Logarithmic and Exponential Transients in GNSS Trajectory Models as Indicators
of Dominant Processes in Post-Seismic Deformation

THESIS

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Abstract

Simple or multiple timescale transient models for post-seismic transient displacements can be formulated using logarithmic and exponential decay formulas. The logarithmic form is associated with rate and state friction theory and afterslip, while the exponential form is associated with bulk viscoelastic relaxation of coseismic stresses. Many theorists have suggested that afterslip will be the dominant driver of post-seismic displacement transients in the months and perhaps even years following an earthquake, but viscoelastic relaxation will eventually dominate. It is now quite widely understood that one can model GPS/GNSS time series manifesting post-seismic transient displacements almost equally well using trajectory models constructed using logarithmic or exponential transients. This is consistent with the consensus established by the late 1970's that it is difficult to use geodetic observations to distinguish between deep aseismic afterslip and more diffuse viscoelastic relaxation as the primary mechanism of post-seismic deformation (Thatcher and Rundle, 1979). We assess the relative explanatory value of both logarithmic and exponential forms by focusing on GNSS time series measured with better than typical signal-to-noise ratios. We find that the double logarithmic transient typically provides much better fits than double exponential transient, when both models are given equal degrees of freedom. We will also discuss the relative utility of the hybrid transient formulas in which the logarithmic component is assigned shorter decay time scale parameters than the exponential component. These models fit observed post-seismic displacements almost as well as double logarithmic transients.

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Publications

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Table of Contents

Abstract	ii
Acknowledgments	iii
Vita	iv
Publications	iv
Fields of Study	iv
List of Tables	vii
List of Figures	viii
Chapter 1: Introduction	1
1.1 Motivation	1
1.2 Objectives	2
1.3 Background	3
Chapter 2: Theoretical framework	5
2.1 The seismic cycle	5
2.1.1 Inter-seismic phase	6
2.1.2 Co-seismic phase	7
2.1.3 Post-seismic phase	8
2.1.3.1 Poroelastic Rebound	8
2.1.3.2 Afterslip	9
2.1.3.3 Bulk Viscoelastic Relaxation	10
2.2 Geocentric Reference Frames	11
2.2.1 Inner Geometry, Outer Geometry and GNSS Time Series	12
2.2.2 Precise Point Positioning (PPP)	14
2.2.3 Noise in GNSS data	15
2.2.4 White noise and Flicker noise	16
2.3 GNSS Trajectory Models	18
2.3.1 Components of the Trajectory Models	19
2.3.1.1 Post-seismic Transients: Logarithmic, Exponential and Hybrid	22
Chapter 3: Synthetic analysis: Monte Carlo experiment for noisy data inversion	24

Chapter 4: GNSS network under study.....	30
4.1 Data preparation	32
4.1.1 ECEF to ENU	33
4.1.2 Time conversions	35
4.1.3 Data quality check	37
4.1.4 Jump table	38
Chapter 5: GLTM implementation	40
5.1 Robust Least Squares Fit:	42
5.2 Search for optimum non-linear parameters T_1 and T_2	44
Chapter 6: Results	48
6.1 Optimum T_1 and T_2 for post-seismic transients	48
6.2 Parameters of the Trajectory Model and Horizontal WRMS misfit.....	49
6.3 Empirical Cumulative Distribution Function	53
6.4 Co-seismic and accumulated post-seismic displacements	54
Chapter 7: Conclusions	56
References	58
Appendix A: List of station names and locations	61
Appendix B: Table of jumps	62
Appendix C: Results of Log+Log Model	68
Appendix D: Results of Log+Exp Model	71
Appendix E: Results of Exp+Exp Model	74

List of Tables

Table 1. Components of the Standard Linear Trajectory Model	23
Table 2. Components of the Generalized Linear Trajectory Model	23
Table 3. Summary of decay time-scales and Horizontal WRMS misfit.....	49

List of Figures

Figure 1. The seismic cycle in a strike-slip fault (Turcotte and Schubert, 2014)	6
Figure 2. White and Flicker Noise.....	17
Figure 3. Synthetic analysis results for different post-seismic timespans.	26
Figure 4. Percentage of best fits of log+log model, for different post-seismic measurement timespans, respect to noise levels. Pink noise introduced.	27
Figure 5. Percentage of correct best fits for log+log designed model. Pink noise.	28
Figure 6. Area of study and CGNSS stations used.	31
Figure 7. Reference Systems: ECEF and ENU (Navarro Tarin, 2014)	34
Figure 8. The PPP solution at the day of the earthquake is a mixture of the pre- and post- earthquake positions, therefore is artificial. We removed this measurement at every GNSS station.....	37
Figure 9. a) Example of down-weighted data (in red) with general penalty function. b) Down-weighted data after customizing penalty function.	43
Figure 10. Example of two-dimensional grid search for transient decay time-scales (WRMS in meters). Optimum combination of T_1 and T_2 marked with a white cross.....	46
Figure 11. Box plot that characterizes the variability of WRMSH over the network, for each class of transient model.	50
Figure 12. Example of fitted models zoomed to the first months after the earthquake	51
Figure 13. Histograms of Horizontal WRMS misfit results of 130 CGNSS stations.....	52
Figure 14. Empirical Cumulative Distribution Function for Horizontal WRMS misfit...	53

Figure 15. Co-seismic jump. Tohoku Earthquake. March 11 th , 2011.....	55
Figure 16. Post-seismic Cumulative Displacement up to March, 2018.....	55

Chapter 1: Introduction

1.1 Motivation

Our knowledge about the seismic cycle and the Earth's crust response to major seismic events has significantly improved in the past few decades. However, there are still some basic physical processes that we do not fully understand. One of them is the overall interaction between the viscous upper mantle and the much stiffer elastic lithosphere, in the aftermath of a major earthquake. The post-seismic displacements that we can now observe with continuous GPS and GNSS networks are thought to be driven by three main processes: poroelastic rebound, afterslip, and viscoelastic relaxation. Afterslip and/or viscoelastic relaxation are almost universally regarded as the most important of these mechanisms (Scholz, 2002).

Earthquakes arise from stick-slip frictional instabilities on faults (Brace and Byerlee, 1966; Scholz, 1998). Rate and State theories of friction, which are in large part based on laboratory measurements (Dieterich, 1979; Ruina, 1983; Marone, 1998; Nagata et al., 2012), suggest that after an earthquake, afterslip on adjacent parts of a fault should decay as a logarithmic function of the time elapsed since the main shock occurred (Scholz, 1998; Marone, 1998). This has proven to be consistent with direct measurements of postseismic displacement in the months following many major earthquakes (Smith and

Wyss, 1968; Bucknam et al., 1978; Williams and Magistrale, 1989; Marone et al., 1991; Freed, 2007). But most geomechanical models of the earthquake deformation cycle suggest after some period of time, typically asserted to be several months to several years after the earthquake, viscoelastic relaxation of coseismic stresses take over as the dominant driver of postseismic transient deformation (Nur and Mavko, 1974; Rundle and Jackson, 1977; Thatcher and Rundle, 1979; 1984; Freed et al., 2012; Wang et al., 2012; Sun and Wang, 2015). Viscoelastic transients tend to decay exponentially in time, rather than logarithmically (Haskell, 1935). As a result, if we believe that postseismic transient behavior is dominated by afterslip, we would expect to see these transients to decay logarithmically, whereas if afterslip is eventually superceded by viscoelastic relaxation, then we would expect logarithmic decay to give way, eventually, to exponential decay. Thus the way in which postseismic deformation decays as a function of the time that has elapsed since the earthquake has occurred, should provide us with insight into the physical mechanisms driving this process.

