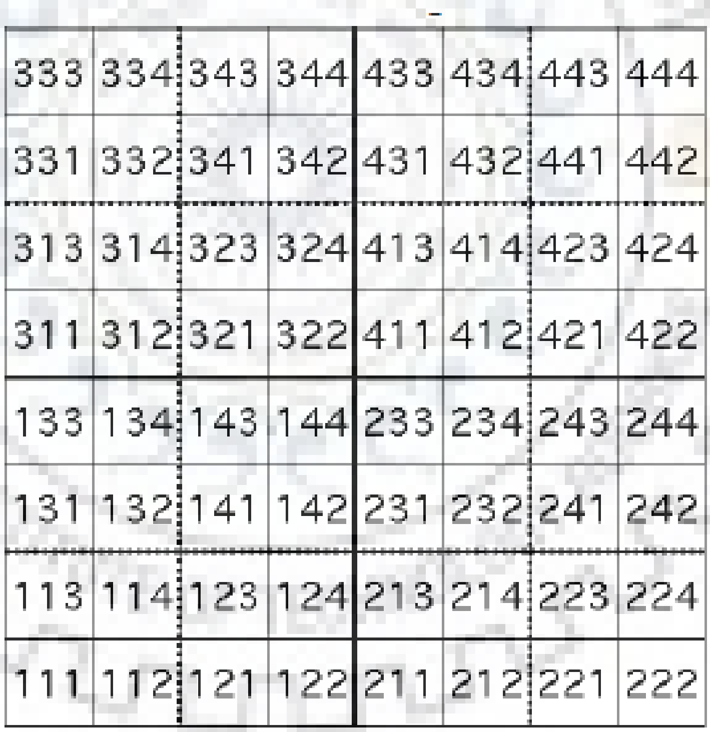


Figure 8: *3-bit Fractal Address*

LENGTH 3 ADDRESS: Every new smaller zone is further divided into 4 sub-zones and the address for each subzone is even more precise.

8.2 METHOD

Using the data set, we have generated a 1D array of zone numbers. Example,

112433321142331422141332142412224441211122442……

Elements of this array are utilized to develop 1-bit, 4-bit and 8-bit Fractal addresses in a square grid.

Each box in this fractal figures corresponds to a fractal addresses. For example,

4-bit

1112, 1212, 4123

8-bit

11134212, 32112312, 41231121, 42323434

Every single fractal address corresponds to a single bin. Longer fractal address will have more detailed and precise fractal figures.

8.3 CODE FOR FACTAL MAPPING

```
rng('default')

nvrtx = 4;

filename='Grading.xlsx';

coarse = xlsread(filename);

vrtx = [0 0 ;20 0; 0 20 ;20 20];            % Vertices

sz=size(coarse);

niter=sz(1,1);                              % Number of iterations

point=zeros(niter,2) ;

point(1,:)=vrtx(4,:)/2;

for a = 2:niter

   vIdx = coarse(a-1,1);

   point(a,:) = vrtx(vIdx,:) - (vrtx(vIdx,:) - point(a-1,:))/2;

end

image,

cla                                         % Plot

plot(point(:,1), point(:,2), 'LineStyle', 'none', '.', 'MarkerSize', 5)


%4 bit

frbit=zeros(16,16);

p=1;

q=1;

for a=1:niter

   for p=1:16

      if (point(a,1)<=p && point(a,1)>(p-1))

      for q=1:16

   if( point(a,2)<=q && point(a,2)>(q-1))
```

```
        frbit(p,q)=frbit(p,q)+1;
    end
        end


        end
    end
end
s = sum(frbit'all');
image,
pcolor(1:16,1:16frbit);
caxis([0 200]);
shading flat

% 8 bit address
vrtxeit = [0 0 ;257 0; 0 257 ;257 257];
pointeit = zeros(niter2) ;
pointeit(1,:) = vrtxeit(4,:)/2;
for a = 2:niter
    vIdx = coarse(a-1,1);
    pointeit(a,:)=vrtxeit(vIdx,:)-(vrtxeit(vIdx,:)-pointeit(a-1,:))/2;
end
etbit= zeros(257,257);
p=1;
q=1;
for a=1:niter
    for p=1:257
        if (pointit(a,1)<=p && pointit(a,1)>(p-1))
```

```
    for q=1:257
  if( pointit(a,2)<=q && pointit(a,2)>(q-1))
    etbit(p,q)=etbit(p,q)+1;
  end
    end



    end
  end
end
s2=sum(etbit,'all');
image,
pcolor(1:256,1:256,eitbit);
caxis ([0 1]);
```

RESULTS

A total number of 24 cases are possible to plot, yet, only 6 are unique. Those six unique plots are shown below in 1-bit, 4-bit and 8-bit.

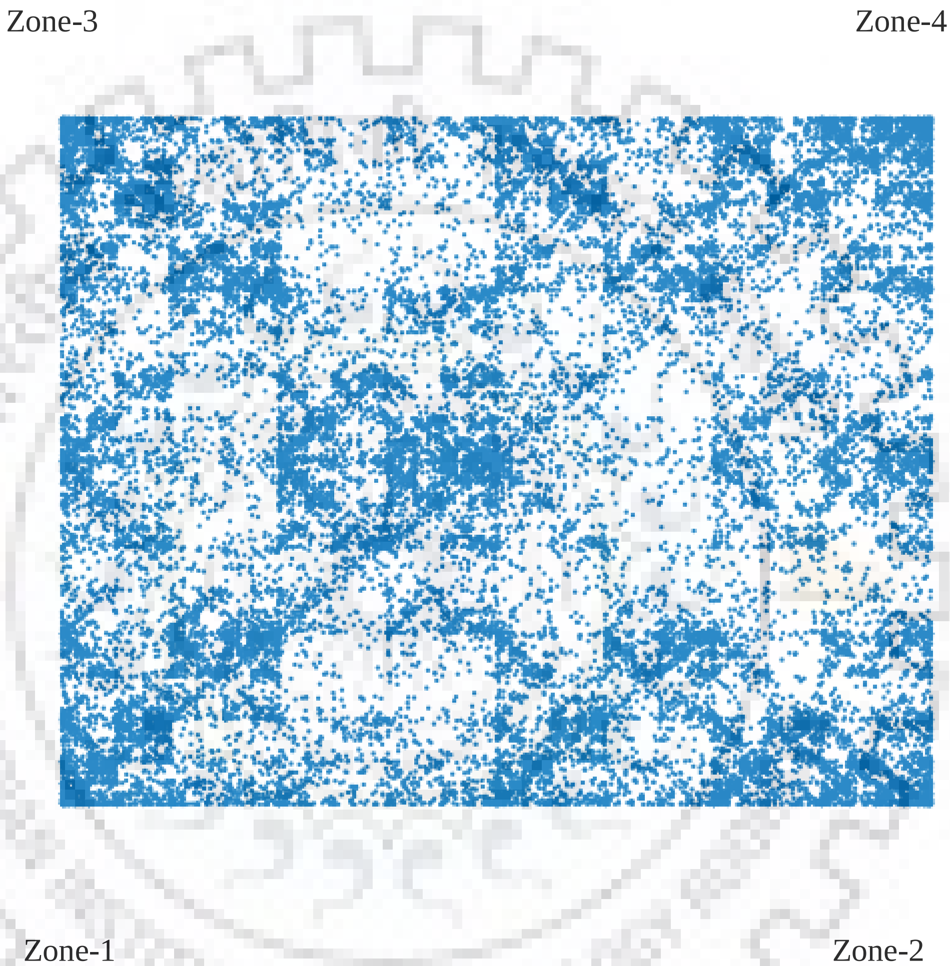
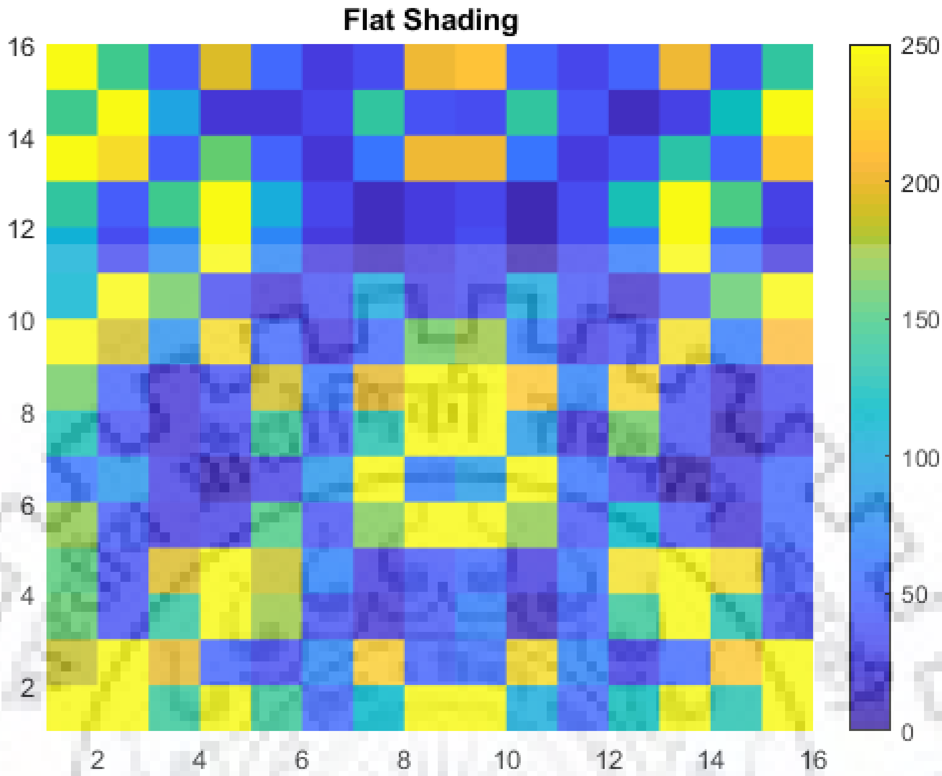


