

- 1 Submitted on 09 Aug 2015
- 2 Anonymous Referee #1

**Anonymous during peer-review: Yes No**

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**Recommendation to the Editor**

- Does the paper contain new and significant results? **Yes No**
- Is the paper of an international standard? **Yes No**
- Is the presentation clear and concise? **Yes No**
- Does the paper put the obtained results into context, with relevant references? **Yes No**
- Is the length of the paper appropriate? **Yes No**
- Is the text fluent and precise? **Yes No**
- Are the title and the abstract pertinent and understandable to a wide audience? **Yes No**
- Are all figures necessary, and of appropriate quality? **Yes No**

For final publication, the manuscript should be **accepted as is.**

**Suggestions for revision or reasons for rejection (will be published if the paper is accepted for final publication)**

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- 1 Submitted on 09 Aug 2015  
2 Anonymous Referee #2

**Anonymous during peer-review: Yes No**  
**Anonymous in acknowledgements of published article: Yes No**

**Recommendation to the Editor**

Does the paper contain new and significant results?	<b>Yes No</b>
Is the paper of an international standard?	<b>Yes No</b>
Is the presentation clear and concise?	<b>Yes No</b>
Does the paper put the obtained results into context, with relevant references?	<b>Yes No</b>
Is the length of the paper appropriate?	<b>Yes No</b>
Is the text fluent and precise?	<b>Yes No</b>
Are the title and the abstract pertinent and understandable to a wide audience?	<b>Yes No</b>
Are all figures necessary, and of appropriate quality?	<b>Yes No</b>

For final publication, the manuscript should be  
**accepted subject to technical corrections.**

**Suggestions for revision or reasons for rejection (will be published if the paper is accepted for final publication)**

The authors have improved the overall presentation of the manuscript answering satisfactorily all my concerns and criticisms. Therefore, I recommend the publication in Nonlinear Processes in Geophysics.

I have only a final minor point concerning the notation used in the manuscript. There are three different notations for the coupling strength, see Eq. 1, 5 and 9.

I suggest then to employ a common symbol to denote this variable in order to avoid confusion.

- 3  
4

The equations 1 and 5 will remain the same except that we substitute  $K$  for  $A$  in equation (2) and  $K_{ij}$  for  $\sigma_{ij}$  in equation (9) to ensure that we have a common symbol for the global coupling parameter.

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**Earthquake Sequencing: Chimera States with Kuramoto Model  
Dynamics on Directed Graphs**

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**Keywords:** Earthquake sequencing, global seismicity, Kuramoto model, Chimera states,  
directed graphs, complex networks

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**Abstract.** Earthquake sequencing studies allow us to investigate empirical relationships among spatio-temporal parameters describing the complexity of earthquake properties. We have recently studied the relevance of Markov chain models to draw information from global earthquake catalogues. In these studies, we considered directed graphs as graph theoretic representations of the Markov chain model, and analyzed their properties. Here, we look at earthquake sequencing itself as a directed graph. In general, earthquakes are occurrences resulting from significant stress-interactions among faults. As a result, stress-field fluctuations evolve continuously. We propose that they are akin to the dynamics of the collective behaviour of weakly-coupled non-linear oscillators. Since mapping of global stress-field fluctuations in real time at all scales is an impossible task, we consider an earthquake zone as a proxy for a collection of weakly-coupled oscillators, the dynamics of which would be appropriate for the ubiquitous Kuramoto model. In the present work, we apply the Kuramoto model with phase-lag to the non-linear dynamics on a directed graph of a sequence of earthquakes. For directed graphs with certain properties, the Kuramoto model yields synchronization, and inclusion of non-local effects evokes the occurrence of chimera states or the co-existence of synchronous and asynchronous behaviour of oscillators. In this paper, we show how we build the directed graphs derived from global seismicity data. Then, we present conditions under which chimera states could occur and subsequently, point out the role of Kuramoto model in understanding the evolution of synchronous and asynchronous regions. We surmise that one implication of the emergence of chimera states will lead to investigating the present and other mathematical models in detail to generate global chimera-state maps similar to global seismicity maps for earthquake forecasting studies.

## 1 **1 Introduction**

2  
3 Earthquakes of differing magnitudes occur at different locations and depths in many  
4 tectonically active regions of the earth. The magnitude is the most widely used and  
5 theoretically studied earthquake parameter (Kanamori and Anderson, 1975; Hanks, T.C.,  
6 and Kanamori, H., 1979). The moment magnitude scale,  $M_w$ , provides an estimate for all  
7 medium to large earthquake magnitudes. Continuous recording and analysis of  
8 earthquakes that occur in different regions of the earth has led to earthquake catalogues.  
9 These catalogues carry information about the epicenter and the estimated hypocenter, the  
10 time and the magnitude of the earthquakes, leading to a set of empirical rules for different  
11 earthquake regions and the global seismicity (Omori, 1895; Gutenberg and Richter, 1954;  
12 Bath, 1965; Bufe and Varnes, 1993; Utsu et al., 1995; Ogata, 2011). The empirical rules  
13 allow us to understand and expand on the inter-relationships between the earthquake  
14 magnitude and the frequency of occurrence of events, and the main shocks and their  
15 aftershocks in space and in time.

16  
17 The earthquake catalogues have recently become the basis for Markov chain models of  
18 earthquake sequencing to explore probabilistic forecasting from the point of view of  
19 seismic hazard analysis (Nava et al., 2005; Cavers and Vasudevan, 2014). Cavers and  
20 Vasudevan (2014) have incorporated the spatio-temporal complexity of the earthquake  
21 recurrences (Davidsen et al. 2008; Vasudevan et al., 2010) into their Markov chain  
22 model.

23  
24 Intrinsic to earthquake sequencing studies is the observation made on scaling behavior  
25 and earthquake cycles (Turcotte, 1997; Rundle et al., 2002, 2003). In this regard, fractal  
26 and fractal-rate stochastic point processes were found to be useful (Thurner et al., 1997).  
27 Telesca et al. (2011) applied such models to earthquake sequencing. Vasudevan and  
28 Cavers (2013) have recently extended the application of this model to study time-  
29 correlative behavior in earthquake sequencing by carrying out Fano factor and Allan  
30 factor analysis to a time-series of state-to-state transition frequencies of a Markov chain.

31

1 One aspect of earthquake sequencing that requires a close look is a model for the non-  
2 linear dynamics of earthquakes. In this paper, we investigate the synchronization  
3 behavior of weakly-coupled “earthquake oscillations”. Such oscillations in the Earth’s  
4 crust and the epileptic brain strike certain commonalities in that the distributions of  
5 energies and recurrence times exhibit similar power-law behavior (Herz and Hopfield,  
6 1995; Rundle et al., 2003; Osorio et al., 2010; Chialvo, 2010). A growing interest in  
7 understanding the behavior of earthquakes and epileptic seizures with a view to exploring  
8 possible forecasting methods is one reason for the present study. In the case of epileptic  
9 seizures, the non-linear dynamics of pulse-coupled neuronal oscillations as an alternative  
10 to Kuramoto model (1975) are under close scrutiny (Rothkegel and Lehnertz, 2014). To  
11 our knowledge, neither a simple Kuramoto model nor a modification of it has been  
12 worked out for earthquake sequencing studies. Mirollo and Strogatz (1990), Kuramoto  
13 (1991) and Rothkegel and Lehnertz (2014) considered the synchronization of pulse-  
14 coupled oscillators in which single oscillators release energy rapidly when they reach a  
15 trigger threshold and become quiescent for some time until they reach the trigger  
16 threshold again. Examples falling into this category are earthquakes and spiking neuronal  
17 activities (Herz and Hopfield, 1995; Beggs and Plenz, 2002; Rundle et al., 2002, 2003;  
18 Scholz, 2010; Karsai et al., 2012; Rothkegel and Lehnertz, 2014). Herz and Hopfield  
19 (1995) studied the collective oscillations with pulse-coupled threshold elements on a fault  
20 system to capture the earthquake processes. There are two time scales: the first is given  
21 by the fault dynamics defining the duration of the earthquake, and the second time scale  
22 is given by the recurrence time between “characteristic events”, the largest earthquakes  
23 on a fault. The known recurrence times on several fault systems are 6 to 8 orders of  
24 magnitude longer than the duration of single events. Rundle et al. (2002) examined the  
25 self-organization in “leaky” threshold systems such as networks of earthquake faults. In  
26 their paper, they argued that on the “macroscopic” scale of regional earthquake fault  
27 systems, self-organization leads to the appearance of phase dynamics and a state vector  
28 whose rotations would characterize the evolution of earthquake activity in the system.  
29 Scholz (2010) invoked the Kuramoto model to represent the fault interactions, although  
30 no numerical synchronization-simulation results were presented. He postulated that the  
31 common occurrence of triggering of a large earthquake by other earthquakes on nearby

1 faults and the observation of space-time clustering of large earthquakes in the  
2 paleoseismic record were both indicators of synchronization occurring between faults.  
3 However, we need to bear in mind here that incorporating fault-fault interactions on a  
4 global scale involving all the networks of earthquake faults is formidable and nearly  
5 impossible. In this paper, we modify the simple non-linear mathematical model, the  
6 Kuramoto model with a phase-lag, for the sequencing of global earthquake data. We  
7 show here that the solutions to the Kuramoto model with phase-lag and with non-local  
8 coupling effects reveal the co-existence of synchronized and asynchronized states or  
9 chimera states for certain parameter values. We use this model as a precursor to our  
10 planned studies on other mathematical models such as integrate and fire models.