1.2 Objectives

In this work, we seek to determine which transient form better fits the displacement signal after a major seismic event. The logarithmic form is associated with rate and state friction theory and afterslip, while the exponential form is associated with bulk viscoelastic relaxation of coseismic stresses. Many theorists have suggested that afterslip will be the dominant driver of post-seismic displacement transients in the months and perhaps even years following an earthquake, but viscoelastic relaxation will eventually

dominate. We aim to determine if this is true for a large number of CGNSS stations with several years of data after a major event.

Therefore, the biggest purpose of this research is to find out whether one of the transient types is better than the other, as this could be considered an indicator of the predominant physical phenomenon driving the displacement.

1.3 Background

Crustal motion geodesy has flourished in the last decades due to the implementation of CGNSS Stations and GNSS campaigns all over the world. The new technology has allowed us to measure sub-millimeter displacements of the Earth's crust, and therefore, better understand the underlying processes that drive such motions.

Such techniques are useful to measure, describe and model the displacements that occur before, during and after an earthquake. For the specific case of the post-seismic movements, they can be modelled using logarithmic and exponential decay functions. However, recent tests carried out with longer datasets suggest that post-seismic displacements are better represented with double decay functions, rather than single ones. This is especially true for the post-seismic time series of the 2011 Tohoku-Oki earthquake (Tobita and Akashi 2015; Fig. 2).

Previous studies have focused on finding the optimum transient types, but unlike this work, they either used different approaches or focused on larger areas. Tobita (2016) used combinations of double and triple post-seismic transients ($\log+exp$), ($\log+\log+exp$) and ($\log+exp+exp$), in an attempt to improve the fitting performance of the models, and

paid special attention to finding unique relaxation times that adjust the data of a whole network. Unlike our work, their approach focused on fitting the data of a few stations very accurately, while we aim to pick the model that best fits a statistically large number of stations. Besides, we did not consider triple transients. Although sometimes they fit the data better than a double transient, they make the model significantly more unstable, as minor changes in the data alter the results disproportionately.

Other studies, such as Perfettini and Avouac (2004), successfully modelled post-seismic deformation considering the time evolution of afterslip and the aftershocks decay, not taking into account the viscous relaxation of the deep crust or upper mantle.

This vastly diverse bibliography shows that it is not perfectly clear how to address the issue of modelling post-seismic deformation.

Chapter 2: Theoretical framework

2.1 The seismic cycle

Earthquakes are associated with sudden displacements on faults in the lithosphere in what is called the co-seismic phase of the earthquake (Section 2.1.2), which can last a few seconds to several minutes. These displacements relieve shear stress that was accumulated due to tectonic motion, on a locked fault during the inter-seismic phase (the time between two consecutive seismic events) (Section 2.1.1). During the earthquake, the displacement on the fault takes place suddenly and generates seismic waves that propagate through the surrounding rock, and can be transmitted by the solid earth over large distances (Turcotte and Schubert, 2014). After the earthquake happens, post-seismic deformation initiates. This is caused by three main physical processes: poroelastic rebound, afterslip, and bulk viscoelastic relaxation. These phenomena can last for several years or even decades (Section 2.1.3), but eventually dissipate, and the inter-seismic phase begins once again.

Turcotte and Schubert (2014) describes this cycle in terms of stick-slip behavior (between earthquakes the fault remains locked) and elastic rebound (the accumulated shear strain is recovered by the plates). (See Figure 1).

Figure 1. The seismic cycle in a strike-slip fault (Turcotte and Schubert, 2014)

2.1.1 Inter-seismic phase

The Inter-seismic phase is the time between earthquakes, when stress accumulation occurs. Due to tectonic motion, the rocks on a locked fault begin to accumulate stress, in what is known as stick-slip behavior. The shear strain increases during periods of time that go from months to several decades or centuries, depending on the physical properties of the rocks, the geometry and dimensions of the locking and the relative motion in the fault. A fault remains locked until the stress builds up to a level that causes the fault to rupture and slip.

Elastic strain energy is accumulated during the inter-seismic phase of the cycle, and much of the energy is released during the co-seismic phase of the cycle (Figure 1b).

We can distinguish three types of faults (Turcotte and Schubert, 2014):

- Thrust faulting: it occurs when oceanic lithosphere (denser) is thrust under the adjacent continental or oceanic lithosphere at an ocean trench. This kind of faulting accommodates horizontal compressional strain. Most of the world's great earthquakes (such as Mw 9.1 Tohoku-Oki earthquake, Japan, 2011) are the result of thrust faulting due to the convergence of the two lithospheres.
- Normal faulting: it occurs on the flanks of ocean ridges where new lithosphere is being created, as well as in continental rift valleys where the lithosphere is being stretched. This means that Normal faulting accommodates horizontal extensional strain.
- Strike-slip faulting: it is a type of fault along which the displacement is strictly horizontal, as shown in the example of Figure 1.

Both normal and thrust faulting are called dip-slip faulting, because the displacements along the fault takes place on a dipping plane. In reality, the displacements on an actual fault are almost always a combination of dip-slip and strike-slip motion, but one component often dominates.

2.1.2 Co-seismic phase

When the stress on a fault reaches a critical value, the fault slips and generates an earthquake. The co-seismic displacement occurs in a few seconds so that the edges of the plates can be assumed to be stationary during this time. The accumulated shear strain is recovered by the plates in a process known as *elastic rebound*. The displacement on a fault during an earthquake generates seismic waves that propagate through the

surrounding rock. An important part of the elastic energy that had been stored goes into the seismic waves, and the other fraction is dissipated as heat by friction. The displacements on the fault could be of the order of some decimeters, or up to 30 meters, for the case of the largest earthquakes.

Even though the whole co-seismic phase takes place in a few seconds, the rupture generates different types of seismic waves that may take up to some minutes to completely dissipate.

2.1.3 Post-seismic phase

The effects on the rocks continue after an earthquake. Due to a series of physical processes, the fault and its surrounding areas present displacements with non-linear tendencies (negative acceleration) for a period of time that could go up to several years after the event.

The physical phenomena that is widely thought to be driving the post-seismic deformation are: poroelastic rebound, afterslip and bulk viscoelastic relaxation (Bevis and Brown, 2014). These three processes are explained in further detail in the following sections.

2.1.3.1 Poroelastic Rebound

During an earthquake, the volume of rocks adjacent to the fault undergoes compression or stretching. The strain results in small volume changes and generates pore fluid pressure gradients in the shallow crust. After the earthquake, fluid flows allow pore

pressure gradients to dissipate, eventually reaching a drained condition. This pore fluid flow causes deformation (Peltzer et al. 1998).

Usually, poroelastic rebound is not a strong contributor to post-seismic deformation. Besides, it greatly differs from the two other mechanisms, as it is relatively short-lived (often being unresolvable after a few weeks).

2.1.3.2 Afterslip

Afterslip is a type of aseismic slip, that occurs on a fault or plate boundary in the months or years after an earthquake. It is generally measured by direct observations or inferred from geodetic measurements (Crook et al. 1982). Usually, afterslip is differentiated from large-scale post-seismic relaxation of crustal strain arising from viscoelastic interaction with the lower crust and uppermost viscoelastic asthenosphere (see Section 2.1.3.3), as afterslip is considered to involve shorter time scales, with half of its first year's effect happening in the first fortnight (Marone, 1998).

Afterslip commonly involves a rapid initial rate of slip and a logarithmic decay in slip rate toward the long-term interseismic rate. It can present a great variety of magnitudes, but in some cases, it can be equal or even larger than the coseismic fault slip (e.g Heki et al 1997).

Of the three post-seismic mechanisms that drive deformation, this is usually the easiest to model, using a simple mathematical formula. It is known to generate transient displacements that can be approximated quite accurately with logarithmic decay formula, with the form:

$$d = A \log \left(1 + \frac{\Delta t}{T} \right)$$

Where, A is the amplitude of the transient, T the relaxation time, and Δt is the time since the earthquake occurred.