Figure 9: *1-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-4(Indo-Australian 2), Zone-3(Indo Australian 1) [Counter-clockwise from bottom left]*

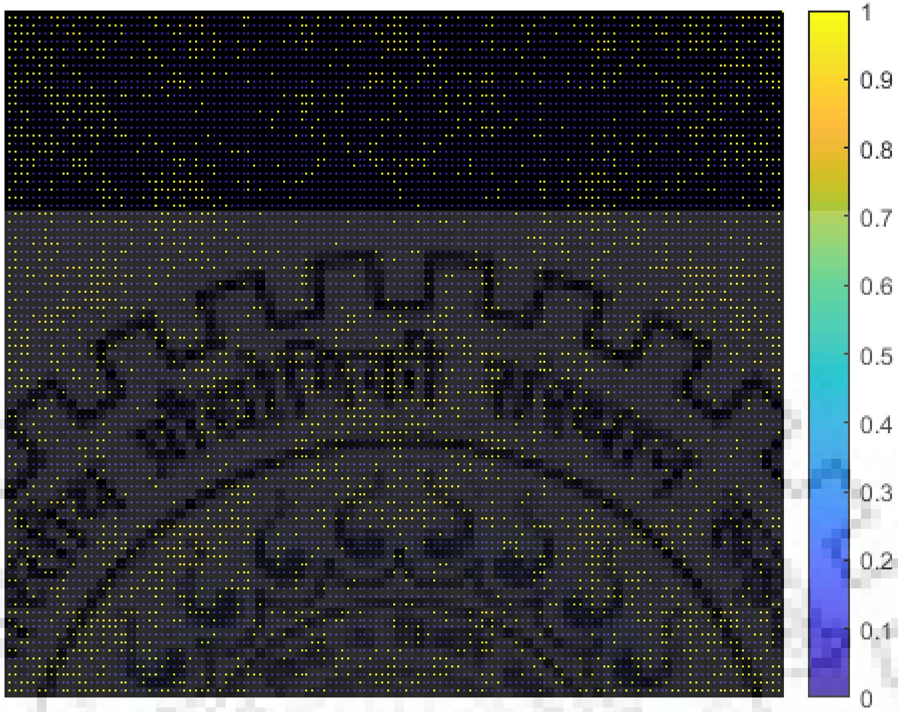
Zone-3 Zone-4



Zone-1 Zone-2

Figure 10: *4-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-4(Indo-Australian 2), Zone-3(Indo Australian 1) [Counter-clockwise from bottom left]*

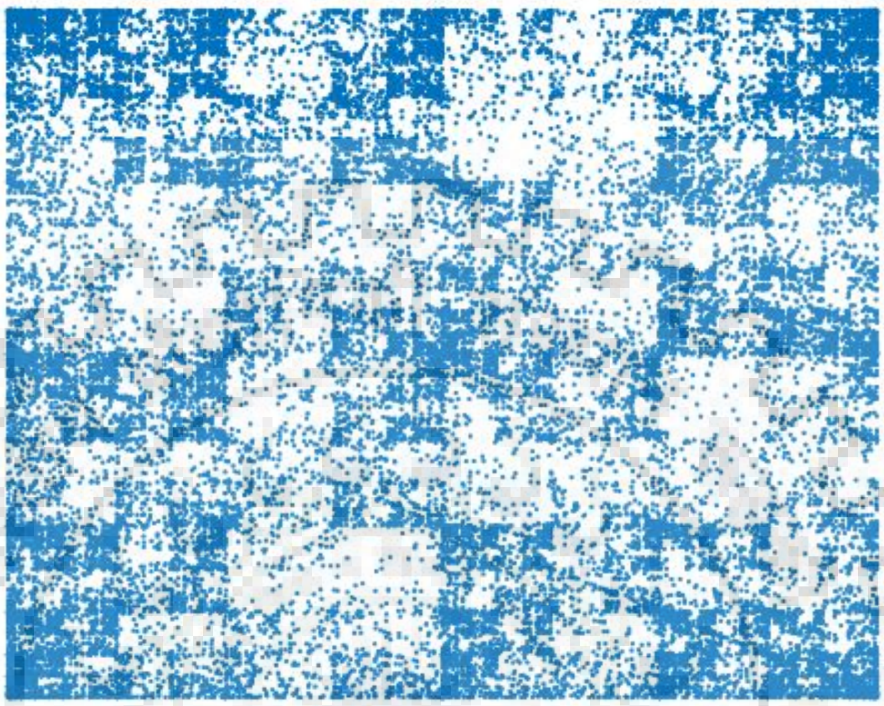
Zone-3 Zone-4



Zone-1 Zone-2

Figure 11: *8-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-4(Indo-Australian 2), Zone-3(Indo Australian 1) [Counter-clockwise from bottom left]*

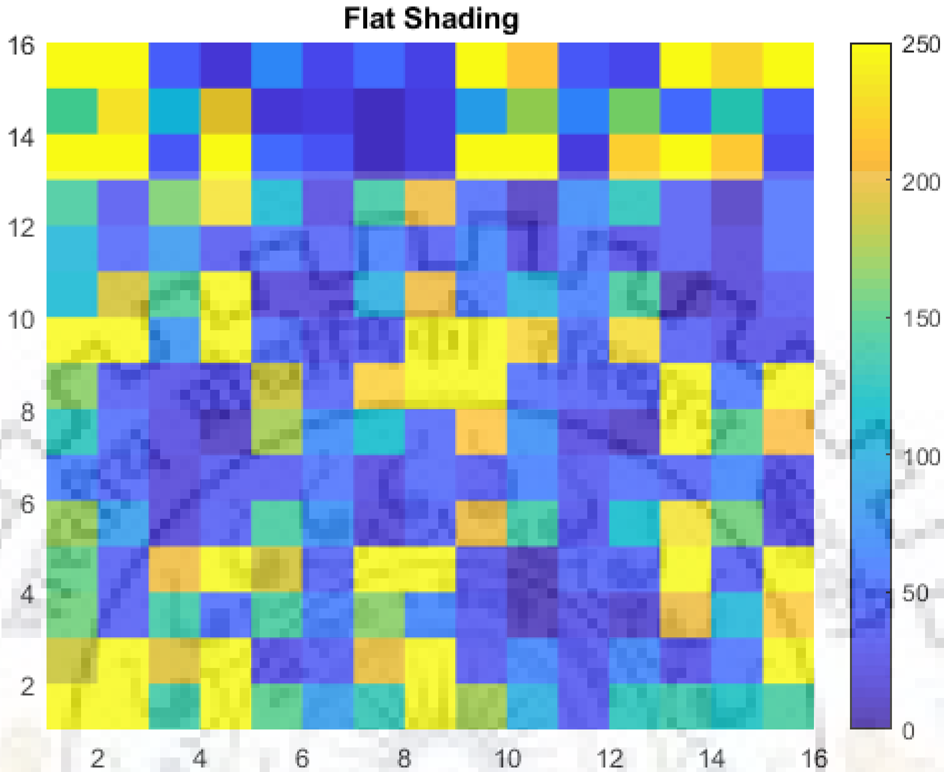
Zone-4 Zone-3



Zone-1 Zone-2

Figure 12: *1-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-3(Indo-Australian 1), Zone-4(Indo Australian 2) [Counter-clockwise from bottom left]*