11  
12 As alluded earlier, there is a quiescence period between earthquakes in an earthquake  
13 zone, also known as the recurrence times. Since the globally recorded earthquake data  
14 are only available for a short-time period, incorporating the recurrence times into the  
15 earthquake catalogue is impossible. Here, we consider the model proposed by Davidsen  
16 et al. (2008) to include the spatio-temporal complexity of recurrences by identifying the  
17 earthquakes occurring in close proximity to any occurred event in the record-breaking  
18 sequence. In this paper, we also investigate the Kuramoto model with a phase-lag for the  
19 sequencing of global earthquakes data influenced by the recurrences to point out the  
20 emergence of chimera states under certain conditions.

## 21 22 **2 Mathematical model of the earthquake sequencing**

23  
24 The Kuramoto model (1975) for a large number of weakly-coupled oscillators has  
25 become a standard template in non-linear dynamical studies, pertinent to synchronization  
26 behavior, following the ground-breaking study of Winfree (1967). To apply this model to  
27 earthquake sequencing studies, we need to make a few justifiable assumptions and  
28 incorporate certain essential features of earthquakes that we have come to know. For  
29 example, plate motions and, hence, plate tectonics (Stein, 1993; Kagan et al., 2010;  
30 DeMets, 2011) suggest that most of the earthquakes occur in and around plate boundaries  
31 because of the varying plate motions of the plates that uniquely encompass the earth's

1 crust. In particular, different plates move at different rates and along different  
2 orientations resulting in stress-field changes at the plate boundaries. When stress-field  
3 accumulation reaches, at a particular location or in a zone, a certain critical threshold,  
4 energy is released in the form of an earthquake. The relaxed system goes through the  
5 stress-build-up process again, a similar mechanism being operative in neuronal  
6 communication dynamics. We assume that there is a uniform stress increase during the  
7 quiescent period. Collective synchronization of threshold-coupled or pulse-coupled  
8 oscillators would be a candidate for such a study (Mirollo and Strogatz, 1990; Kuramoto,  
9 1991; Rothkegel and Lehnertz, 2014). However, we defer the extension of their approach  
10 to earthquake sequencing studies to a future date. Since the quiescence period is 6 to 8  
11 orders of magnitude longer than the event time duration, it would be an ideal platform on  
12 which to carry out this study. We surmise that the behavior of earthquake cycles noted in  
13 earthquake sequencing does not lend support, however, to a full synchronization or full  
14 asynchronization as a solution to this non-dynamics problem. One proven modification is  
15 the inclusion of non-local effects of the geometry of the system that has been shown to  
16 lead to a co-existence of partially synchronized and partially asynchronized states of  
17 oscillators as a steady-state solution. Such states, addressed as chimera states, are the  
18 subject of recent theoretical and experimental studies (Kuramoto and Battogtokh, 2002;  
19 Abrams and Strogatz, 2004; Abrams et al., 2008; Ko and Ermentrout, 2008;  
20 Omel'chenko et al., 2008; Sethia et al., 2008; Sheeba et al., 2009; Laing, 2009a, 2009b;  
21 Laing et al., 2012; Martens et al., 2013; Yao et al., 2013; Rothkegel and Lehnertz, 2014;  
22 Kapitaniak et al., 2014; Pazó and Montbrió, 2014; Panaggio and Abrams, 2014; Zhu et  
23 al., 2014; Gupta et al., 2014; Vasudevan and Cavers, 2014a, 2014b). We target our  
24 present study to defining a Kuramoto model with a phase-lag that would accommodate  
25 the existence of chimera states. The Kuramoto model has been extensively studied for a  
26 system made up of a large number of weakly-coupled oscillators, where most of the  
27 physical problems are finite and can be described as non-linear dynamics on complex  
28 networks (Acebrón, 2005; Arenas et al., 2008). In the realm of graph theory, complex  
29 networks can be cast as either undirected or directed graphs. In our studies on earthquake  
30 sequencing, we consider a directed graph as a representation of an earthquake complex  
31 network. The occurrence of chimera states as solutions to non-linear dynamics on both

1 undirected and directed graphs has recently been investigated (Zhu et al., 2014;  
 2 Vasudevan and Cavers, 2014a). As a precursor to studying earthquake sequencing with  
 3 real data from the earthquake catalogues, we investigated the Kuramoto model on  
 4 synthetic networks that mimic Erdős-Rényi random networks, small- world networks,  
 5 and scale-free networks and directed graphs adapted from them, and examined chimera  
 6 state solutions (Vasudevan and Cavers, 2014a). For the earthquake sequencing studies  
 7 here, we use the following Kuramoto model with a phase-lag,  $\alpha$ , with non-local coupling  
 8 effects terms added explicitly:

9

$$10 \quad \dot{\theta}_i = \omega_i - \frac{1}{N} \sum_{j=1}^N G_{ij} \sin(\theta_i - \theta_j + \alpha) \quad (1)$$

11 Here,  $\dot{\theta}_i$  is the time-derivative of the phase of the  $i^{th}$  oscillator. The angle  $\alpha$  ( $0 \leq \alpha \leq \pi/2$ )  
 12 corresponds to the phase lag between oscillators  $i$  and  $j$ .  $G_{ij}$  is the non-local coupling  
 13 function that depends on the shortest path length,  $d_{ij}$ , between oscillators  $i$  and  $j$  in the  
 14 complex network:

$$15 \quad G_{ij} = \underline{KA}e^{-\kappa d_{ij}} \quad (2)$$

16  $\underline{A-K}$  is the global coupling strength and  $\kappa$  is the strength of the non-local coupling. For  
 17 convenience, we use a constant natural frequency for all the oscillators, i.e.,  
 18 homogeneous case, and thus, we could use  $\omega_i = 0$  for  $i = 1, \dots, N$ . Although we have not  
 19 investigated the influence of the global coupling strength on the steady-state solution of  
 20 the Kuramoto model, we treat this term to be constant, in particular  $\underline{A-K} = 1$ , based on  
 21 observations made by Zhu et al. (2014).

22 We would like to stress that the model in Equation 1 is not a pulse-coupled or threshold-  
 23 coupled oscillator model. Although it would be appropriate to consider a variation of the  
 24 Kuramoto model such as the Shinomoto-Kuramoto model (Shinomoto and Kuramoto,  
 25 1986; Sakaguchi et al., 1988; Lindner et al., 2004), we limit ourselves to a simpler model  
 26 which does not include the excitable behaviour of the model. We intend to use this  
 27 model as a precursor to our planned studies on other mathematical models such as

1 integrate and fire models.

2 A comment on the phase-lag parameter,  $\alpha$ , in equation is also in order. Panaggio and  
3 Abrams (2014) interpret the phase lag as an approximation for a time-delayed coupling  
4 when the delay is small. The value of  $\alpha$  used is  $(\pi/2) - 0.10$ . In some ways, we treat the  
5 phase lag as a proxy for time delay. As Panaggio and Abrams (2014) demonstrate in  
6 their paper, the value of  $\alpha$  determines a balance between order and disorder. We have not  
7 done an exhaustive search on the  $\alpha$  parameter for the cases discussed in this paper.

8 Here, we construct a directed graph of earthquake events from the Incorporated  
9 Institutions for Seismology (IRIS) earthquake catalogue for the time period between 1970  
10 and 2014. We consider earthquake events with magnitudes exceeding or equal to **M<sub>w</sub> 5.5**  
11 observed to a depth of 70 kilometers. We partition the general latitude/longitude map of  
12 the earthquake events into a grid. We show two maps of such grid matrices (Figure 1).  
13 A cell in a smaller grid (128x128) could have higher multiplicity of earthquake events  
14 than that in a large grid (1024x1024). We consider the coordinates of the topological  
15 centre of each cell to represent the coordinates of the earthquake events that fall into that  
16 cell. Thus, we explore the effect of hubs and community effects by looking at transition  
17 probability matrices generated from grids of different orders such as 128, 192, 256, 512,  
18 and 1024 representing the seismicity map on a global longitude-latitude grid. We  
19 compute the transition probability matrix and the shortest-path distance matrix for the  
20 directed graphs resulting from the catalogue considered. To keep the Kuramoto model  
21 simple, we assume a constant phase-lag,  $\alpha$ , in the phase of the ensemble of oscillators.  
22 The value of  $\alpha$  used is  $(\pi/2) - 0.10$ . We relax this condition in subsequent simulations.  
23 The most difficult parameter to deal with here is the period of quiescence after the energy  
24 release following a certain stress threshold. We incorporate the build-up of the threshold  
25 effect indirectly by positing the inclusion of earthquake recurrences in transition  
26 probability matrices. Here, we use the spatio-temporal recurrences based on the record-  
27 breaking model of Davidsen et al. (2008). In all our initial simulations, we ignore the  
28 influence of amplitude effects on the stability of the chimera states. We carry out  
29 simulations on the Kuramoto model for 200,000 time-steps for the 128x128 oscillator  
30 grid matrices and for the 1024x1024 oscillator grid matrices. We report here the

1 preliminary results of our simulations.

### 2 **3 Results**

3

4 We report the Kuramoto model experimental results for oscillators resulting from  
5 128x128, 192x192, 256x256, 512x512, and 1024x1024 grids of the latitude-longitude  
6 map of the earthquakes. We consider a total of 13190 earthquakes. We construct the  
7 transition probability and the shortest-path distance matrices for the grids without (“non-  
8 recurrence” results) and with the consideration of the spatio-temporally complex  
9 recurrences (“recurrence” results), as shown in Figures 2 and 3.