2.1.3.3 Bulk Viscoelastic Relaxation

The asthenosphere behaves as a linear viscoelastic solid at time periods of a few years, so after an earthquake, the stress released that is redistributed in the lithosphere causes flow in the asthenosphere with corresponding time-dependent surface deformation (Nur and Mavko, 1974). The effect of viscoelastic relaxation lasts for several years and may affect a wide region.

The displacements are observed by CGNSS stations, and are typically modelled using complicated numerical methods, such as finite element models (e.g Wahr and Wyss, 1980) due to the lack of a closed-form analytical expression for the transient generated. Nevertheless, it is also possible to approximate the displacements with an exponential decay function:

$$d = A \left(1 - e^{-\left(\frac{\Delta t}{T}\right)} \right)$$

Where, analogously to the afterslip logarithmic decay function, A is the amplitude of the transient, T is the relaxation time, and Δt is the period of time since the earthquake occurred.

2.2 Geocentric Reference Frames

In science and engineering, the most common definition of a reference system describes it as a set of conventions and parameters needed to define a Coordinate System in terms of orientations, scale and origin with the purpose of assigning coordinates to points respect to the Cartesian axis system (Torge, 2001). However, it is also valid to say the reverse: assigning coordinates to points defines the axes of the coordinate system. This is precisely the procedure carried out in Space Geodesy, mainly because in the real world, the set of axes of a geocentric reference system is inaccessible.

The points that belong to the reference system, whose coordinates -and eventually velocities- we know, and to which we have access, materialize such system in what we call a Reference Frame (RF). This realization of points on the Earth surface is performed using various techniques: GPS/GNSS, VLBI, SLR, LLR, Doppler (Doris).

Many countries and international organizations develop their own reference frames, but all of them are geocentric, and in accordance with the guidelines from the International Earth Rotation and Reference System Service (IERS), the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG).

IERS is responsible for defining and maintaining the International Reference System (IRS) which is realized through the International Terrestrial Reference Frame (ITRF) at a specific epoch. For instance, the current IERS frame is ITRF2014, which is the materialization of ITRS on January 1st, 2010 (epoch 2010.0), and it encompasses data up to the year 2014.

This presents a problem, since the whole Earth system is not static and the points on the Earth surface are in constant movement, including the points which had previously been used to define the reference frame. To address this issue, we need to introduce the concept of Reference Frame Model: “a model that predicts the coordinates for a global set of GNSS stations, allowing us to use these stations to invoke or realize a particular and named axis system” (Bevis and Brown, 2014).

A RF Model is a Network Trajectory Model, consisting of individual Station Trajectory Models for each station involved in the definition of the RF. They are, essentially, models that characterize the position of geodetic stations as a function of time. These models are particularly useful because they allow us to describe in three dimensions the displacements of the stations on the Earth surface, but more importantly, to *predict* their future positions, which is the true value of a RF model.

2.2.1 Inner Geometry, Outer Geometry and GNSS Time Series

A position solution for a GNSS network is the result of a process that involves gathering data from GNSS receivers around the world, computing GNSS orbits and clocks, resolving phase ambiguities, removing outliers, searching for breaks, applying transformation parameters, and finally coming up with a daily solution. This process is done for every epoch, so the geometric configuration of the network defines a global polyhedron for each day, which is very similar to the polyhedron from the day before, but not exactly the same, turning the alignment of consecutive polyhedra into a quite complex task. In order to address it, we first need to define some concepts.

The geometrical properties of the network (polyhedron) can be described in terms of the distances between the vertices (stations), but the terminology to refer to such properties is not homogeneous throughout the literature. So, we choose to use the terminology adopted by Bevis and Brown (2014) in order to describe two basic and fundamental concepts: *Inner and Outer Geometry*.

- Inner Geometry is the geometry that can be defined exclusively in terms of the lengths between points (vertices of the polyhedron). It is basically the size and shape of the polyhedron, and it depends only on the metric or scale associated with the measurements. Therefore, the inner geometry is invariant under rotation and translation of the RF, and this is why it is thought to be the more fundamental description of the polyhedron's geometry.
- Outer Geometry: it implies the inner geometry, but it also describes the position and orientation of the polyhedron, respect to an external reference frame (Cartesian axes system). The outer geometry is defined by assigning the coordinates (X, Y, Z) to each station. Thus, the outer geometry depends on the particular choice of axis system.

GNSS Geodesy is a differential positioning technique, so it can determine the inner geometry of every polyhedron much more accurately than their outer geometry. This is when the RF models (Section 2.2) become relevant. RF models can be used to predict the position of the stations and align the polyhedron with the predicted coordinates from the previous epoch. The “target” frame is defined by the RF model based only on a subset of stations, but after the alignment all of the stations of the polyhedron will have their

coordinates determined, since the inner geometry is strongly constrained by the GNSS measurements. The “evolution” of the polyhedra through time is what we call “GNSS Time Series”.

GNSS Time Series are essentially daily GNSS position estimates, presented in a Time vs. Position plot, that shows the movements of a CGNSS station over a period of time. They are expressed either in local coordinates (East, North, Up), where the displacements are respect to the position at the first epoch, or in geocentric Cartesian coordinates respect to the X, Y, Z axes in the Earth-Centered Earth-Fixed system.

2.2.2 Precise Point Positioning (PPP)

PPP is a positioning technique that was developed to overcome the disadvantages of traditional differential techniques. It removes or models the errors in the GNSS system in order to obtain the position with high accuracy, using the data from an individual double-frequency receiver. It uses accurate ephemeris and clock corrections, which are provided by IGS. Moreover, PPP incorporates troposphere models in order to account for the tropospheric path delay for each satellite, receiver and satellite antenna phase-center corrections, as well as solid-earth tide effects and ocean tide loading corrections.

The main advantage of PPP technique is the possibility of obtaining the position of a single receiver with sub-centimeter accuracy, with a relatively quick procedure.

NGL publishes daily PPP solutions for their global network of CGNSS stations, and they are the coordinates that we use in this work.

2.2.3 Noise in GNSS data

There are several sources of noise that affect GNSS data. Some of them are related to the way in which GNSS measures the distances from the receivers to the satellites, and calculates coordinates. A number of indirect measurements and physical properties are necessary in order to obtain a final position value. For instance, the measurement of time, receivers and antennas characteristics, satellite's orbits, geometry of the satellites' positions, multipath effects, etc. Besides, there are other sources of error, which are related to natural phenomena that might affect the measurements, such as: Total Electron Content (TEC) in the atmosphere, tropospheric and ionospheric conditions, stability of the monuments, etc.

It is known that errors in GNSS measurements do not present a normal distribution, and also show some level of correlation. Mao et al. (1999) performed a spectral analysis and Maximum Likelihood Estimation on the noise in time series from GPS stations, and showed that a combination of white noise and flicker noise (see Section 2.2.4) appears to be a good model for the noise characteristics of all three East, North and Up components. Moreover, they concluded that both white and flicker noise amplitudes are largest in the vertical component. This distinction between Horizontal and Vertical coordinates will become relevant for our research, as we need data with the best signal to noise ratio possible.

2.2.4 White noise and Flicker noise

Noise is a random signal, which means that it is produced by a stochastic process. However, it can present statistical characteristics and properties. One of them is the Power Spectral Density (PSD), which refers to its power and distribution in the frequency spectrum, and it is expressed in decibels (dB). Depending on the PSD, we can distinguish several types or “colors” for the noise. Such classification in terms of spectral density is analogous to the classification of the visible spectrum in groups (colors) depending on the wavelengths.

Therefore, a noise that contains a uniform distribution in the frequency spectrum would be white, in the same way that the white color contains all of the frequencies of the visible spectrum.