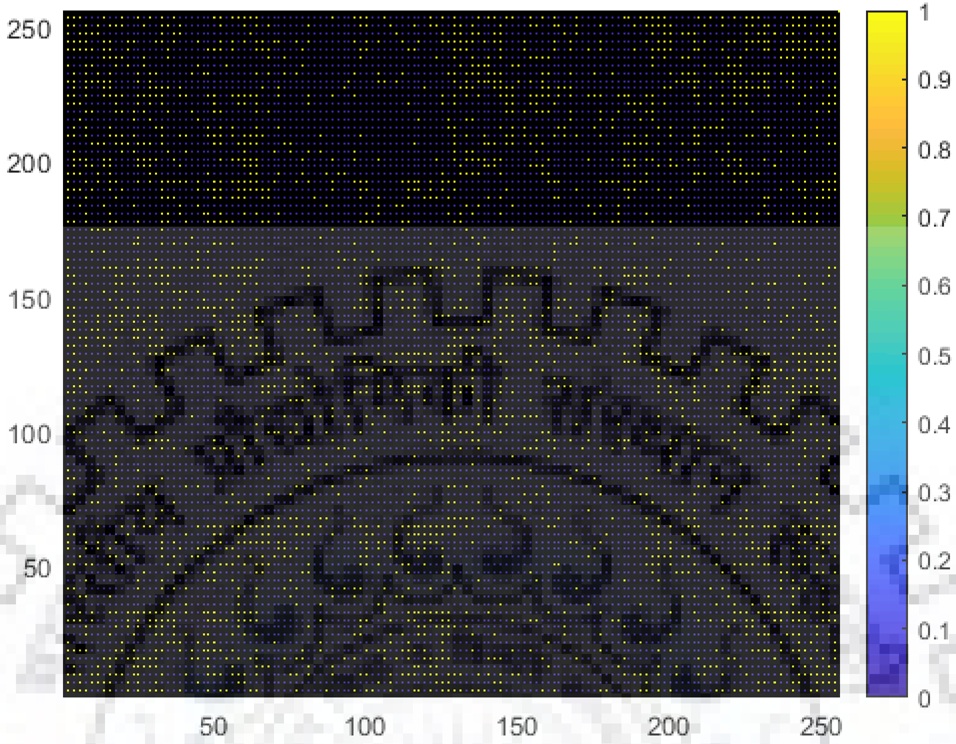
Zone-4 Zone-3



Zone-1 Zone-2

Figure 13: *4-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-3(Indo-Australian 1), Zone-4(Indo Australian 2) [Counter-clockwise from bottom left]*

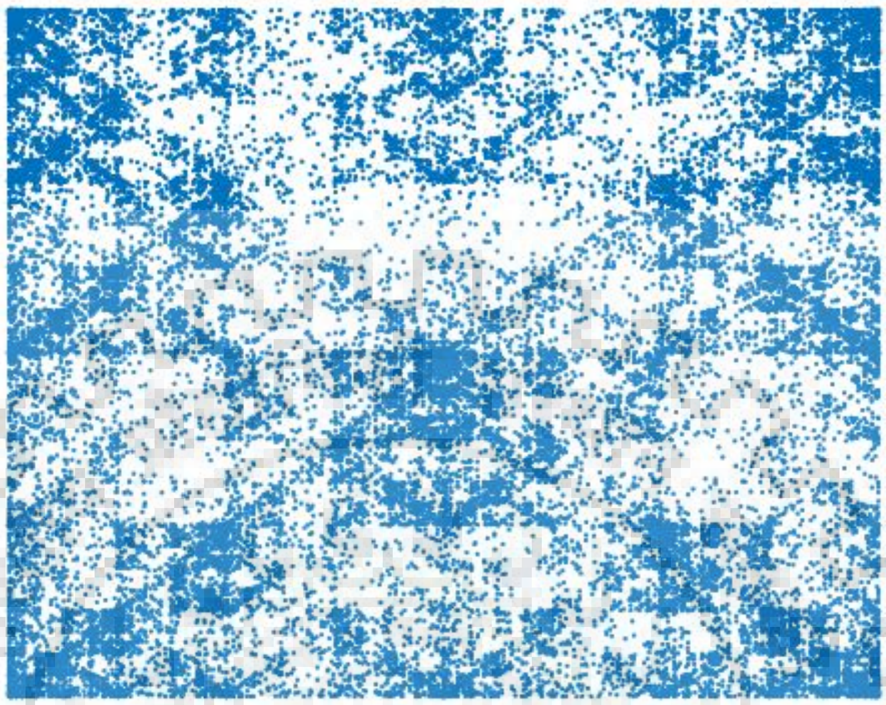
Zone-4 Zone-3



Zone-1 Zone-2

Figure 14: *8-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-3(Indo-Australian 1), Zone-4(Indo Australian 2) [Counter-clockwise from bottom left]*

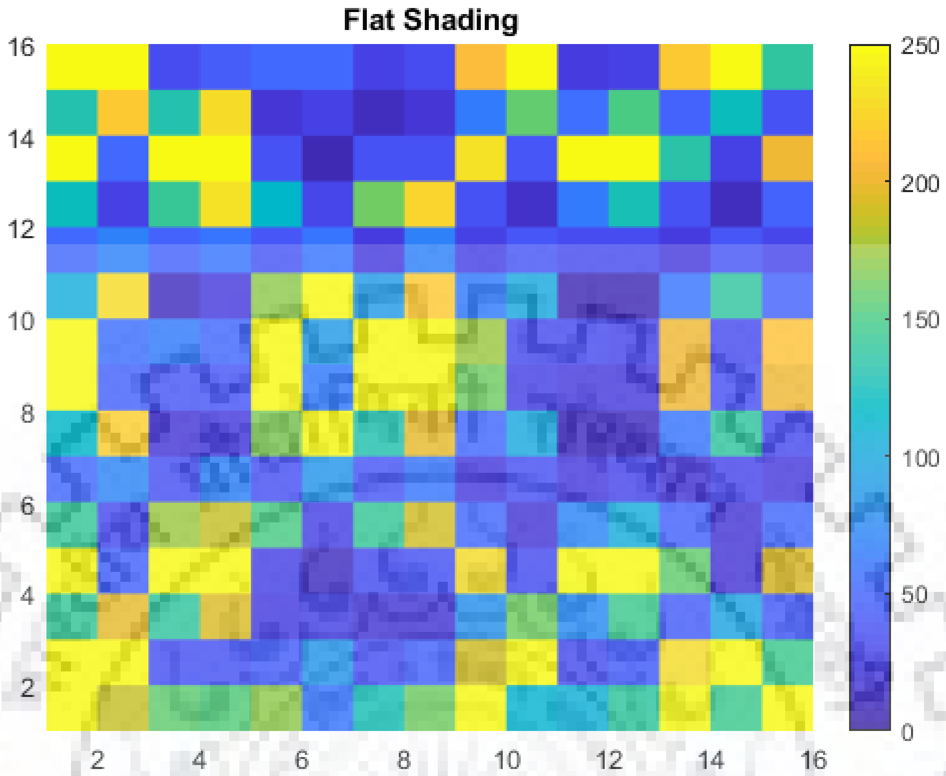
Zone-2 Zone-4



Zone-1 Zone-3

Figure 15: *1-bit Fractal map for Zone 1(North American), Zone-3(Indo-Australian 1), Zone-4(Indo Australian 2), Zone-2(Philippine) [Counter-clockwise from bottom left]*

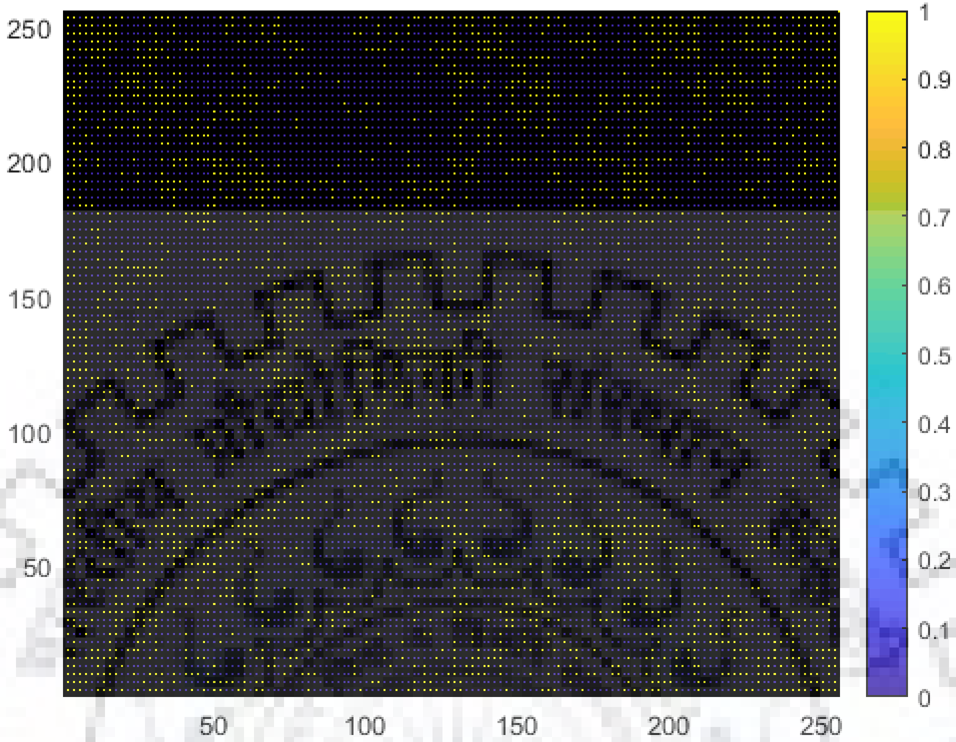
Zone-2 Zone-4



Zone-1 Zone-3

Figure 16: *4-bit Fractal map for Zone 1(North American), Zone-3(Indo-Australian 1), Zone-4(Indo Australian 2), Zone-2(Philippine) [Counter-clockwise from bottom left]*