10 To represent the results, we use snapshots of three attributes (Zhu et al. (2014)): (i) the  
11 phase profile, (ii) the effective angular velocities of oscillators and (iii) the fluctuation of  
12 the instantaneous angular velocity of oscillators. The effective angular velocity of  
13 oscillator  $i$  is defined as

$$14 \quad \langle \omega_i \rangle = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{t_0}^{t_0+T} \dot{\theta}_i dt \quad (3)$$

15 Here, we take  $T = 1000$  so that the effective angular velocities of the oscillators are  
16 averaged over the last 1000 time-steps. We take  $t_0 = 199,001$  for the 128x128 grid and  
17 for the 1024x1024 grid.

18 The fluctuation of the instantaneous angular velocity,  $\sigma_i$ , of an oscillator  $i$  around its  
19 effective velocity is defined as

$$20 \quad \sigma_i^2 = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{t_0}^{t_0+T} (\dot{\theta}_i - \langle \omega_i \rangle)^2 dt \quad (4)$$

21

22 If  $\sigma_i = 0$  then oscillator  $i$  rotates at a constant angular velocity. We show the non-  
23 recurrence and recurrence results obtained from the behavior of the last 1000 time-steps  
24 of the simulations involving 200,000 time-steps. We present the results for the 128x128  
25 grid without and with recurrences in Figures 4 and 5 for the three attributes using  $\kappa =$   
26 0.10. Figures 6 and 7 show these attributes for the 1024x1024 grid without and with

1 recurrences respectively for  $\kappa = 0.1$

2 Whether or not the Kuramoto model reaches the steady-state, we examine the ratio of the  
3 number of coherent or synchronous oscillators to the total number of oscillators or  
4 “chimera index” as a function of the number of time steps. Here, we carry out 200,000  
5 time steps. After every 20,000 time-steps, we look at the chimera index for the last 1000  
6 time-steps. As an example, in Figure 8, we find the asymptotic behaviour of the scatter  
7 of the chimera index for ten such intervals for the 128x128 grid for  $\kappa = 0.10$  suggesting  
8 that the Kuramoto model has reached the steady-state.

9 We investigate the influence of the non-local coupling coefficient,  $\kappa$ , on the chimera  
10 index for each grid and summarize our results for the non-recurrent 128x128 and  
11 1024x1024 grids in Figure 9.

12

13 Most of the initial computations reported in this work were on a HP C7000 chassis cluster  
14 system with dual-core 2.4 GHz AMD Opetron processors at the high performance  
15 computing facility at the University of Calgary. We carried out a series of runs for  
16 200,000 time steps on a Mac Pro Six-Core Intel Xeon E5 3.9GHz, 16 GB RAM desktop  
17 work station and on Intel Xeon E7-4870 2.40 GHz 256 GB RAM processors. We used  
18 the Matlab ODE113 solver to solve the Kuramoto model.

19

## 20 **4 Discussion**

### 21 **4.1. Building the directed graph**

22 Earthquake sequencing is a well-studied problem in earthquake seismological  
23 communities around the globe, and yet, it hides a suite of phenomenological mysteries  
24 that stand in the way of successful earthquake forecasting. One of the first steps in  
25 carrying out any investigative work on earthquake sequencing is to look at the global  
26 seismicity map such as the one posted by IRIS on a regular basis, with continuous  
27 updating of the associated catalogue. In Figures 1a and 1b, we summarize the cumulative  
28 results of the catalogue for magnitudes of earthquakes exceeding Mw 5.5 and the depths  
29 of occurrence not exceeding 70 kilometres, recorded between January 1970 and  
30 September 2014. One difference in the two figures lies in the coarseness of the gridding

1 with the first one being coarser than the second. A cursory glance at the figures  
2 immediately suggests the relevance of plate tectonics in that most earthquakes seem to  
3 occur at and around plate boundaries. A broad classification of these earthquakes could  
4 consist of the following categories: strike-slip earthquakes, subduction-zone seismicity,  
5 oceanic earthquakes, continental extensional regimes, intraplate earthquakes, and slow  
6 earthquakes (Scholz, 2002). The interplay between these remains a topic of research  
7 among seismologists. In general, fault systems play an important role in understanding  
8 the cause and recurrence of earthquakes. Scholz (2002) provides an excellent account of  
9 the mechanics of earthquakes and faulting. Ben-Zion and Sammis (2003) examined the  
10 continuum-Euclidean, the granular, and the fractal views of the geometrical, mechanical,  
11 and mathematical nature of faults and concluded that many aspects of the observed  
12 spatio-temporal complexity of earthquakes and faults might be explained using the  
13 continuum-Euclidean model. They contended that a continuum-based description would  
14 provide a long-term attractor for structural evolution of fault zones at all scales. The  
15 underpinning point in these works is the importance of the faulting in earthquake  
16 processes. Earthquakes are known to occur at different depths. Excepting in instances  
17 where there are surface ruptures as a result of earthquakes, fault zones at seismogenic  
18 depths in kilometres cannot be directly observed (Ben-Zion and Sammis, 2003).  
19 Continued geological mapping and high-resolution geophysical measurements afford a  
20 mechanism to improve our understanding of the fault zones.

21  
22 Rundle et al. (2003) took a statistical physics approach in emphasizing the significance of  
23 faults and fault systems as high-dimensional non-linear dynamical systems characterized  
24 by a wide range of scales in both space and time, from centimeters to thousands of  
25 kilometers, and from seconds to many thousands of years. The signature of the residual  
26 behavior in these systems is chaotic and complex. Understanding the coupling between  
27 different space and time scales to comprehend the non-linear dynamics of the fault  
28 systems is not an easy problem. In this regard, any attempt to explore the possibilities  
29 that accrue from non-linear dynamics studies is welcome.

1 In earlier studies on model and theoretical seismicity (Burridge and Knopoff, 1967;  
2 Vieira, 1999), special attention was paid to finding out if chaos was present in the  
3 symmetric non-linear two-block Burridge-Knopff model for earthquakes. Viera (1999)  
4 demonstrated with a three-block system the appearance of synchronized chaos. A  
5 consequence of this study was the speculation that earthquake faults, which are generally  
6 coupled through the elastic media in the earth's crust, could in principle synchronize even  
7 when they have an irregular chaotic dynamics (Viera, 1999). Going one step further  
8 would be to suggest that the occurrence of earthquakes and the space-time scale patterns  
9 they leave behind is a sound proxy for modeling and theoretical studies of the fault  
10 systems. It is this point that is pursued in this work.

11  
12 In this study, we focus on the non-linear dynamics of weakly-coupled oscillators. Each  
13 oscillator (corresponding to the occurrence of an earthquake) is a proxy for a fault system  
14 or network with known information on its location, the time when the earthquake event  
15 occurred, and magnitude. This defines an element in the earthquake sequence. A  
16 continued sequence of events is represented as a directed graph (Vasudevan et al., 2010;  
17 Cavers and Vasudevan, 2014; Vasudevan and Cavers, 2014b) with the vertices  
18 representing the earthquakes (and their attributes) and the arcs the connecting links  
19 between neighbours in a sequence. Figures 2a and 3a show the transition matrices for the  
20 directed graphs of the two grids, 128x128 and 1024x1024 grids. The oscillator index is  
21 determined by the grid partition with non-zero cells labelled in row-by-row order. A  
22  $\log(\log)$  display scale is used to highlight the "clustering". The level of clustering along  
23 the first leading off-diagonal elements of the transition matrix is highlighted and indicates  
24 the partitioning and the relative significance of the seismicity zones in the globe.  
25 However, this does not invoke any causality argument. Since the multiplicity of the  
26 earthquakes in the cells of the grids used varies from '0' to a large number, for the reason  
27 mentioned concerning the Euclidean geometry mentioned earlier, inter-cell and intra-cell  
28 transitions populate the transition matrices. These transition matrices are not symmetric.  
29 The non-linear dynamics of weakly-coupled oscillators on such matrices has not been  
30 fully understood.

31

1 As mentioned earlier, the quiescence period between earthquakes in an earthquake zone  
 2 is what we interpret here as recurrence period. Studies on plate-boundary motions (Bird,  
 3 2002; DeMets, 2010; Stein, 1993) will provide an insight into the recurrence period for  
 4 earthquakes in certain major fault zones. Even in instances where knowledge of the  
 5 recurrence periods is known, it is usually punctuated by random fluctuations, the statistics  
 6 of which are not unknown. The quiescence period is analogous to the process in human  
 7 brains that precedes epileptic seizures (Berg et al., 2006; Rothkegel and Lehnertz, 2014),  
 8 the structure of which has been modeled using pulse-coupled phase-oscillators. Such  
 9 pulse-coupling or threshold-coupling remains to be quantified for earthquakes. We defer  
 10 this aspect of the work to future studies. Furthermore, the historical seismicity data set is  
 11 short and, therefore, any information to be drawn from global records will be insufficient.  
 12 However, the recurrence model introduced by Davidsen et al. (2008) offers a simple  
 13 remedy to the problem. It rests in identifying the earthquakes occurring in close  
 14 proximity to any occurred event in the record-breaking sequence. Incorporating this  
 15 feature into the transition matrices results in modified transition matrices, as shown in  
 16 Figures 2b and 3b. We propose that accounting for the quiescence period in this manner  
 17 opens additional options such as feedback effects on the non-linear dynamics of weakly-  
 18 coupled oscillators.