The relation between the PSD and the frequency is given by

$$PSD = P_0 \frac{1}{f^\alpha}$$

Where α is the spectral index, f is the frequency and P_0 is a constant. Larger values of α indicate a more correlated process and more relative power at lower frequencies (Mao et al. 1999).

White noise contains all of the frequencies, and all of them present the same PSD. This means that the power in any band of a given bandwidth is constant (see figure 2) and therefore, the signal is not band-limited. The spectral index of white noise is 0 (zero).

A noise signal whose spectrum is not flat is considered to be “colored” or self-correlated. In this case, the PSD is not the same for all frequencies.

There are different types of colored noise. We are especially interested in pink noise (also called “flicker” noise) because it is present in the GNSS signal (Mao et al. 1999).

The spectral index of pink noise is 1. So, its PSD is proportional to $\frac{1}{f}$. Figure 2 shows how the power of pink noise decreases for higher frequencies (notice that the frequencies are presented in a logarithmic scale in the x-axis).

$\frac{1}{f}$ noise is of interest because it occurs in various systems, both in the natural world and in man-made processes.

Figure 2. White and Flicker Noise

Up to this point, we have presented the spectral characteristics of white and flicker noise, but it is important to see how these types of noise behave in time, as this is how they appear in GNSS data. In Figure 2 we can see the temporal distribution of both kinds of noise. White noise is uncorrelated in time, which means that each value is independent from the previous and the following one.

Pink noise, however, is self-correlated. The distribution of the observation values in time presents some kind of dependence. This causes that the signal is not completely random, and therefore, it is necessary to have some consideration while performing statistical analysis on it, otherwise we could reach erroneous results.

2.3 GNSS Trajectory Models

Trajectory models are mathematical models used by geodesists and geophysicists to characterize the position of geodetic stations as a function of time (Bevis and Brown, 2014).

These models consist in a combination of functions that tend to reproduce the spatial displacements of CGNSS stations, and predict their future behavior. They are purely kinematic as they do not take into account the dynamical processes that drive the movements, even though they can be used as a tool to infer the dynamical behavior of the solid Earth.

From a geodesy perspective, the main advantage of having better and improved trajectory models is that a more precise and consistent prediction ability leads to a more consistent and stable reference frame.

On the other hand, for geophysicists studying station trajectories is a source of information that complements other measurement techniques, in order to understand and describe physical processes which take place inside the Earth.

2.3.1 Components of the Trajectory Models

Trajectory models need to account for every type of phenomenon that the CGNSS stations might be affected by, both natural and artificial ones. Regardless of the nature of the phenomenon, we aim to reproduce the effect on the time series as faithfully as possible, and in doing so, improve the prediction ability of the model.

We can identify five different kinds of displacements in CGNSS time series:

- 1- Steady motion: constant velocity characteristic of the interseismic phase.
- 2- Jumps: sudden offsets that can be natural, due to a seismic event (co-seismic phase), or artificial, due to a change in the hardware (antenna, radome or receiver).
- 3- Cycles: annual and semi-annual oscillations on the ground, as Earth's elastic response to seasonal changes in the loads upon the lithosphere, such as surface water, snow and ice.
- 4- Accelerating displacement trends: observed near or within active ice sheets, as well as near active volcanoes.
- 5- Acceleration that decays in time: logarithmic or exponential transients during the post-seismic phase.

Until recently, the most common trajectory models used by the scientific community were the Constant Velocity Models in which the coordinates for each geodetic station were expressed as a linear function of time.

The so called “modern” trajectory models include the rest of the effects and they are described in detail by Bevis and Brown (2014). Here we present a brief summary of them:

Steady motions are modelled with a linear function:

$$\vec{x} = \vec{x}_R + \vec{v}(t - t_R)$$

where t is the time of each epoch, t_R is a reference time (adopted by convention), $\vec{x}$ is the vector of geocentric coordinates $[x,y,z]$, $\vec{x}_R$ is the position at the reference time $[x_R, y_R, z_R]$, and $\vec{v}$ is the velocity vector in the three directions.

Jumps are accounted for using a Heaviside function, sometimes referred to as the “unit step” function:

$$H(t) = 0 \text{ for } t < 0$$

$$H(t) = 1/2 \text{ for } t = 0$$

$$H(t) = 1 \text{ for } t > 0$$

It is possible, and quite likely, that the time series of a CGNSS station present more than one jump, so several Heaviside functions are introduced as a summation:

$$jumps = \sum_{j=1}^{n_j} b_j H(t - t_j)$$

where n_j is the number of jumps, b_j characterizes the j^{th} jump and t_j is the time at which the jump happened.

Cycles can be approximated by a four-term Fourier series, consisting of two annual and two semi-annual terms (Dong et al. 2002)

$$cycle = \sum_{k=1}^{n_F} [s_k \sin(\omega_k t) + c_k \cos(\omega_k t)]$$

where n_F corresponds to the number of frequencies used to model the annual displacement cycle,

$$\omega_k = 2\pi/\tau_k$$

$$\tau_1 = 1 \text{ year}$$

$$\tau_2 = 1/2 \text{ year}$$

$$\tau_3 = 1/3 \text{ year}$$

and so on.

Accelerating displacement trends can be accounted for with a polynomial trend model:

$$accelerated \text{ trend} = \sum_{i=1}^{n_p+1} p_i (t - t_R)^{i-1}$$

n_p is the order of maximum power of the polynomial. Notice that if $n_p = 1$, then the trend is linear, with $p_1 = x_R$ and $p_2 = v$. However, according to Bevis and Brown (2014), for a very large majority of CGPS stations, it is perfectly adequate to set $n_p = 1$.

Up to this point, we have defined the Standard Linear Trajectory Model (SLTM), summarized in Table 1.

$$x_{sltm}(t) = x_{trend}(t) + x_{jump}(t) + x_{oscil}(t)$$

The number of parameters and coefficients for each Cartesian coordinate X, Y and Z, involves a total of $(2 n_F + n_J + n_P + 1)$.

Finally, the effect of “Acceleration that decays in time” is described in detail in the following section, since it is the most important for this work.

2.3.1.1 Post-seismic Transients: Logarithmic, Exponential and Hybrid

In Section 2.1 we explained that post-seismic deformation can be accommodated using logarithmic or exponential decay formulas independently. But we can also combine them, in order to better model the signal. In this work, we use double timescale transients, based on the combination of logarithmic and exponential functions. The first transient accounts for the displacements in the first days after the co-seismic shock, while the second transient accommodates the movements of the following months and years.

We consider 3 possible two-timescale or “double” transient forms:

$$\text{"log + log" transient} = \sum_{i=1}^2 \mathbf{a}_i \log \left(1 + \frac{\Delta t_i}{T_i} \right)$$

$$\text{"exp + exp" transient} = \sum_{i=1}^2 \mathbf{a}_i \left(1 - e^{\left(-\frac{\Delta t}{T_i} \right)} \right)$$

$$\text{"log + exp" transient} = \mathbf{a}_1 \log \left(1 + \frac{\Delta t_i}{T_i} \right) + \mathbf{a}_2 \left(1 - e^{\left(-\frac{\Delta t}{T_i} \right)} \right)$$

where $\mathbf{a}_i$ is the amplitude of the transient with time scale T_i , and Δt is the time since the earthquake occurred. By convention, $T_1 < T_2$.

This augmentation of the SLTM model yields what we will call Generalized Linear Trajectory Model (GLTM), which is composed by the terms presented in Table 2.