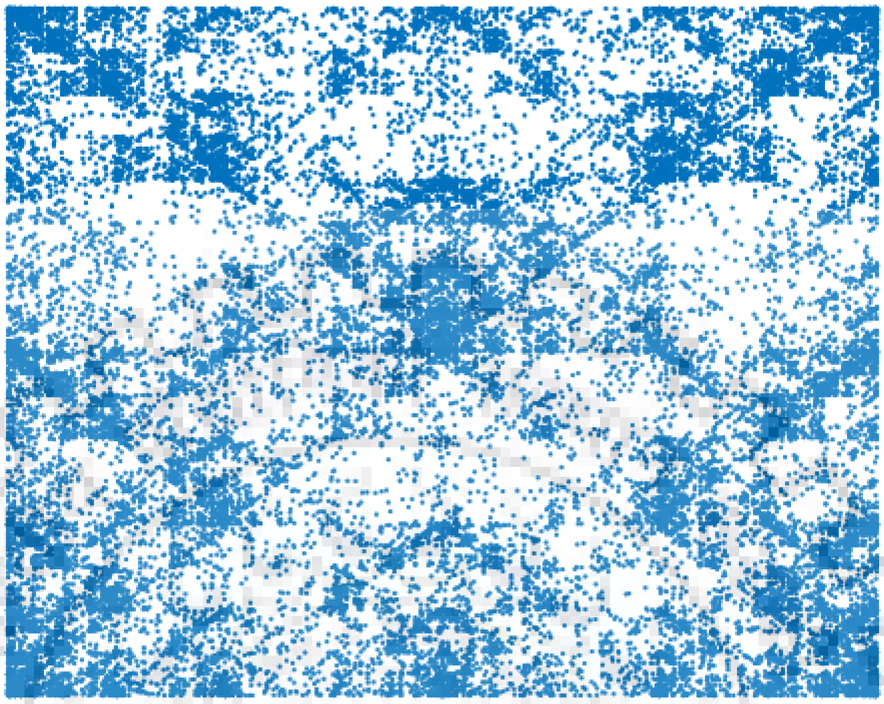
Zone-2 Zone-4



Zone-1 Zone-3

Figure 17: *8-bit Fractal map for Zone 1(North American), Zone-3(Indo-Australian 1), Zone-4(Indo Australian 2), Zone-2(Philippine) [Counter-clockwise from bottom left]*

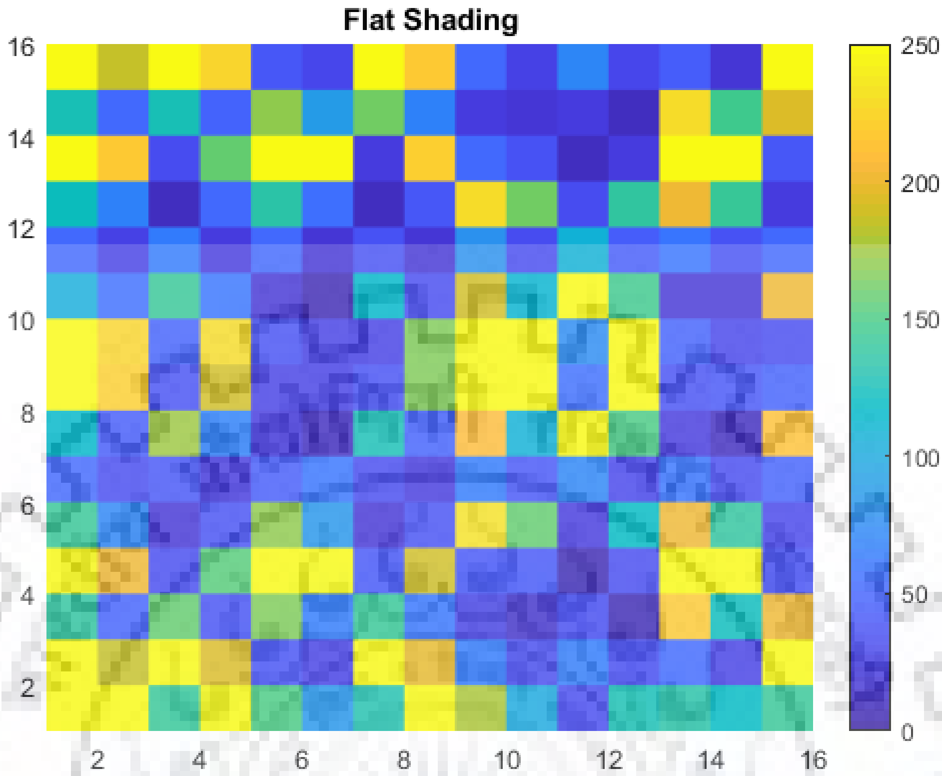
Zone-4 Zone-2



Zone-1 Zone-3

Figure 18: *1-bit Fractal map for Zone 1(North American), Zone-3(Indo-Australian 1), Zone-2(Philippine), Zone-4(Indo Australian 2) [Counter-clockwise from bottom left]*

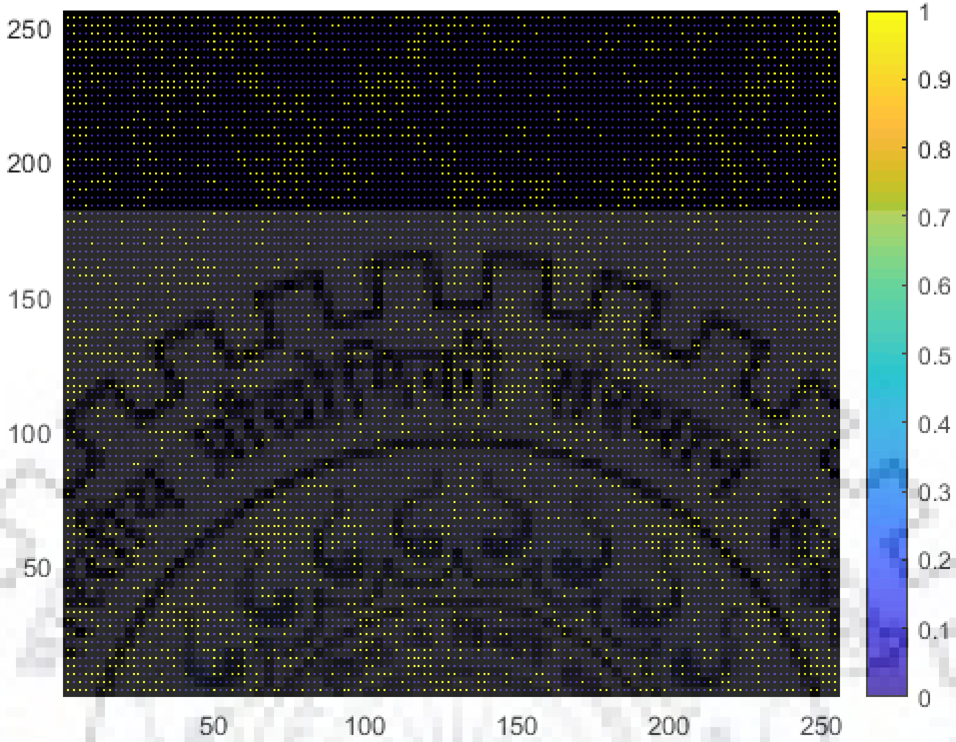
Zone-4 Zone-2



Zone-1 Zone-3

Figure 19: *4-bit Fractal map for Zone 1(North American), Zone-3(Indo-Australian 1), Zone-2(Philippine), Zone-4(Indo Australian 2) [Counter-clockwise from bottom left]*