## 20 4.2. Synchronization

21  
 22 Scholz (2010) argued for the role of synchronization in fault interactions and earthquake  
 23 clustering and for the usefulness of the Kuramoto model. Kuramoto (1975) proposed a  
 24 mathematical model of phase oscillators interacting at arbitrary intrinsic frequencies and  
 25 coupled through a sine of their phase differences. He suggested the following equations  
 26 for each oscillator in the system:

$$28 \quad \dot{\theta}_i = \omega_i + K_i \sum_{j=1}^N \sin[\theta_j(t) - \theta_i(t)] \quad (i = 1, \dots, N) \quad (5)$$

29  
 30 where  $\theta_i$  is the phase of the  $i^{\text{th}}$  oscillator,  $\dot{\theta}_i(t)$  is the first derivative of the phase of the  $i^{\text{th}}$   
 31 oscillator with time,  $\omega_i$  is the natural frequency of the oscillator,  $K_i$  is the strength of

1 coupling of the  $i^{th}$  oscillator to other oscillators and  $N$  is the size of the population of the  
 2 oscillators. The frequencies  $\omega_i$  are chosen from a uniform distribution. Kuramoto (1975)  
 3 demonstrated that synchronization was accomplished in the case of mean-field coupling  
 4 with

$$5 \quad K_i = \frac{K}{N} > 0 \quad (i = 1, \dots, N) \quad (6)$$

6 in the above equation. We can describe the Kuramoto model in a simpler form by  
 7 introducing the complex-valued order parameter  $r(t)$ :

$$9 \quad Z = r(t)e^{i\psi(t)} = \frac{1}{N} \sum_{j=1}^N e^{i\theta_j(t)} \quad (7)$$

10  
 11 where  $\Psi(t)$  is the average phase and  $r(t)$  honours  $0 \leq r(t) \leq 1$ . The expression of the  
 12 Kuramoto model becomes:

$$14 \quad \dot{\theta}_i(t) = \omega_i + Kr \sin[\psi - \theta_i(t)] \quad (i = 1, \dots, N) \quad (8)$$

15  
 16 The collective behavior of all the oscillators is monitored by examining the time  
 17 evolution of the order parameter,  $r$ , (Kuramoto (1975), Strogatz (2000); Pikovsky et al.  
 18 (2003); Strogatz (2003)). The order parameter can assume values in the range 0 to 1  
 19 including the limits. From this, it is obvious that each oscillator is connected to the  
 20 common average phase with the coupling strength is given by  $Kr$ . A value of ‘0’ for  $r$   
 21 corresponds to total incoherence, i.e., no phase locking of the phases of the oscillators; a  
 22 value of ‘1’ for  $r$  corresponds to full coherence, i.e., phase locking of all the phases of the  
 23 oscillators. The time evolution of the Kuramoto model can be monitored either by  
 24 looking at the polar plots of the phases on a unit circle (Kuramoto (1975)) or by  
 25 following the plot of the order parameter,  $r$ , as a function of the coupling strength,  $K$ .  
 26 Acebrón et al. (2005) have provided a comprehensive review of the Kuramoto model.

27  
 28 For the stability of the solution from the Kuramoto model, use of a large population of  
 29 oscillators for calculability in the thermodynamic limit is a pre-requisite. Over the last  
 30 decade, efforts have gone into considering a finite number of oscillators satisfying the

1 original conditions of the Kuramoto model. Easing the restrictions on the interaction  
2 model can be cast as an investigation of synchronization on complex networks. This  
3 would allow one to relate the complex topology and the heterogeneity of the network to  
4 the synchronization behavior.

5  
6 We rewrite the original Kuramoto model for a complex network corresponding to  
7 undirected and directed graphs as

$$9 \quad \dot{\theta}_i(t) = \omega_i + \sum_{j=1}^N \sigma_{ij} K_{ij} a_{ij} \sin[\theta_j(t) - \theta_i(t)] \quad (i = 1, \dots, N) \quad (9)$$

10  
11 where  $\sigma_{ij} K_{ij}$  is the coupling strength between pairs of connected oscillators and  $a_{ij}$  refers  
12 to the elements of the adjacency or connectivity matrix. Much effort has gone into  
13 understanding the role of the coupling strength (Hong et al. 2002; Arenas et al., 2008;  
14 Dörfler et al., 2013) in the synchronization behavior of small-world and scale-free graphs.  
15 Here, we leave the coupling strength term a constant, unlike in the model under the  
16 thermodynamic limit where the size of the population,  $N$ , enters explicitly in the coupling  
17 strength term as a divisor. The structure of the adjacency matrix decides essentially the  
18 nature of the interaction term made up of the sine coupling of the phases. Vasudevan and  
19 Cavers (2014a) have investigated the synchronization behaviour of the random graphs  
20 under different rewiring probabilities and the scale free-graphs from a spectral graph  
21 theory point of view. These studies did not include a study on the effect of clustering on  
22 the synchronization. In this regard, the work of McGraw and Menzinger (2005) is quite  
23 appealing. They conclude that for random networks and scale-free networks, increased  
24 clustering promotes the synchronization of the most connected nodes (hubs) even though  
25 it inhibits global synchronization. We see the role of the effect of clustering on the nature  
26 of synchronization behaviour in earthquake sequencing studies and will constitute a  
27 separate study. Whether or not we reach similar conclusions for directed graphs, we have  
28 recently investigated synthetic networks that mimic real data structures (Vasudevan and  
29 Cavers, 2014a). In this regard, it is worth mentioning that synchronization of Kuramoto  
30 oscillators in directed networks has been subjected to a detailed study (Restrepo et al.,  
31 2006).

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### 4.3. Chimera states

While the synchronization and asynchronization studies on earthquake sequencing are important in terms of the Kuramoto model given in Equation 9, very little attention has been paid to the co-existence of synchronized and asynchronized states or the chimera states. Kuramoto and Battogtokh (2002) and Abrams and Strogatz (2004) paved the way for such a study by including the non-local effects into the Kuramoto model, as expressed in Equations 1 and 2. Non-local effects mean simply the inclusion of geometry effects. For the global seismicity map considered in this study, we generated the shortest-path distance matrices with and without the inclusion of recurrences (Figures 2c, 3c, 2d, and 3d). The shortest-path algorithm encapsulates both the cascading effects of earthquakes and the negation of long-range distance effects. In this study, we kept the global coupling strength constant and allowed the non-local coupling strength,  $\kappa$ , to vary from one simulation to the next one, similar to what was done in the recent work of Zhu et al. (2014).

Symmetry breaking phenomena like chimera states have also been observed for two-cluster network of oscillators with a Lorentzian frequency distribution (Montbrió et al., 2004) for all values of time-delay. A crucial result by Laing (2009a, 2009b) extends the previous observation to oscillators with heterogeneous frequencies. Also interesting to observe in this regard is that these heterogeneities can lead to new bifurcations allowing for alternating synchrony between the distinct populations over time. Ko and Ermentrout (2008) demonstrated the presence of chimera-like states when the coupling strengths were heterogeneous. The last study used coupled Morris-Lecar oscillators. Although there is overwhelming evidence for the existence of chimera states in the presence of time delay or phase-lag, all of our initial Kuramoto model simulations on the directed graph transition matrices and the associated shortest-path distance matrices included a constant phase-lag only.

1 A postulation for the existence of evolving chimera states in data from earthquake  
2 catalogues has certain implications. For instance, it would pave way for understanding  
3 the evolving alterations in stress-field fluctuations in fault-zones frequented by  
4 earthquakes. Also, it would suggest a need to consider steps to quantify partially or fully  
5 the ratio of the number of synchronized oscillators to the total number of oscillators. The  
6 steps would involve extensive testing of the dependence of the parameters and additional  
7 mathematical models. We interpret the zones with synchronized oscillators as the ones  
8 being susceptible to earthquakes and the zones with asynchronised oscillators as the ones  
9 going through a quiescence period. The hope is that confirmation of chimera states in  
10 earthquake sequencing would signal a possible use for earthquake forecasting studies.

#### 11 12 **4.4. Simulation results and analysis**

13  
14 The Kuramoto model simulation with non-local coupling effects ( $\kappa=0.10$ ) with a phase-  
15 lag, as expressed in Equation 1 for a 128x128 grid transition probability, and the  
16 corresponding shortest-path distance matrices, lead to snapshots of three attributes: (1)  
17 the phase profile; (ii) the effective angular velocities of oscillators, and (iii) the  
18 fluctuation of the instantaneous angular velocity of oscillators. We did not sort the results  
19 according to an increase in the values of the attributes. Panels (a), (b), and (c) in Figure 4  
20 show that, for a case of no recurrences, there exists a chimera state. The ensemble  
21 averages from the last 1000 time steps of the 200,000 time steps in the numerical  
22 simulations reveal the co-existence of synchronous and asynchronous oscillators. This  
23 means that some of the cells in the grid strike a synchronous behavior and some others do  
24 not. In this particular case of no recurrences (Figure 4), the number of synchronous  
25 oscillators to the number of asynchronous oscillators is large. In the case of recurrences,  
26 as shown in Figure 5, this ratio is much larger. Also, the chimera pattern of the  
27 synchronized and asynchronized components of the oscillators is similar to what was  
28 observed by Abrams and Strogatz (2004). Figures 4a and 5a are the first evidence of the  
29 possible existence of a chimera state in earthquake sequencing. Figures 4b, 4c, 5b, and  
30 5c confirm this.

1 Going from the 128x128 grid to 1024x1024 grid, there are more non-zero cells with  
2 multiplicity of earthquakes at least 1. The number of oscillators is substantially larger,  
3 1693 vs 7697. Figures 6 and 7 reveal the chimera state as the steady-state solution to the  
4 non-linear dynamics on weakly-coupled oscillators without and with recurrences for the  
5 1024x1024 grid with the non-local coupling coefficient,  $\kappa = 0.1$ . Figure 8 shows the  
6 behaviour of the chimera index as a function of the number of time-steps for the non-  
7 recurrent 128x128 grid with the non-local coupling coefficient,  $\kappa$ , set at 0.10. The  
8 purpose of this figure is to demonstrate that the asymptotic behaviour of the chimera  
9 index with an increase in the number of time steps could be used to look at the steady-  
10 state solution of the Kuramoto model.