Table 1. Components of the Standard Linear Trajectory Model

SLTM =	Trend	+ Jumps	+ Cycles
$x(t)_{SLTM} =$	$\sum_{i=1}^{n_p+1} \mathbf{p}_i (t - t_R)^{i-1}$	$+ \sum_{j=1}^{n_j} \mathbf{b}_j H(t - t_j)$	$+ \sum_{k=1}^{n_F} [\mathbf{s}_k \sin(\omega_k t) + \mathbf{c}_k \cos(\omega_k t)]$

Table 2. Components of the Generalized Linear Trajectory Model

GLTM =	SLTM	+ Post-seismic Transients
$x(t)_{GLTM} =$	$x(t)_{SLTM}$	$+ \sum_{i=1}^2 \mathbf{a}_i \log \left(1 + \frac{\Delta t_i}{T_i} \right)$
		$+ \sum_{i=1}^2 \mathbf{a}_i \left(1 - e^{\left(-\frac{\Delta t_i}{T_i} \right)} \right)$
		$+ \mathbf{a}_1 \log \left(1 + \frac{\Delta t_i}{T_i} \right) + \mathbf{a}_2 \left(1 - e^{\left(-\frac{\Delta t_i}{T_i} \right)} \right)$

It is important to say that not all stations need a GLTM, since many of them are not located in seismically active areas. This is the case of most Australian stations, for example, where the time series present an essentially linear trend for several years or decades. However, in this work we analyze only stations located in seismic areas, and strongly affected by a major earthquake, so we need to apply the extended model to all of them.

Chapter 3: Synthetic analysis: Monte Carlo experiment for noisy data inversion

One of the biggest problems that we encounter while modelling a signal is its intrinsic noise, which is added up to the errors due to the measurement technique used to gather the data. This is a particularly important issue while dealing with GNSS signals, because, apart from the mentioned effects, the direct measurements undergo a post-process that involves the application of ionospheric and tropospheric models, satellite orbit coordinates, reference frame definitions, inner geometry alignments (stacking), etc. All of this extra processing introduces new sources of noise in the data that are difficult to model.

So, the data that we measure is composed by two parts:

$$\mathbf{DATA} = \mathbf{SIGNAL} + \mathbf{NOISE}$$

Furthermore, once we apply a specific model that adjusts the data, we obtain residuals, which are defined as the difference between the model and the data points at each measurement epoch:

$$\mathbf{DATA} = \mathbf{MODEL} + \mathbf{RESIDUAL}$$

Now, we could be tempted to say that $Model \leftrightarrow Signal$ and $Residuals \leftrightarrow Noise$, but these equivalencies only hold if the model is the correct one.

The noise affects our ability to choose the correct model to reproduce or predict the signal, and if we use the wrong model, then we are incurring in a different type of error: the Model Specification Error (MSE).

$$\mathbf{RESIDUALS} = \mathbf{NOISE} + \mathbf{MSE}$$

In the case of picking the correct model, we can see that the residuals will entirely be due to the noise in the data. If we want to pick the best model with the minimum WRMS misfit, we should try to use data with the minimum amount of noise possible.

In our case, the “model options” are three: GLTM with a log+log transient, GLTM with a exp+exp transient, and GLTM with a log+exp transient.

So, how does the level of random noise affect our ability to correctly identify the transient type?

To find out, we performed a synthetic analysis that simulates a GNSS time series affected by different levels of noise.

We carried out a Monte Carlo experiment (computational algorithms that rely on random sampling to obtain numerical results), generating a time series with a pure log+log transient, adding noise, and then inverting this simulated dataset assuming log+log, exp+exp and log+exp forms. We did this repeatedly so as to determine what fraction of the time the best-fitting transient form is the ‘correct’ one, for each noise level.

In our first attempt to perform the Monte Carlo experiment, we only introduced white noise, but the results that we obtained were not consistent with the empirical experience for typical noise levels in GNSS data. That lead us to think of considering pink noise (see Section 2.2.4), which made our results more realistic. Some authors, such as Mao et al.

(1999), suggest that GNSS data presents a combination of white and flicker noise, in percentages that vary depending on the study.

Figure 3. Synthetic analysis results for different post-seismic timespans. Log+log Transient model. Pink noise introduced. Model parameters: $A1 = -0.1\text{mm}$, $A2 = -0.5\text{mm}$, $T1 = 0.02\text{ yr}$, $T2 = 2\text{ yr}$

We decided to introduce pure flicker noise, since the ratio of flicker noise to white noise varies from station to station, and may be affected by the way in which the data is

processed. The data processing protocols used at The Ohio State University produce time series in which the percentage of flicker noise varies between 50% and 100%.

We considered 10 levels of noise ($1\text{mm} < \sigma_{\text{noise}} < 10\text{mm}$), and performed 500 trials per noise level, fitting each dataset with all three transient models, and for each trial we identified the model that provided the smallest WRMS misfit. As we can see in Figure 3, when there is zero noise, the log+log model is the best fit, as expected, 100% of the times. But as the data gets noisier, an ‘incorrect’ transient form can better fit the observations than the form actually used to generate the data, leading to a point at which the amount of noise makes it almost impossible to pick an optimum model.

Figure 4. Percentage of best fits of log+log model, for different post-seismic measurement timespans, respect to noise levels. Pink noise introduced. Model parameters: $A_1 = -0.1\text{mm}$, $A_2 = -0.5\text{mm}$, $T_1 = 0.02\text{ yr}$, $T_2 = 2\text{ yr}$.

Our ability to resolve which transient type was used to generate the data not only depends on the level of noise, but also on the number of observations available after the seismic event. Logically, longer time series make it easier to adjust a model correctly. Figure 4 compares the percentage of trials that the correct transient form was chosen, for datasets with different post-seismic timespans.

Figure 5. Percentage of correct best fits for log+log designed model. Pink noise.
Model parameters: $A_1 = -0.1\text{mm}$, $A_2 = -0.5\text{mm}$, $T_1 = 0.02\text{ yr}$, $T_2 = 2\text{ yr}$.

The relation between the post-seismic timespan, the level of noise and the model performance for our synthetic analysis is summarized in Figure 5. It shows that with 3 years of post-seismic data and a typical noise level of 4 mm we will pick the correct model 65% of the times. This indicates that even with high quality data the chances of

choosing the wrong model are considerable.

The noise level for the vertical coordinate is typically higher (4-7 mm). According to the synthetic analysis for that level of noise, we will pick the correct model less than 65% of the time. Besides, the vertical signal is weaker, which yields a lower signal-to-noise ratio (SNR), whereas the post-seismic signal is much stronger for the East and North coordinates and, as previously mentioned, they present lower noise levels.

We realized that if we wanted to correctly identify which of the three possible transient forms is occurring in nature, we needed to avoid data with low SNR. Therefore, we decided to work only with the horizontal components of displacement, and ignore the vertical coordinate.

Chapter 4: GNSS network under study

Originally, we meant to study the displacements after several mega-earthquakes around the world. Unfortunately, not many countries or regions count with a CGNSS network that is dense or old enough to perform detailed analysis to clearly distinguish between transient forms.

The Geospatial Information Authority of Japan (GSI) (known before 2010 as the Geographical Survey Institute), operates the GNSS Earth Observation Network System (GEONET). It consists of around 1300 CGNSS stations distributed all over Japan, with time series longer than 6 years in most cases.

We therefore decided to study only one major earthquake, located near Japan. Thus, this work focuses on the time series of CGNSS stations affected by the Mw 9.1 Tohoku-Oki earthquake, that occurred on March 11th, 2011 at 05:46:24 UTC near the east coast of Honshu, Japan (38.297°N, 142.373°E).

Figure 6. Area of study and CGNSS stations used.

The transients produced by this Mw 9.1 earthquake were recorded by the many hundreds of CGNSS stations comprising GEONET. We focused on the region with maximum co-seismic and post-seismic displacements, and minimum effects of aftershocks, such as the Mw 7.9 earthquake that occurred further south (36.281°N , 141.111°E), 30 minutes later that day (March 11th, 2011 at 06:15:40 UTC).