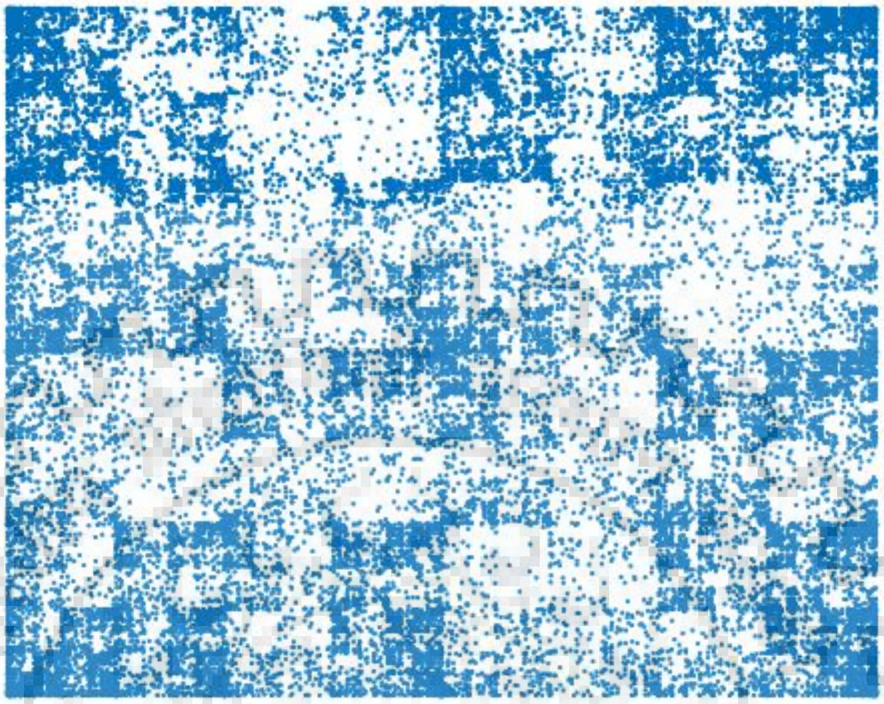
Zone-4 Zone-2



Zone-1 Zone-3

Figure 20: *8-bit Fractal map for Zone 1(North American), Zone-3(Indo-Australian 1), Zone-2(Philippine), Zone-4(Indo Australian 2) [Counter-clockwise from bottom left]*

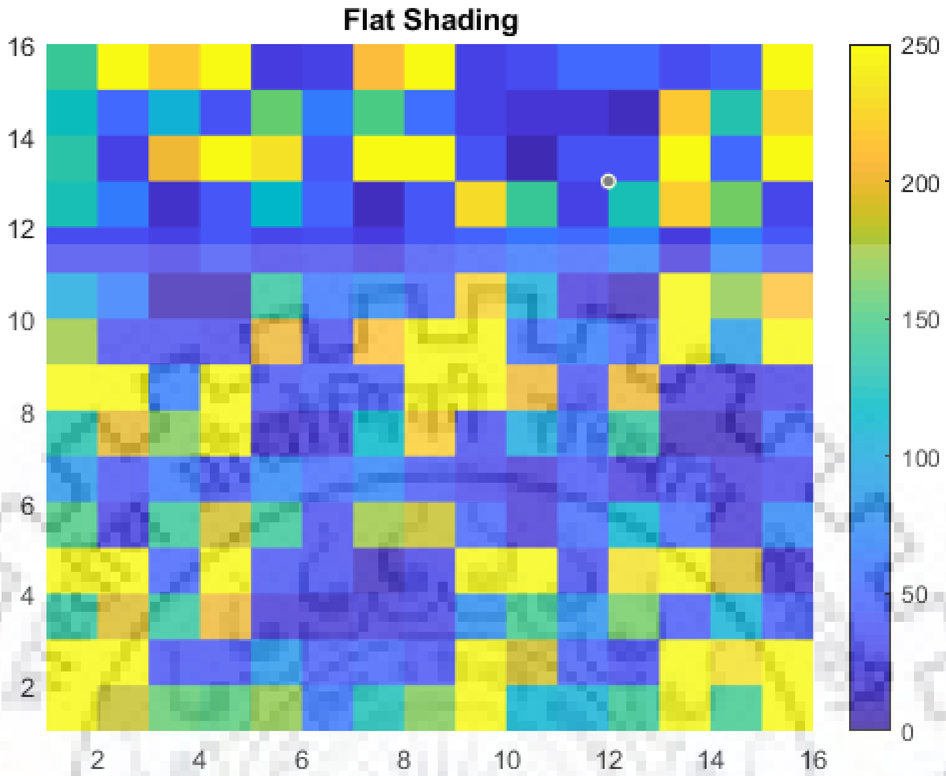
Zone-2 Zone-3



Zone-1 Zone-4

Figure 21: *1-bit Fractal map for Zone 1(North American), Zone-4(Indo Australian 2), Zone-3(Indo-Australian 1), Zone-2(Philippine) [Counter-clockwise from bottom left]*

Zone-2 Zone-3



Zone-1 Zone-4

Figure 22: *4-bit Fractal map for Zone 1(North American), Zone-4(Indo Australian 2), Zone-3(Indo-Australian 1), Zone-2(Philippine) [Counter-clockwise from bottom left]*

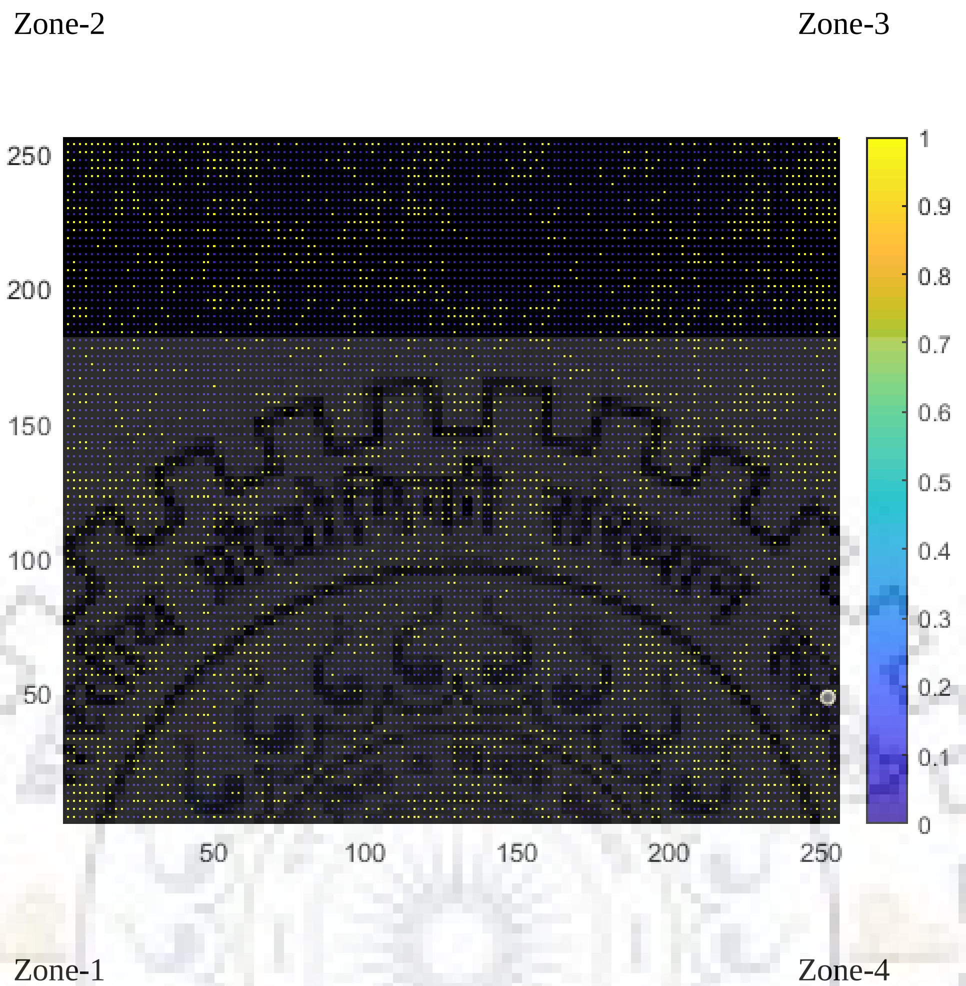
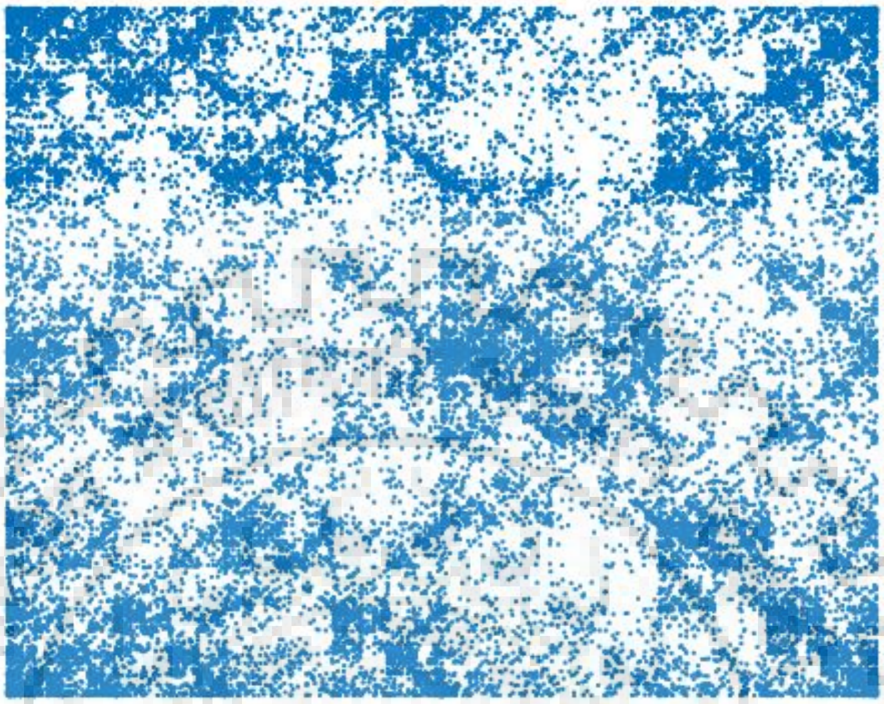