11

12 We looked at the influence of the non-local coupling coefficient,  $\kappa$ , on the ratio of the  
13 number of coherent oscillators to the total number of oscillators for both the 128x128 and  
14 1024x1024 grids without recurrences in Figure 9. A similar observation is made for the  
15 case of recurrences. As the non-local coupling coefficient,  $\kappa$ , increases from 0.01 to 1.0,  
16 the ratio decreases. For values of  $\kappa$  approaching 0, the non-local Kuramoto model acts as  
17 a simple Kuramoto model in that there is full synchronization for the global coupling  
18 parameter,  $A$ , (or used as  $K$  in literature) of 1.0. What is surprising to begin with is that,  
19 as  $\kappa$  approaches 1, the steady-state solution becomes more asynchronized. Investigations  
20 on the effect of the non-local coupling effect parameter,  $\kappa$ , on the steady-state solution of  
21 the phase angle distribution in the chimera state (Figures 10a, 10b, 11a and 11b) suggest  
22 that for both the 128x128 grid and the 1024x1024 grid, for larger  $\kappa$  values, the number of  
23 asynchronous oscillators is larger, and for smaller  $\kappa$  values, the presence of synchronous  
24 oscillators becomes dominant. For in-between values, i.e., between 1.0 and 0.03, the  
25 nature of the chimera states changes.

26

27 The outcome of each one of the simulations described for both the non-recurrence and  
28 recurrence cases contains synchronous and asynchronous vectors. Mapping these vectors  
29 on the respective grids (128x128 or 1024x1024 grids) should reveal the “non-readiness or  
30 readiness” cells or zones for earthquakes. One such map for a 128x128 grid without

1 recurrences for  $\kappa = 0.10$  is shown in Figure 12. This qualitative description of the  
2 evolutionary dynamics of the earthquake sequencing is highly instructive.

## 3 4 5 **5 Conclusions and future work**

6  
7 Earthquake sequencing is an intriguing research topic. The dynamics involved in the  
8 evolution of earthquake sequencing are complex. Very much has been understood, and  
9 yet, the evolving picture is incomplete. In this regard, the work of Scholz (2010) acted as  
10 a catalyst in us investigating the synchronization aspect of earthquakes using the  
11 Kuramoto model. To name a few, the works of Vieira (1999), Rundle et al. (2002, 2003),  
12 Kuramoto and Battogtokh (2002), Abrams and Strogatz (2004), and Laing (2009a,  
13 2009b) have helped us take this step forward with this work. We summarize below the  
14 main points of this paper and also, point out the direction in which we are going:

- 15  
16 (1) Earthquake sequencing from the IRIS earthquake catalogue browser can be  
17 expressed as a transition matrix of a directed graph. Partitioning of the  
18 latitude/longitude grid of the globe into grids of finite dimensions such as  
19 128x128, 192x192, 256x256, 512x512, and 1024x1024 grids result in differing  
20 dimensions of transition matrices of oscillators in increasing order. Short-path  
21 distance matrices for the latter are generated concurrently to study the non-local  
22 effects used in the Kuramoto model.
- 23 (2) Inclusion of the non-local effects in the Kuramoto model of the directed graphs is  
24 tested for different values of the non-local coupling coefficient,  $\kappa$ .
- 25 (3) For a non-local coupling strength,  $\kappa$ , of 0.10, the Kuramoto model yields chimera  
26 states as a steady-state solution, i.e., co-existence of synchronized and  
27 asynchronous states. This is true for all the grid sizes considered. Differences  
28 exist in the ratio of the number of coherent oscillators to the number of incoherent  
29 oscillators.
- 30 (4) As the non-local coupling strength,  $\kappa$ , is lowered from 1.0 to 0.01, there is a  
31 general tendency towards an increase in synchronization, as is expected. While

1 this general trend is observed for directed graphs generated from grids of orders  
2 128, 192, 256, and 512, the graph from 1024x1024 grid reveals the presence of  
3 the chimera state.

4 (5) As the non-local coupling strength is increased from 0.1 to 1.0, there is a steady  
5 increase in the asynchronous behavior.

6 (6) The recurrence results support the presence of chimera states for both 128x128  
7 and 1024x1024 grids. However, it is quite intriguing to find out that the  
8 asynchronous oscillators come from a sub-set of the oscillators in both cases.

9 (7) There is still a nagging question about which non-local coupling coefficient would  
10 be an ideal candidate for understanding the global stress-field fluctuations.

11 Figure 12 illustrates an example of how a chimera state could be displayed on the  
12 map grid. Imposing geophysical and geodetic constraints on the earthquake zones  
13 in terms of heterogeneity of the natural frequencies would provide a quantitative  
14 answer to the above question.

15 (8) In general, the hypothesis that all networks of earthquake faults around the globe  
16 go through full synchronization still needs to be strongly tested. On the other  
17 hand, the prevalence of chimera states or multi-chimera states is an attractive  
18 option to understand the earthquake sequencing.

19 (9) We believe that there is, now, a mechanism available to us to explore and seek an  
20 answer to the non-linear dynamics of earthquake oscillations.

21 Needless to say, the role of the parameters such as the heterogeneity of the oscillators as  
22 expressed in the natural frequency of the oscillators, the variability of the time-delay  
23 corrections instead of a constant time-delay, and the heterogeneity of the non-local  
24 coupling strength and the global coupling strength in the present Kuramoto model  
25 remains to be investigated. Work is currently in progress.

26

27

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**List of tables**

**Table 1.** Grid sizes and the number of oscillators corresponding to non-zero cells.

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**List of figures**

**Fig. 1.** Partitioning of the global seismicity map: a) 128x128 gridding of the latitude-longitude map. b) 1024x1024 gridding of the latitude-longitude map. Earthquakes of magnitudes exceeding or equal to  $M_w$  5.5 and location depth not exceeding 70 kilometres for the time period from January 1970 to September 2014 constitute the glacial seismicity map. Earthquake information was downloaded from IRIS (Incorporated Research Institutions for Seismology). The earthquake frequency used in the maps is plotted on a log(log) display scale, with larger circles representing higher frequencies.

**Fig. 2.** 128x128 gridded map: a) Transition probability matrix without recurrences. b) Transition probability matrix with recurrences. c) Shortest-path distance matrix without recurrences. d) Shortest-path distance matrix with recurrences. In a) and b), the transition frequencies used in the maps are plotted using a log(log) display scale, with larger circles representing higher frequencies.

**Fig. 3.** A 1024x1024 gridded map: a) Transition probability matrix without recurrences. b) Transition probability matrix with recurrences. c) Shortest-path distance matrix without recurrences. d) Shortest-path distance matrix with recurrences. In a) and b), the transition frequencies used in the maps are plotted using a log(log) display scale, with larger circles representing higher frequencies.

**Fig. 4.** Three attributes of a chimera state of the 1693 oscillators for a 128x128 gridded map **without** recurrences using  $\kappa = 0.10$ . a) Stationary phase angle. b) Effective angular velocity. c) Fluctuations in instantaneous angular velocity.

**Fig. 5.** Three attributes of a chimera state of the 1693 oscillators for a 128x128 gridded map **with** recurrences using  $\kappa = 0.10$ . a) Stationary phase angle. b) Effective angular velocity. c) Fluctuations in instantaneous angular velocity.

**Fig. 6.** Three attributes of a chimera state of the 7697 oscillators for a 1024x1024 gridded map **without** recurrences using  $\kappa = 0.10$ . a) Stationary phase angle. b) Effective angular velocity. c) Fluctuations in instantaneous angular velocity.

**Fig. 7.** Three attributes of a chimera state of the 7697 oscillators for a 1024x1024 gridded map **with** recurrences using  $\kappa = 0.10$ . a) Stationary phase angle. b) Effective angular velocity. c) Fluctuations in instantaneous angular velocity.

**Fig. 8.** Chimera index as a function of time-steps for the 128x128 grid **without** recurrences for  $\kappa = 0.10$ .

**Fig. 9.** Influence of the non-local coupling coefficient parameter,  $\kappa$ , on the ratio of the number of synchronized oscillators to the total number of oscillators for both the 128x128 and the 1024x1024 grids **without** recurrences.

**Fig. 10a.** Effect of the non-local coupling coefficient parameter,  $\kappa$ , on evolution and disappearance of the Chimera states for the 128x128 grid **without** recurrence. Stationary phase angle as a function of the oscillator index: (a) kappa,  $\kappa = 1.0$ ; (b) kappa,  $\kappa = 0.3$ ; (c) kappa,  $\kappa = 0.1$ ; (d) kappa,  $\kappa = 0.03$

**Fig. 10b.** Effect of the non-local coupling coefficient parameter,  $\kappa$ , on evolution and disappearance of the Chimera states for the 128x128 grid **with** recurrence. Stationary phase angle as a function of the oscillator index: (a) kappa,  $\kappa = 1.0$ ; (b) kappa,  $\kappa = 0.3$ ; (c) kappa,  $\kappa = 0.1$ ; (d) kappa,  $\kappa = 0.03$

**Fig. 11a.** Effect of the non-local coupling coefficient parameter,  $\kappa$ , on evolution and disappearance of the Chimera states for the 1024x1024 grid **without** recurrence. Stationary phase angle as a function of the oscillator index: (a) kappa,  $\kappa = 1.0$ ; (b) kappa,  $\kappa = 0.3$ ; (c) kappa,  $\kappa = 0.1$ ; (d) kappa,  $\kappa = 0.03$

1 **Fig. 11b.** Effect of the non-local coupling coefficient parameter,  $\kappa$ , on evolution and disappearance of the  
2 Chimera states for the 1024x1024 grid **with** recurrence. Stationary phase angle as a function of the  
3 oscillator index: (a) kappa,  $\kappa = 1.0$ ; (b) kappa,  $\kappa = 0.3$ ; (c) kappa,  $\kappa = 0.1$ ; (d) kappa,  $\kappa = 0.03$

4 **Fig. 12.** Chimera state map of the synchronous and asynchronous oscillators as a steady-state solution for a  
5 **non-recurrence** case. The non-local coupling coefficient parameter,  $\kappa$ , is 0.1. Blue dots refer to the  
6 asynchronous oscillators and red dots to the synchronous oscillators.