The area of study is delimited by latitudes 37°N ; 41°N , and longitudes 138°E ; 143°E . (Figure 6), comprising a total of 130 stations (See Appendix A). As explained in Chapter 3, because of the high level of scatter in the vertical component (e.g. Fig. 8), we analyze only the horizontal coordinates (East and North).

4.1 Data preparation

The Nevada Geodetic Laboratory (NGL) publishes a daily PPP solution for their global network of stations, that includes GEONET. Time series data are in Ascii text format and can be downloaded for free from the website of NGL (<http://geodesy.unr.edu/NGLStationPages/GlobalStationList>) or using their FTP server. NGL offers three types of solutions:

- 24-hour final solution
- 24-hour rapid solution
- Rapid 5-minute solution

We use the 24-hour final solution, which is given in IGS08 reference frame. IGS08 is a global Earth-centered Earth-fixed reference frame, it is a GPS-only realization of the International Terrestrial Reference Frame 2008 (ITRF 2008) (Altamimi et al. 2011) and its coordinates are aligned to the center of mass of the Earth.

Even though NGL provides both geocentric coordinates (X, Y, Z) and local topocentric coordinates (East, North, Up), we chose to get the XYZ solution and perform the transformation into ENU ourselves.

4.1.1 ECEF to ENU

Geocentric coordinates are expressed in a right-handed Cartesian system which is Earth-centered Earth-fixed (ECEF). Its origin is the center of mass of the Earth, while its z-axis and the mean rotational axis of the Earth coincide, the x-axis points to the mean Greenwich meridian, and the y-axis is directed to complete a right-handed system (Xu and Xu, 2016).

The coordinates X , Y and Z , are the distances to the three axes, but these values do not tell us much about the position of a point respect to the Earth surface. If the goal is to determine the trajectory of a point that is moving on the Earth surface (CGNSS station), the ideal expression would be in Local Geodesic Coordinates (ENU).

ENU coordinates have their origin at the very point where the CGNSS station started measuring, at $t = 0$. According to Navarro Tarin (2014), the Cartesian axes of the ENU system are defined as (Figure 7):

- U-axis: direction of the normal to the ellipsoid at the station point, positive towards the exterior of the ellipsoid.
- N-axis: direction that results from the intersection of the plane perpendicular to the U-axis with the plane that contains the ellipsoid rotation axis and the U-axis, positive towards the geodesic North.
- E-axis: orthogonal to the previous axes and positive clockwise.

Figure 7. Reference Systems: ECEF and ENU (Navarro Tarin, 2014)

In order to transform ECEF coordinates into ENU, we must perform two rotations: one of them along the Z-axis, a magnitude equal to the longitude value, so as to align X and Y axes in both systems. The rotation matrix is:

$$R(\lambda)_x = \begin{pmatrix} \cos \lambda & \sin \lambda & 0 \\ -\sin \lambda & \cos \lambda & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where,

λ = geographic longitude

φ = geographic latitude

The second rotation is along the Y-axis a magnitude of $(90^\circ - \varphi)$:

$$R(\varphi)_y = \begin{pmatrix} \sin \varphi & 0 & -\cos \varphi \\ 0 & 1 & 0 \\ \cos \varphi & 0 & \sin \varphi \end{pmatrix}$$

These two rotations align both systems, but one last rotation of 90° along the Z-axis is necessary, so the X-axis has the same sense as the N-axis:

$$R\left(\frac{-\pi}{2}\right)_z = \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Finally, the formula for the transformation expressed in matrix notation is:

$$\begin{pmatrix} E \\ N \\ U \end{pmatrix} = R\left(\frac{-\pi}{2}\right)_z R(\varphi)_y R(\lambda)_x \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{ECEF}$$

$$\begin{pmatrix} E \\ N \\ U \end{pmatrix} = \begin{pmatrix} -\sin \lambda & \cos \lambda & 0 \\ -\sin \varphi \cos \lambda & -\sin \varphi \sin \lambda & \cos \varphi \\ \cos \varphi \cos \lambda & \cos \varphi \sin \lambda & \sin \varphi \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{ECEF}$$

$$\begin{pmatrix} E \\ N \\ U \end{pmatrix} = R_{ECEF}^{ENU} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{ECEF}$$

We implemented this transformation through a Matlab function that we called *xyz2enu.m* where we provide a mean position, which can be the latitude and longitude of the station or a mean value for the XYZ coordinates, and the vectors of X, Y and Z measurements.

4.1.2 Time conversions

It is important to pay attention to the time format of the GNSS data while processing it. It needs to be consistent with the time format of the jumps that are introduced in the trajectory model to account for earthquakes, antenna and receiver changes. This is not a

minor detail, because the jumps happen at precise times and if they are expressed in a different time system from the GNSS data, then the trajectory model will be incorrect. Even though we encourage users to perform a visual quality check of the model (so as to identify incorrectly placed jumps, for instance), this becomes more difficult when dealing with thousands of stations, so it is always better to double check the time units in advance.

In order to express time as a numeric continuum, it is common in GNSS studies to use real numbers, where the integer part is the year, and the decimal part corresponds to the fraction of year elapsed (days).

In this work, the time unit that we use is the Julian Year (Jyear), defined as 365.25 days of 86400 SI seconds each. (NOTE: NGL data is already expressed in Julian Years). This is the type preferred by IGS and IERS. We developed a Matlab script named *date2jyear.m* that converts dates (year, month, day, hours, minutes, seconds) into Julian Year, in order to introduce jumps into the trajectory model.

It is important to note that some institutions have traditionally used another type of Decimal Year or Float Year “Fyear”, which begins on January 1st, but it has 365 days on non-leap years, and 366 days on leap years. This type is favored mainly by the community who develops GAMIT/GLOBK at the Massachusetts Institute of Technology. Once again, either time type is valid to use, as long as it is consistent along the whole process.

4.1.3 Data quality check

One of the first activities consisted in the evaluation of the quality of the data, detecting outliers, odd values or missing measurements.

In general, most of the stations presented complete time series, without relevant gaps or significant outliers. Nevertheless, we did detect some strange values in some of the stations right after the Tohoku earthquake time, as shown in Figure 8.

Figure 8. The PPP solution at the day of the earthquake is a mixture of the pre- and post-earthquake positions, therefore is artificial. We removed this measurement at every GNSS station.

These odd data points result from the average of pre and post-earthquake time positions, which yields a mean value that is not representative of the actual trajectory, so we removed them from the time series of all stations. It significantly improved the fitting performance of the models.

Outliers were down-weighted, as described in Section 5.1

4.1.4 Jump table

Jumps are sudden offsets in the measurements that can be natural or artificial (see Section 2.3.1). Regardless of their origin, they must be taken into account, otherwise they introduce distortions that affect the rest of the parameters of the trajectory model.

NGL provides a table with most of the jumps present in the time series that they publish. It includes earthquakes that occurred near the stations, as well as antenna and receiver changes. However, we have found that some obvious jumps –probably due to hardware changes- are not reported in the table, while some earthquake jumps are attributed to stations that in fact, were not affected by them. Both scenarios damage the fitting performance of a model. Introducing a jump that is not real, might be contributing to model noise present in the data. At the same time, not introducing a clear jump, forces the model to compensate the offset at the expense of the rest of the parameters in order to reduce the residuals.

For all these reasons, we created a new jump table contrasting the information from the NGL table with the jumps that are actually present in the data and that we can observe. It required to go through all of the stations, one by one, in order to visually detect the

jumps. This process takes time, but it ensures that the resulting jump table is accurate and reflects the reality, ultimately improving the quality of the trajectory model.

Even though jumps can also be detected using relatively simple algorithms, we strongly believe that a “human” quality check should never be avoided.

The final version of the jump table can be found in Appendix B.