Figure 23: *8-bit Fractal map for Zone 1(North American), Zone-4(Indo Australian 2), Zone-3(Indo-Australian 1), Zone-2(Philippine) [Counter-clockwise from bottom left]*

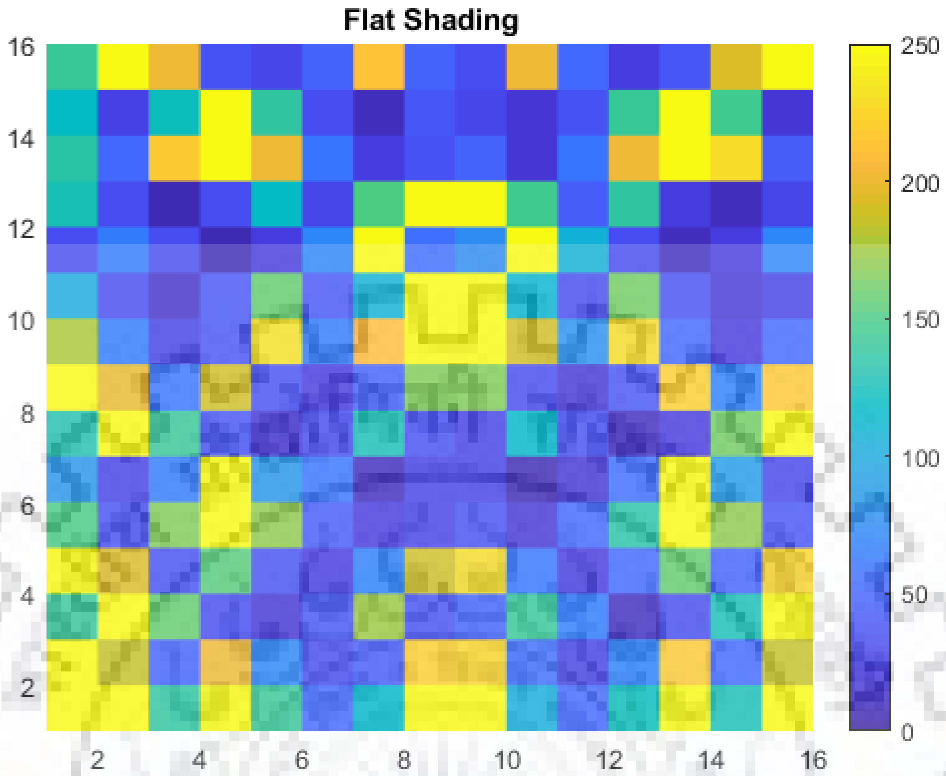
Zone-3 Zone-2



Zone-1 Zone-4

Figure 24: *1-bit Fractal map for Zone 1(North American), Zone-4(Indo Australian 2), Zone-2(Philippine), Zone-3(Indo-Australian 1) [Counter-clockwise from bottom left]*

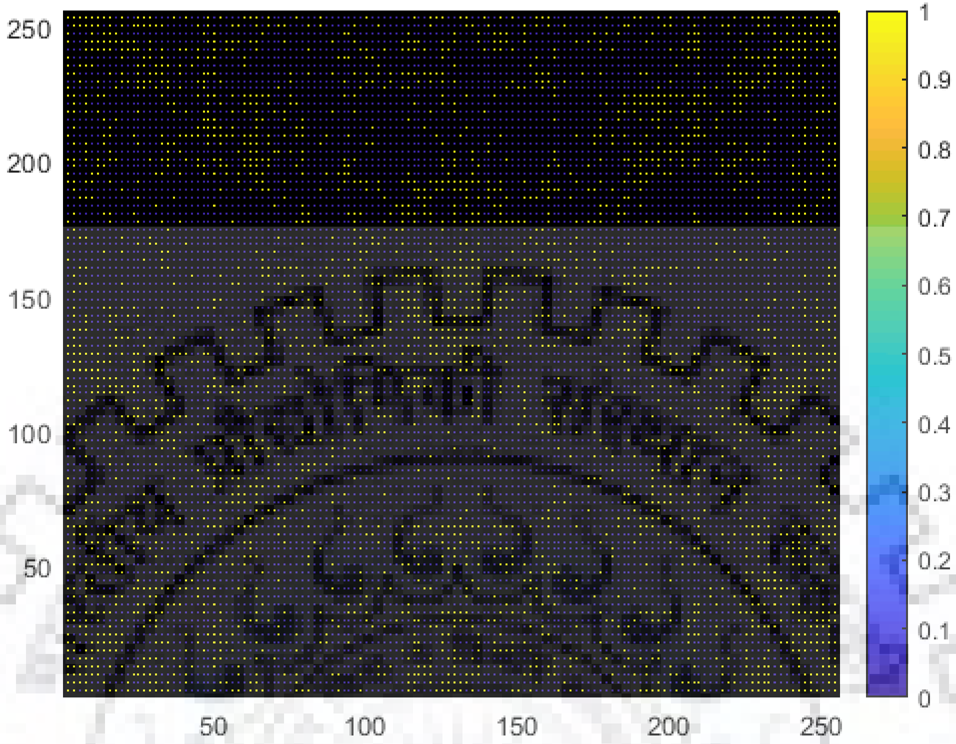
Zone-3 Zone-2



Zone-1 Zone-4

Figure 25: *4-bit Fractal map for Zone 1(North American), Zone-4(Indo Australian 2), Zone-2(Philippine), Zone-3(Indo-Australian 1) [Counter-clockwise from bottom left]*

Zone-3 Zone-2



Zone-1 Zone-4

Figure 26: *8-bit Fractal map for Zone 1(North American), Zone-4(Indo Australian 2), Zone-2(Philippine), Zone-3(Indo-Australian 1) [Counter-clockwise from bottom left]*

Figures shown below are 1-bit, 4-bit and 8-bit Fractal map for data set for time period of 1st January 1970 to 31st December 2006. Total number of data points used are 25,549. Number of data points in each zones are