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1 **Table 1.**  
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<b>Grid Size</b>	<b>Number of Oscillators</b>
128x128	1693
192x192	2390
256x256	3087
512x512	5119
1024x1024	7697



Figure 1.

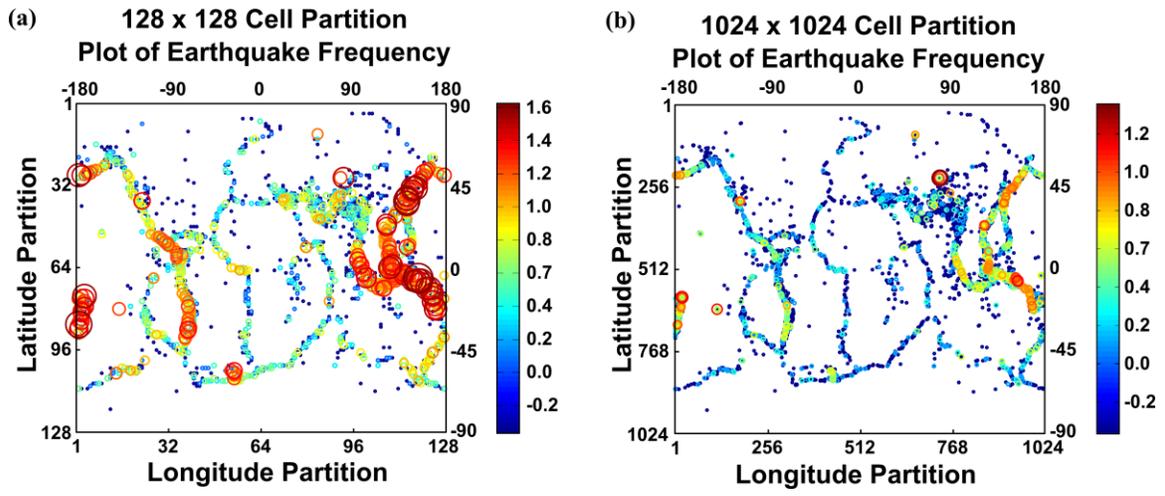


Figure 2.

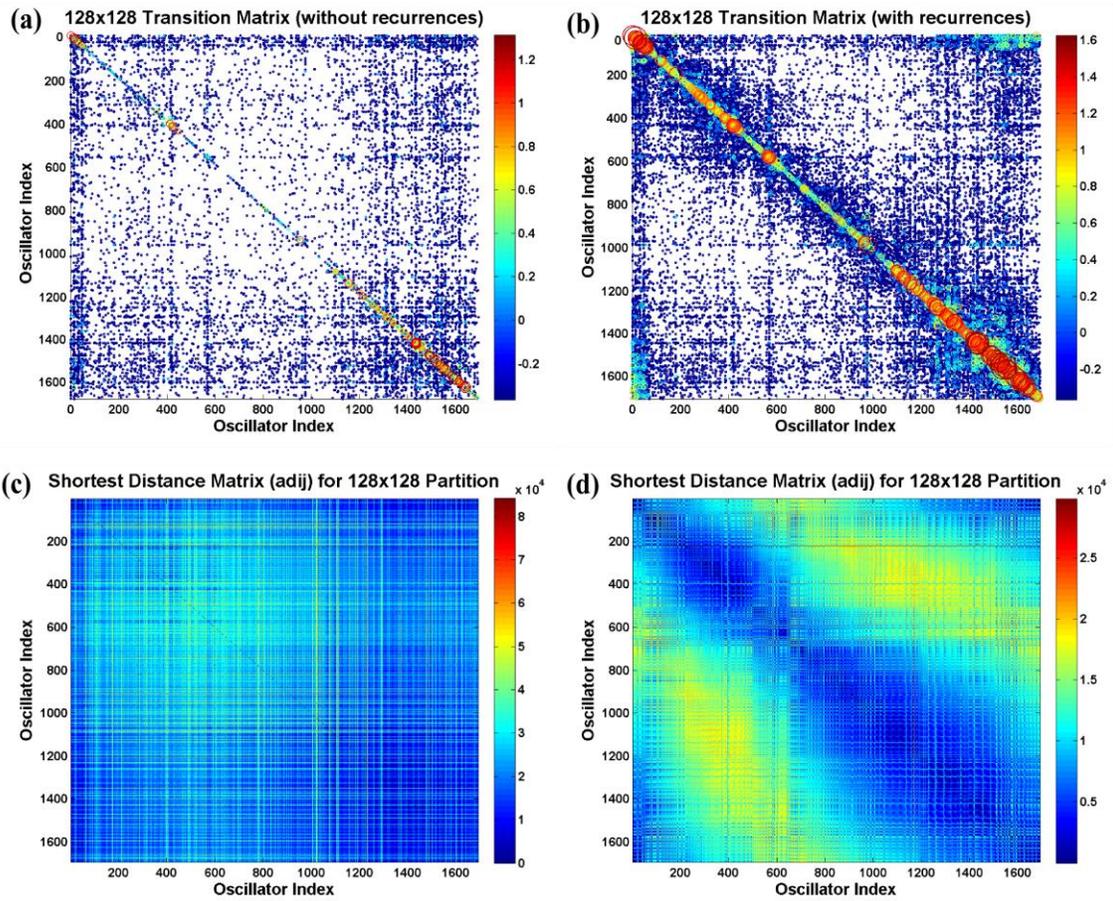


Figure 3.

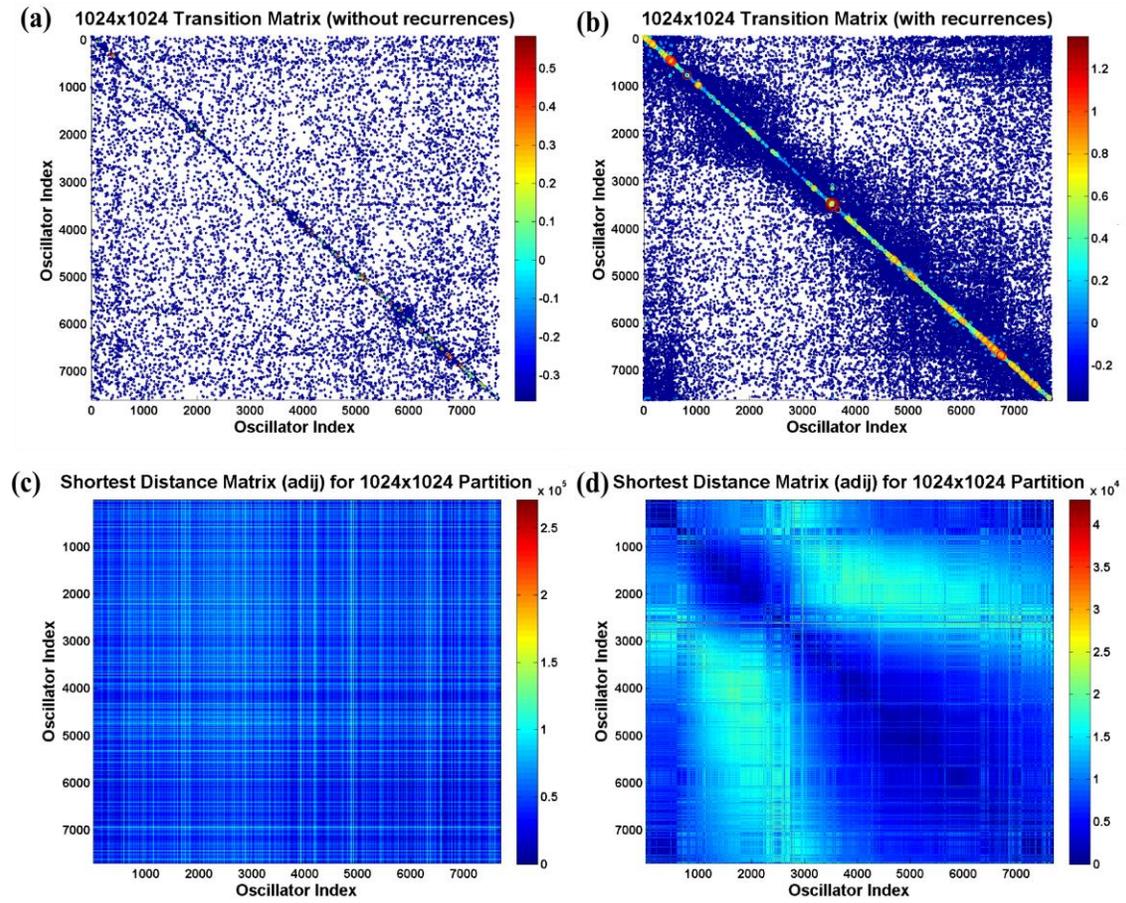


Figure 4.