Chapter 5: GLTM implementation

We implemented three versions of the Generalized Linear Trajectory Model (considering the post-seismic transient forms: log+log, exp+exp, log+exp) through a Matlab script that uses GNSS data to invert for the model parameters that are related linearly: $\mathbf{p}$, $\mathbf{b}$, $\mathbf{s}$, $\mathbf{c}$, $\mathbf{a}_1$, $\mathbf{a}_2$ (trend, jumps, cycles and post seismic transients, respectively) (see Tables 1 and 2). We posed the problem of obtaining the parameters of the model by solving the Least Squares Problem, where the observation at each epoch forms an equation.

We can express the trajectory model in matrix notation. Each observation o_i is approximated using an ELTM evaluated at the appropriate epoch. For the sake of clarity, here we show a simplified version of the model with: a linear trend, one jump, a cyclical term restricted to a single periodicity of 1 year (we actually use annual and semi-annual terms), one logarithmic transient and one exponential transient. It can be easily expanded, incorporating all of the jumps from the jump table (See Section 4.1.4), and as many oscillatory terms and transients as needed:

$$o_i = \mathbf{p} (t - t_R) + \mathbf{b} H(t - t_j) + \mathbf{s} \sin(\omega_1 t) + \mathbf{c} \cos(\omega_1 t) + \mathbf{a}_1 \log \left(1 + \frac{\Delta t}{T_1} \right) + \mathbf{a}_2 \left(1 - e^{\left(-\frac{\Delta t}{T_2} \right)} \right)$$

$$o_i = \mathbf{p} \alpha_i + \mathbf{b} \beta_i + \mathbf{s} \gamma_i + \mathbf{c} \varepsilon_i + \mathbf{a}_1 \theta_i + \mathbf{a}_2 \vartheta_i$$

For n number of observations ($n \gg$ number of parameters):

$$\begin{aligned}
 o_1 &= \mathbf{p} \alpha_1 + \mathbf{b} \beta_1 + \mathbf{s} \gamma_1 + \mathbf{c} \varepsilon_1 + \mathbf{a}_1 \theta_1 + \mathbf{a}_2 \vartheta_1 \\
 o_2 &= \mathbf{p} \alpha_2 + \mathbf{b} \beta_2 + \mathbf{s} \gamma_2 + \mathbf{c} \varepsilon_2 + \mathbf{a}_1 \theta_2 + \mathbf{a}_2 \vartheta_2 \\
 &\vdots \\
 o_n &= \mathbf{p} \alpha_n + \mathbf{b} \beta_n + \mathbf{s} \gamma_n + \mathbf{c} \varepsilon_n + \mathbf{a}_1 \theta_n + \mathbf{a}_2 \vartheta_n
 \end{aligned}$$

In matrix notation:

$$\begin{bmatrix} \alpha_1 & \beta_1 & \gamma_1 & \varepsilon_1 & \theta_1 & \vartheta_1 \\ \alpha_2 & \beta_2 & \gamma_2 & \varepsilon_2 & \theta_2 & \vartheta_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_n & \beta_n & \gamma_n & \varepsilon_n & \theta_n & \vartheta_n \end{bmatrix} \begin{bmatrix} \mathbf{p} \\ \mathbf{b} \\ \mathbf{s} \\ \mathbf{c} \\ \mathbf{a}_1 \\ \mathbf{a}_2 \end{bmatrix} = \begin{bmatrix} o_1 \\ o_2 \\ \vdots \\ o_n \end{bmatrix}$$

Which can be compactly stated as:

$$A \vec{x} = \vec{b}$$

Where A is the design matrix, $\vec{x}$ is the vector of the unknown parameters, and $\vec{b}$ is the vector of GNSS observations.

The matrix is calculated through a function that we called *design_gltm.m* and its dimension depends on n_F , n_J , n_P , n_L , n_e (See Section 2.3). The required inputs for the function are: time vector containing the epochs, the reference time (mean of all epochs), a vector of length n_J with the times for the Heaviside jumps, a vector of length n_F containing the periods of the truncated Fourier Series, a vector of length n_L containing the initiation times of the transients (for those earthquakes that show a transient) and a vector of length n_L with the decay time scales or “response time parameters” (T_1 and T_2) for the double transients.

The output of the function is the design matrix A with which we can obtain the optimum values for the parameters of the model. Among all of the possible solutions for $\vec{x}$, it can be shown that the solution that minimizes the residuals is:

$$\vec{x} = (A^t A)^{-1} A^t \vec{b}$$

Where $\vec{x}$ are the parameters of the trajectory model.

5.1 Robust Least Squares Fit:

We used prior sigma values (σ_0) in the Least Squares fit, in order to minimize the influence of atypical noise and extreme values.

A prior sigma is a value of typical noise, expected for a certain signal. It is introduced in the Least Squares problem with the purpose of down-weighting measurements that are outliers or that show an atypical behavior. This process is iterative, and it is set to down-weight the observations with a residual of a certain magnitude, and recalculate the parameters of the model until all outliers were down-weighted. With this robust approach, known as iteratively reweighted LS, the optimum solution is:

$$\vec{x} = (A^t W A)^{-1} A^t W \vec{b}$$

where W , the matrix of weights, that has been customized according to the residuals associated with each data point. The down-weighting schedule is such that when the residual magnitude equals $3.5 \cdot \sigma_0$ the weight is 0.1, and when it equals $4.5 \cdot \sigma_0$ the weight reduces to 0.01, etc.

We took some precautions, limiting the amount of data that can be down-weighted to 1% of the observations. However, this technique can cause some problems, such as down-weighting good quality points in order to adjust the model that is trying to be “imposed” to the data. We saw this happening with the observations of the first weeks after the seismic event (Figure 9a). The algorithm allowed this to happen because the amount of data that were down-weighted was less than 1% of the total, but concentrated in just a few weeks. This made the short-term transient adjustment meaningless, because the process was discarding crucial observations.

Figure 9. a) Example of down-weighted data (in red) with general penalty function. b) Down-weighted data after customizing penalty function.

As a solution, we implemented a customized penalty function for the stations in this situation. After checking the quality of the data in the first post-seismic weeks, and having made sure that there were no obvious outliers, we forced the algorithm to include all of the observations up to 3 months after the earthquake (excluding the first 2 days), without down-weighting any of them. It remarkably improved the quality of the fitting and we made sure that the short-term transient would be as realistic as possible (Figure 9b).

5.2 Search for optimum non-linear parameters T_1 and T_2

Up to this point, we have dealt with linear equations in terms of the unknown parameters, but in order to fully implement the GLTM we also need to define the decay time scale for each post seismic transient (T_1 and T_2). These parameters present a non-linear relation in the model algorithm, and cannot be estimated using a simple least squares adjustment.

One option is to choose them to be arbitrary values that are proven to fit reasonably well most stations' time series. Usually around 18-20 days (0.051 year) for the short-term transient (T_1), and 1 year for the long-term transient (T_2).

However, in this work we pursue a higher level of detail that might allow us to infer post-seismic physics phenomena, thus we need to improve the estimation of T_1 and T_2 . Since inverting a non-linear system is a lengthy and complicated process, we decided to perform an iterative two-dimensional grid search, combining sets of values for T_1 and T_2 . We considered the combined weighted RMS (WRMS) misfit of the horizontal coordinates as indicator of the performance of the model (excluding the vertical

component, as explained in Chapter 3). In other words, we solved one Least Squares Problem for every combination of T_1 and T_2 , and picked the pair that minimized the horizontal WRMS misfit of the whole model. This process was carried out individually for each time series, yielding different values of T_1 and T_2 for each station.

In order to reduce the algorithm complexity and minimize the search time, we designed the grid search to be iterative. Once a set of T_1 and T_2 is picked, the search grid is redefined, densifying the neighboring area around those values, and the algorithm is re-run. The iteration stops once the difference between the WRMS misfit of two consecutive iterations is smaller than a pre-fixed threshold (0.001 mm).