Zone 1: 7496

Zone 2: 6129

Zone 3: 6411

Zone 4: 5513

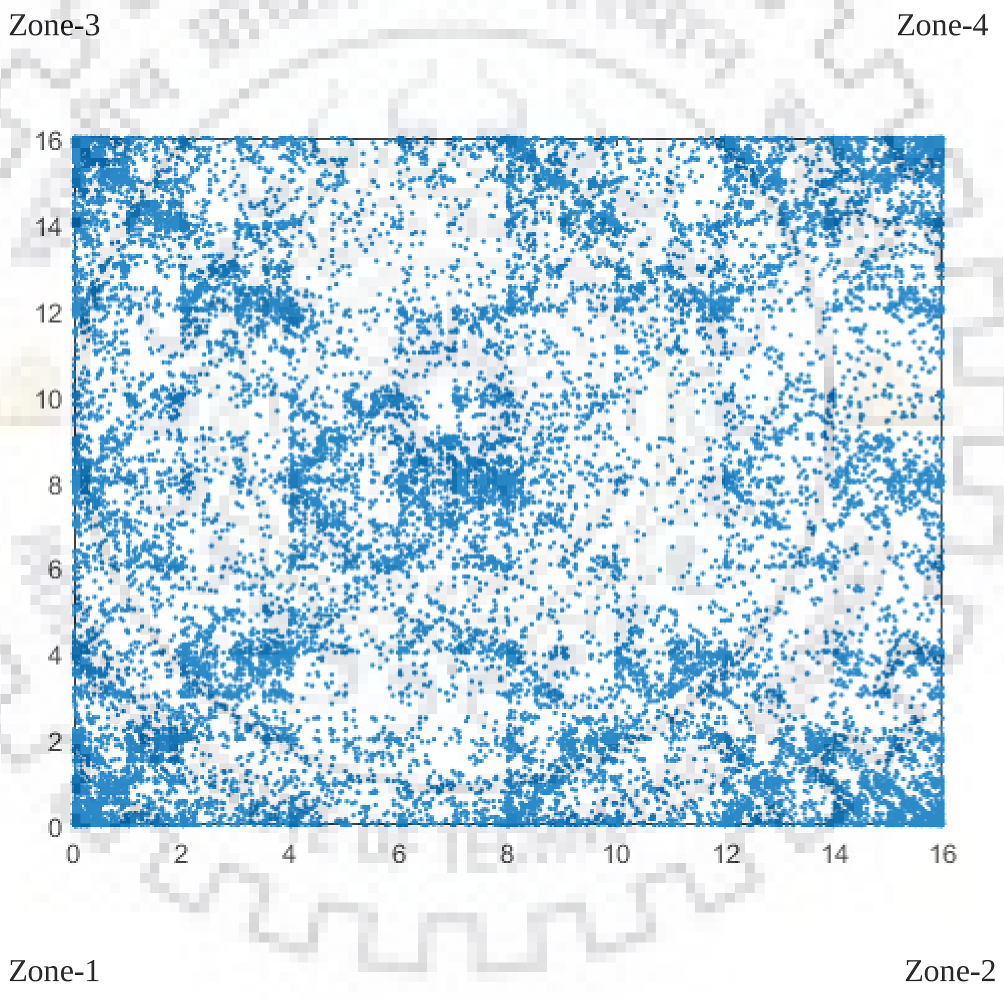
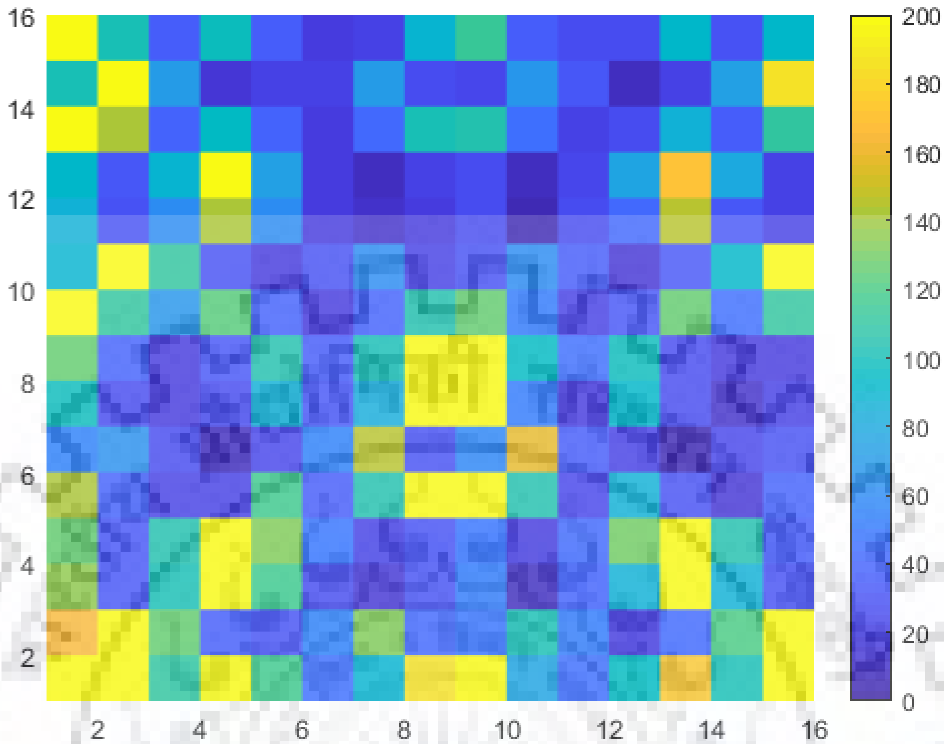


Figure 27: *1-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-4(Indo-Australian 2), Zone-3(Indo Australian 1) [Counter-clockwise from bottom left]*

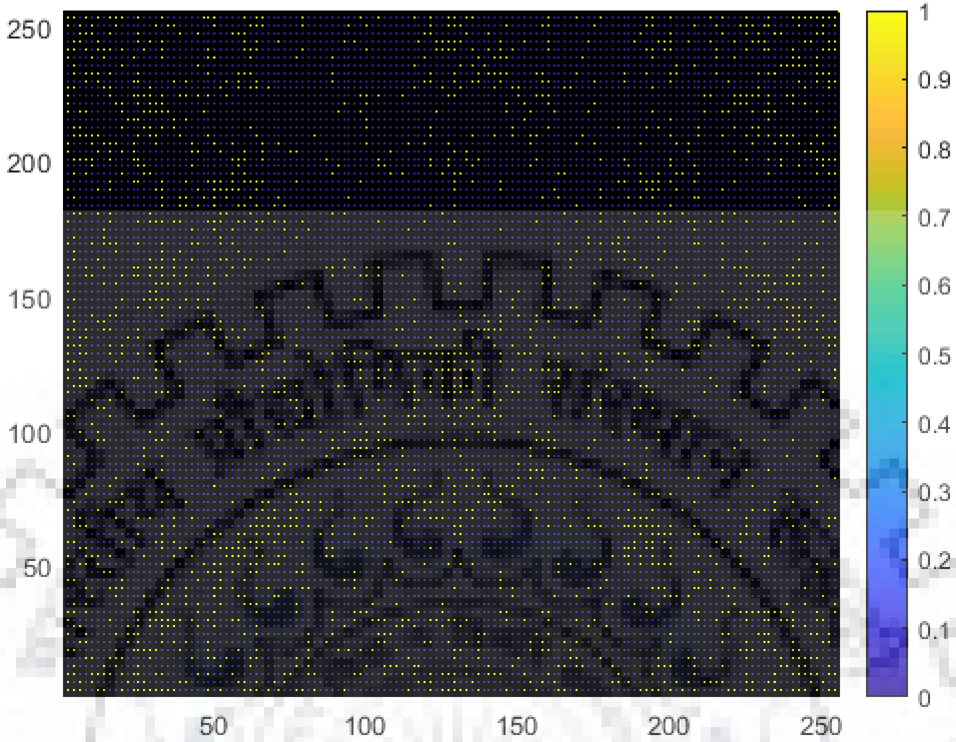
Zone-3 Zone-4



Zone-1 Zone-2

Figure 28: *4-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-4(Indo-Australian 2), Zone-3(Indo Australian 1) [Counter-clockwise from bottom left]*

Zone-3 Zone-4



Zone-1 Zone-2

Figure 29: *8-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-4(Indo-Australian 2), Zone-3(Indo Australian 1) [Counter-clockwise from bottom left]*

Figures shown below are 1-bit, 4-bit and 8-bit Fractal map for data set for time period of 1st January 2007 to 31st December 2017. Total number of data points used are 23,552. Number of data points in each zones are

Zone 1: 4794

Zone 2: 5848

Zone 3: 5538

Zone 4: 7372

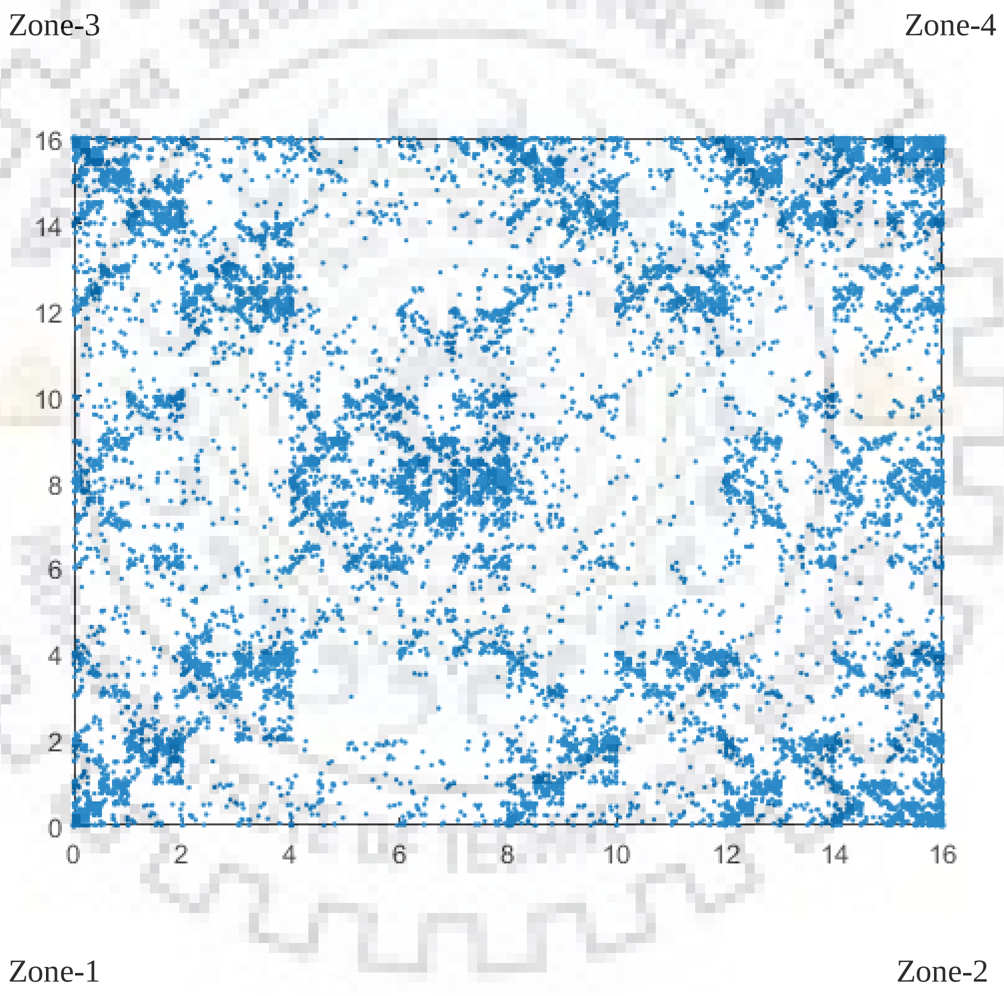


Figure 30: *1-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-4(Indo-Australian 2), Zone-3(Indo Australian 1) [Counter-clockwise from bottom left]*