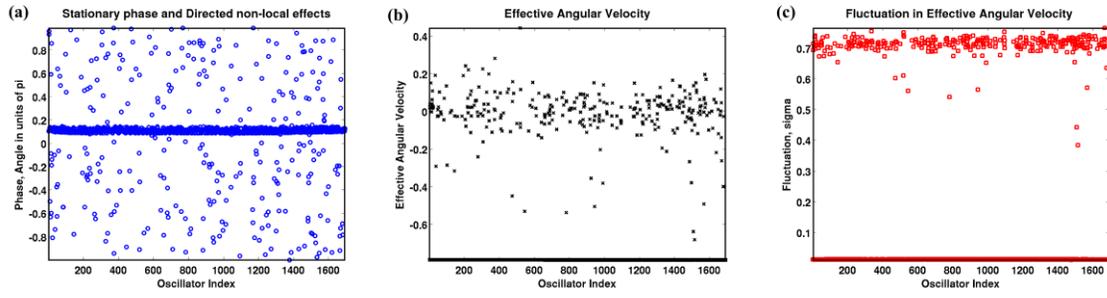


Figure 5.

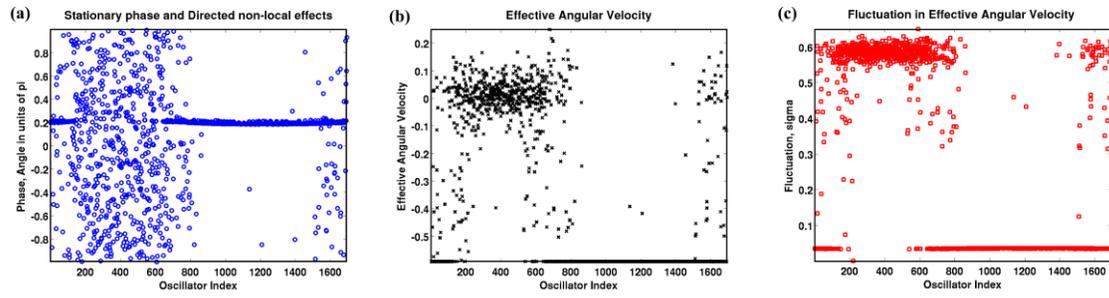
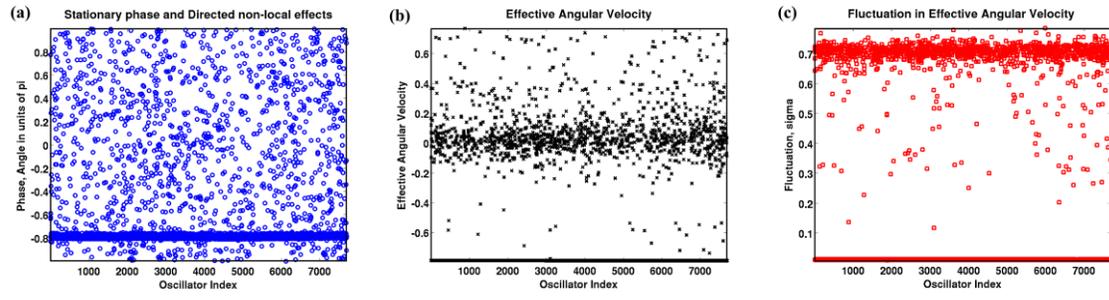


Figure 6.



**Figure 7.**

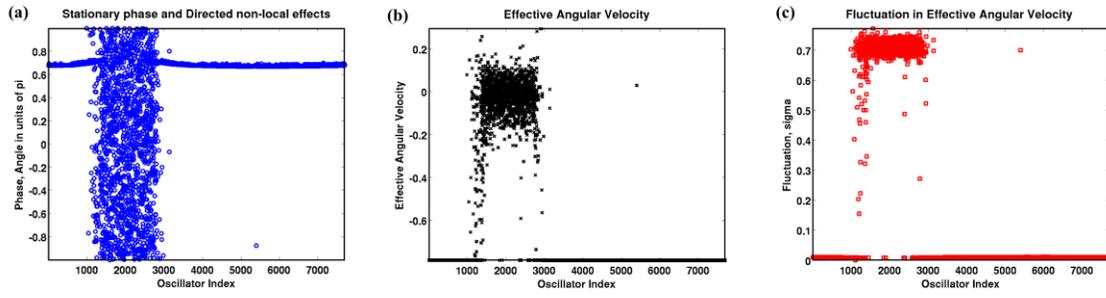


Figure 8.