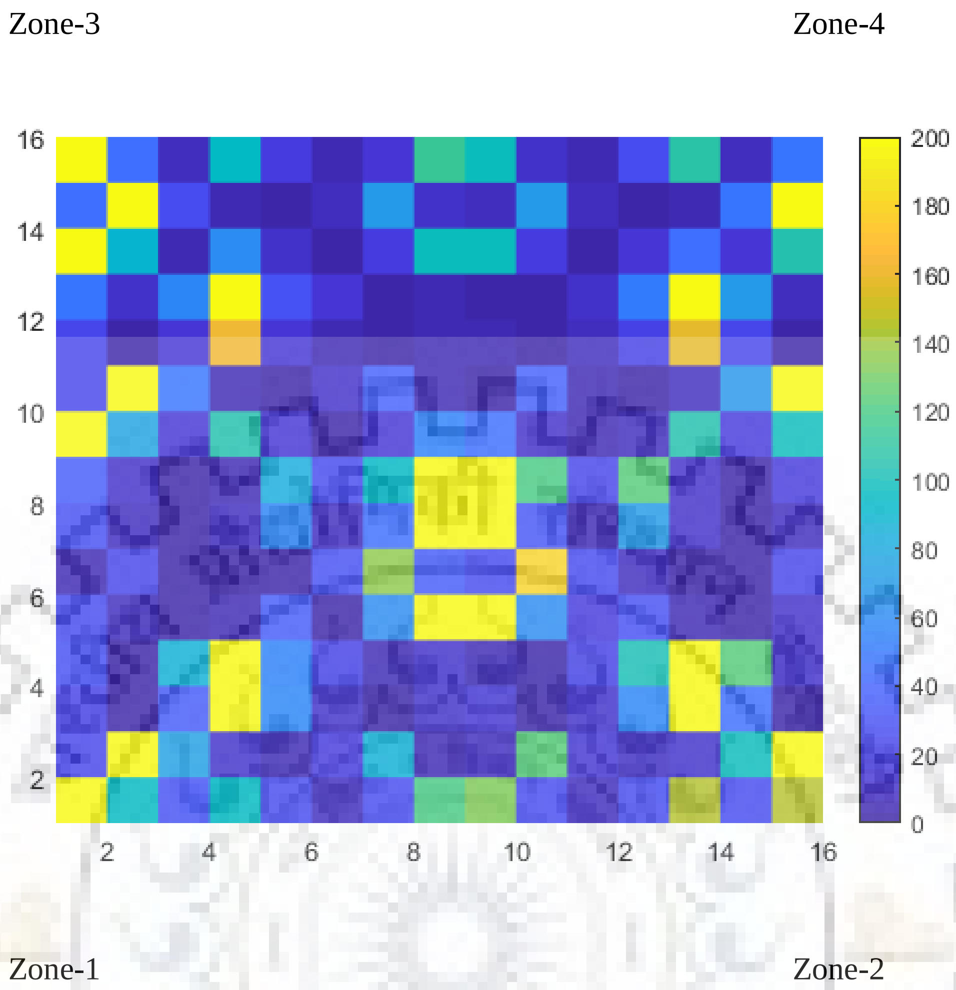
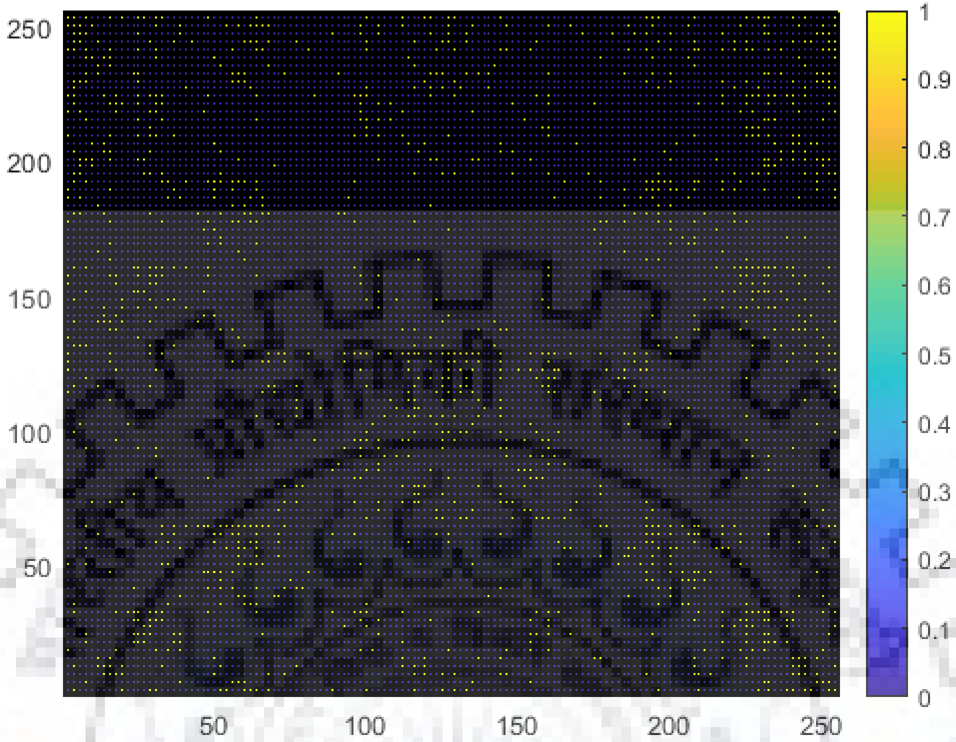


Figure 31: *4-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-4(Indo-Australian 2), Zone-3(Indo Australian 1) [Counter-clockwise from bottom left]*

Zone-3 Zone-4



Zone-1 Zone-2

Figure 32: *8-bit Fractal map for Zone 1(North American), Zone-2(Philippine), Zone-4(Indo-Australian 2), Zone-3(Indo Australian 1) [Counter-clockwise from bottom left]*

INFERENCE

For figures 9 to 26, we can infer that there is a strong correlation between earthquakes of

- North American – Philippine
- Philippine – Indo-Australian 1
- Indo-Australian 2 – Indo-Australian 1

A weaker correlation can be observed between

- North American – Indo-Australian 1
- Indo-Australian 2 – North American

Furthermore, probability of an event to occur in one zone following another particular zone are shown below.

CONCLUSION

Probability of an event in "FIRST ZONE" followed by an event in "SECOND ZONE".

NUMBER	FIRST ZONE	SECOND ZONE	PROBABILITY
1.	North American	Philippine	28%
2.	North American	Indo-Australian 1	13%
3.	North American	Indo-Australian 2	7%
4.	Philippine	North American	8%
5.	Philippine	Indo-Australian 1	27%
6.	Philippine	Indo-Australian 2	12%
7.	Indo-Australian 1	North American	13%
8.	Indo-Australian 1	Philippine	6%
9.	Indo-Australian 1	Indo-Australian 2	28%
10.	Indo-Australian 2	North American	22%
11.	Indo-Australian 2	Philippine	11%
12.	Indo-Australian 2	Indo-Australian 1	6%

NUMBER	FIRST ZONE	SECOND ZONE	PROBABILITY (1970-2006)	PROBABILITY (2007-2017)
1.	North American	Philippine	25%	30%
2.	North American	Indo-Australian 1	14%	12%
3.	North American	Indo-Australian 2	8%	6%
4.	Philippine	North American	12%	6%
5.	Philippine	Indo-Australian 1	27%	28%
6.	Philippine	Indo-Australian 2	13%	10%
7.	Indo-Australian 1	North American	17%	11%
8.	Indo-Australian 1	Philippine	9%	4%
9.	Indo-Australian 1	Indo-Australian 2	24%	29%
10.	Indo-Australian 2	North American	30%	25%
11.	Indo-Australian 2	Philippine	14%	11%
12.	Indo-Australian 2	Indo-Australian 1	9%	6%

REFERENCES

H Joel Jeffrey, Chaos Game Representation of Gene Structure, Nucleic Acids Research, Vol 18 No 8, Northern Illinois University, DeKalb, IL, USA, 1990

Harlan J. Brothers, Brothers Technology, LLC, 1204 Main Street, Branford, CT 06405, 2016

M. F. Barnsley, Fractals Everywhere, Academic Press Prof., San Diego, 1988

https://users.math.yale.edu

http://www.isc.ac.uk/iscbulletin/search/catalogue