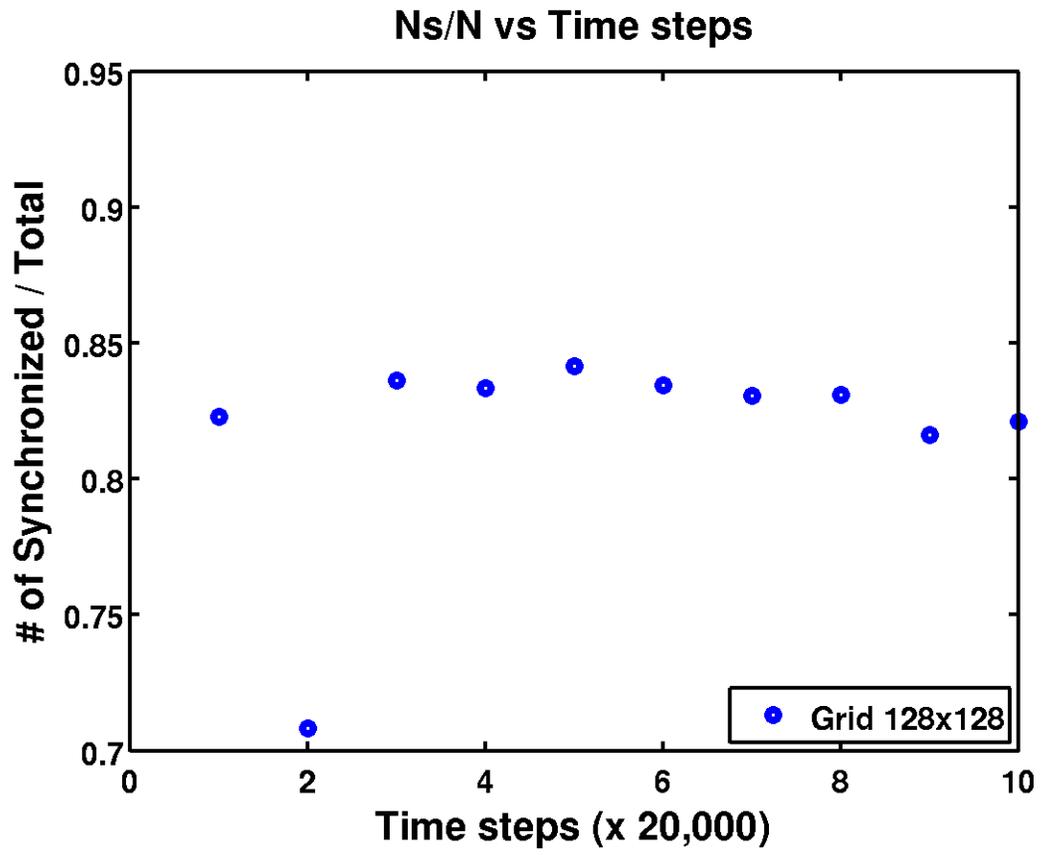


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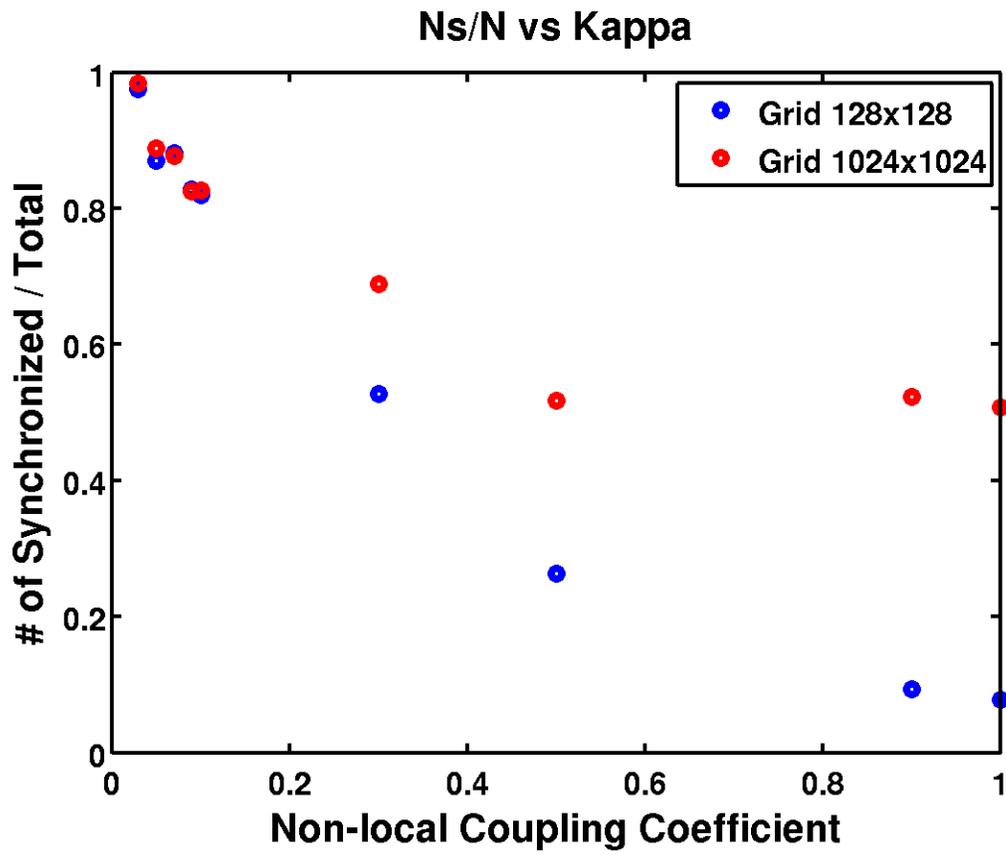
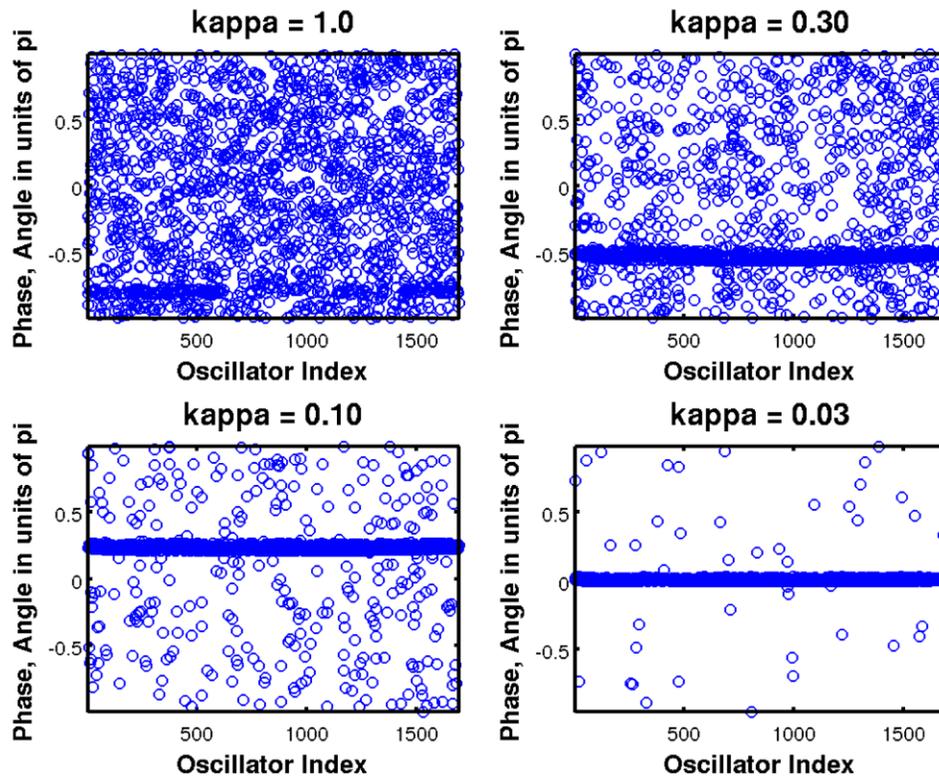
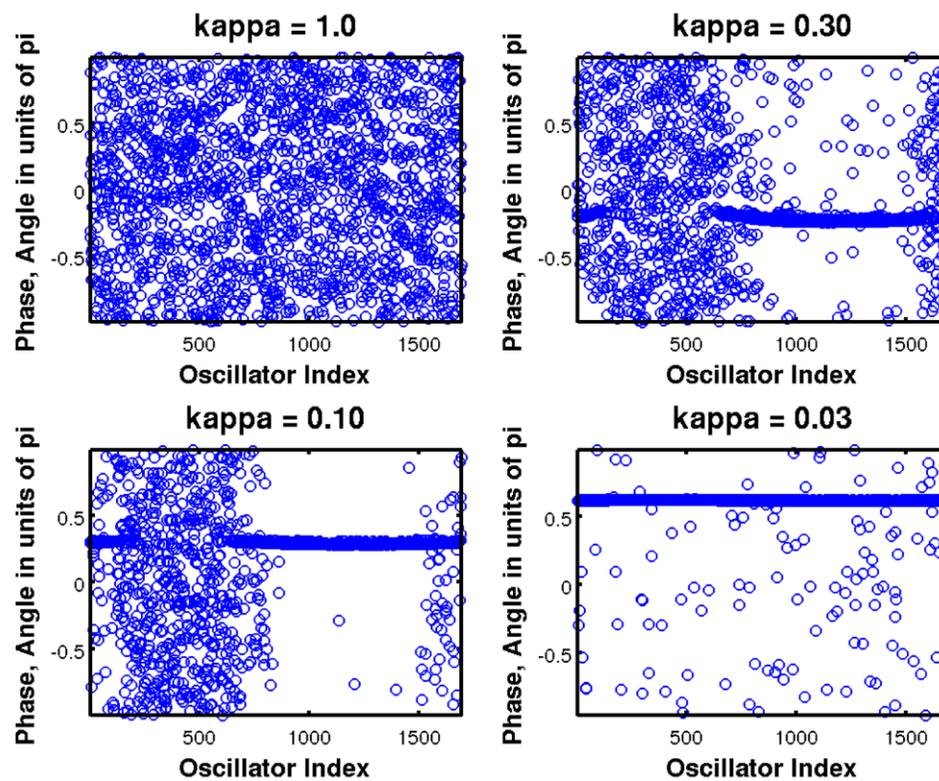


Figure 10.

(a)

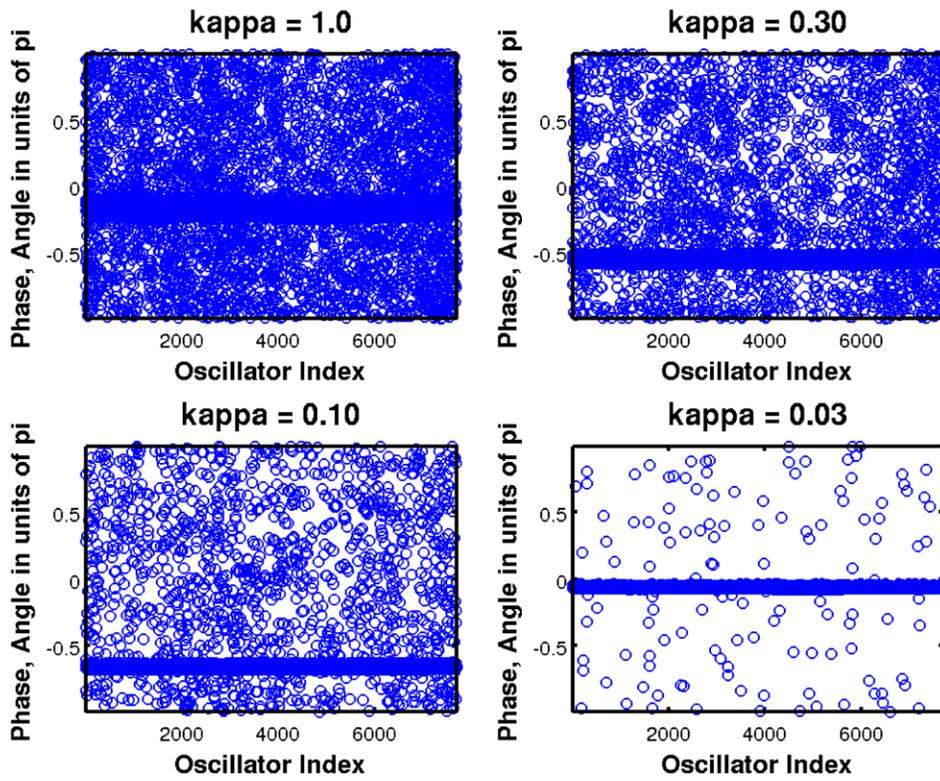


(b)



**Figure 11**

(a)



(b)

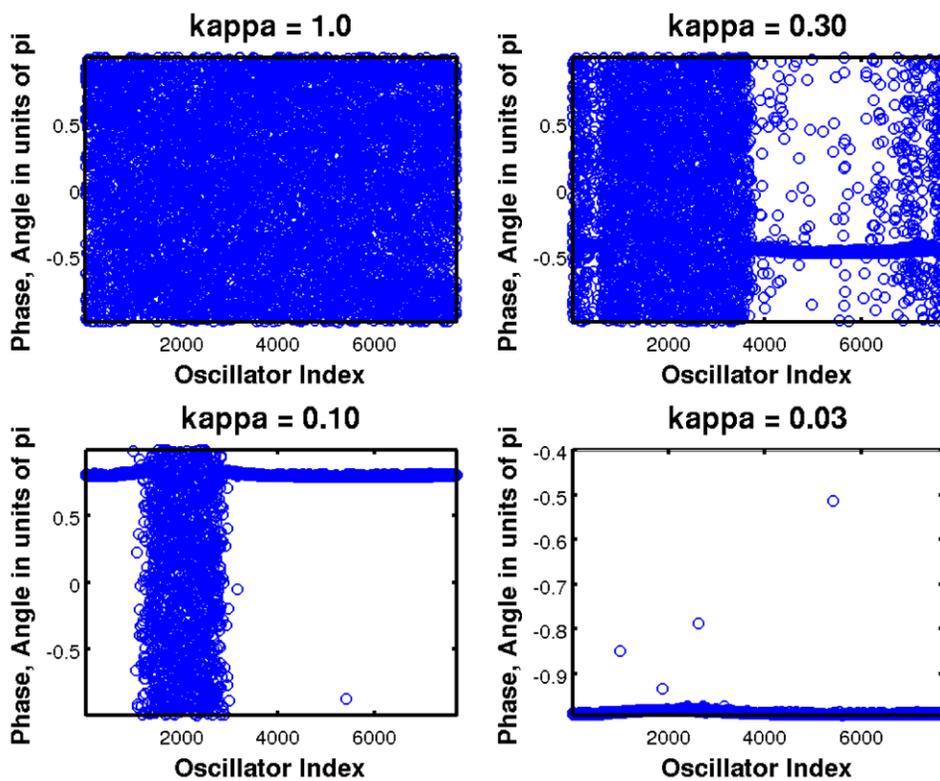


Figure 12.