The two-dimensional grid search can be clearly visualized using contour plots (Figure 10), where T_1 and T_2 are the axes of the plot, and the Horizontal WRMS misfit of the model that results from each combination is represented with colors.

Figure 10. Example of two-dimensional grid search for transient decay time-scales (WRMS in meters). Optimum combination of T_1 and T_2 marked with a white cross.

It is important to consider that the initial “candidate” values for T_1 and T_2 might need to be adjusted for some stations, mainly to ensure that the optimum combination is contained within the boundaries of the search grid.

Moreover, for some stations there might exist more than one combination of T_1 and T_2 that minimizes the Horizontal WRMS misfit. In those cases where the search does not converge to a unique set of values, we might need to:

- Re-check the quality of the data and look for outliers, especially in the first months after the earthquake.

- Analyze the difference between the WRMS misfit values, and evaluate the validity of keep searching for “better” combinations or just stop the iterations.

- Consider picking combinations of T_1 and T_2 that are the most logical and realistic. For instance, if the optimum value found for T_1 is less than 1 or 2 days, then it results meaningless, because it is smaller than the resolution of the measurements.

This shows that the process has some level of “automatization” but it ultimately requires a final quality check.

Chapter 6: Results

6.1 Optimum T_1 and T_2 for post-seismic transients

Even though the decay times vary from one station to another depending on their geographical location and distance from the epicenter, and also that they are different for the different models, the values calculated are within some limits. The final decay time scales for the post-seismic transients of each station and each model in particular are shown in Appendices C, D and E. We present a summary (Table 3) with the maximum, minimum and mean values of the time-scales, as well as the Horizontal WRMS value of each model. We can observe that the mean T_1 is 20 days (0.05 year) for the log+log model and 28 days (0.07 year) for the log+exp model. In the case of exp+exp model, this value goes up to 130 days (0.35 year). The mean values of the long-term time-scale, T_2 , are 7.64 years, 11.65 years and 6.31 years respectively.

Table 3. Summary of decay time-scales and Horizontal WRMS misfit

	Log+Log			Log+Exp			Exp+Exp		
	T ₁ [yr]	T ₂ [yr]	WRMSH [mm]	T ₁ [yr]	T ₂ [yr]	WRMSH [mm]	T ₁ [yr]	T ₂ [yr]	WRMSH [mm]
Max	0.15	20	5.1703	0.45	20	4.9999	0.49	9.83	6.7875
Min	0.01	1.03	1.9226	0.01	0.77	1.9493	0.07	1.20	2.212
Mean	0.05	7.64	2.6911	0.07	11.65	2.7253	0.35	6.31	3.5450
Network WRMSH	2.7486 mm			2.7767 mm			3.6612 mm		

The last row of Table 3 presents the horizontal WRMS for the entire network (all East and North residuals combined), for each model. These values are more representative of the performance than the average of the stations' WRMSH values, but we can see that they show very similar results: the log+log model being the optimum fit, slightly better than the hybrid log+exp model, and significantly better than the exp+exp. model

6.2 Parameters of the Trajectory Model and Horizontal WRMS misfit

The final parameters of the Trajectory Model resulted from the Least Squares Fit, (Section 5.1), after plugging the optimum relaxation times into the post-seismic transients. There are three sets of parameters for each time series, corresponding to the models with the three different transient forms: log+log, log+exp, exp+exp. Figure 11 shows the resulting plots for the case of station J552.

The large magnitude of the co-seismic jump greatly affects the scale of the plot, which makes it difficult to appreciate the adjustment of the model, so we also present a zoomed plot of the 70 days after the event. In the enlarged plot, it is possible to see the poor performance of the exponential function as a short-term transient, especially in the first two weeks after the earthquake.

Figure 11. Box plot that characterizes the variability of WRMSH over the network, for each class of transient model.

The Horizontal WRMS misfit of the models is the indicator that we used to evaluate their performances. They are presented in histograms of Figure 13, as well as in the box plots of Figure 11.

Figure 12. Example of fitted models zoomed to the first months after the earthquake

The most relevant result of this study suggests that the **double logarithmic transient** and the **hybrid log+exp transient** achieved the best **Horizontal WRMS misfit values**.

As we can observe in Figure 13, most of the stations presented a Horizontal WRMS misfit between 2-3 mm when using the log+log model. These results are similar for the log+exp model, although the horizontal WRMS misfit values were slightly smaller in the first case. Finally, the range of horizontal WRMS misfit values obtained with the exp+exp model is wider, going from 2 mm to 5 mm, almost in the same proportion.

Figure 13. Histograms of Horizontal WRMS misfit results of 130 CGNSS stations.

These results clearly confirm that the transit in the first weeks after the earthquake has a logarithmic form, rather than an exponential one. This is coherent with previous research studies.

However, it is noteworthy that the long-term transient (for periods of time longer than 1 year) does not take either predominant form. Both logarithmic and exponential functions, when given equal degrees of freedom seem to fit the data almost equally well, being the logarithmic form slightly better. This contradicts the common assumption that long-term

post-seismic transients are dominated by the phenomenon of viscoelastic relaxation, and therefore better modelled with an exponential decay function.

6.3 Empirical Cumulative Distribution Function

The empirical cumulative distribution function (ECDF) is an easy and clear way to obtain the fraction of sample observations less than or equal to a particular value of horizontal WRMS misfit, for each model.

Figure 14 shows that the log+log model performed the best of all, although the hybrid log+exp model performed almost equally well. On the other hand, the exp+exp model performed badly.

Figure 14. Empirical Cumulative Distribution Function for Horizontal WRMS misfit.

The synthetic analysis carried out in Chapter 3 proved that we need a significant amount of data to have the ability to choose the correct transient model, and that the noise in the data affects such ability. The ECDF shows that, looking at around 50% of the observations, the horizontal WRMS of the exp+exp model is almost 1mm larger than the other models. The optimum one is the log+log model, but only slightly better than the hybrid log+exp model.

6.4 Co-seismic and accumulated post-seismic displacements

We carried out an analysis over the impact of the post-seismic deformation on the overall displacements of CGNSS stations, using the resulting models of this study, aiming to improve our understanding of the effects of a mega-earthquake, which continue as post-seismic deformation, long after the main shock.

The GLTM inversions provided estimates for the co-seismic jumps, which are shown in Figure 15. They are clearly larger near the east coast of Japan, closer to the epicenter. We can also calculate the total post-seismic displacement accumulated by the final day of the time series in March 2018. The horizontal components of the cumulative post-seismic displacements for the log+log model are shown in Figure 16.

The magnitude of the co-seismic jump is much larger than the cumulative post-seismic displacement in areas near the East coast. However, it is interesting to notice that the northern and western stations in the study area accumulated in 7 years after the event, post-seismic displacements that are comparable to, or even larger than the co-seismic jumps. This clearly shows that the deformation following an earthquake is relevant even

several years after it, especially when designing trajectory models aimed to improve or define reference frames.

Figure 15. Co-seismic jump. Tohoku Earthquake. March 11th, 2011

Figure 16. Post-seismic Cumulative Displacement up to March, 2018

Chapter 7: Conclusions

The poor performance of the double exponential model indicates that the short time-scale transient, most evident in the weeks following the earthquake, has logarithmic form, and therefore is driven by afterslip. This is the clearest result of this study, and it supports the general agreement on afterslip being the dominant process in this period of time.

On the other hand, we can say that the nature of the transient with the longer time scale remains uncertain because the double logarithmic transient model fits the data only slightly better than the hybrid log+exp model.

Therefore, the hypothesis that short term transient behavior associated with afterslip is eventually dominated by longer time scale transient behavior associated with viscous relaxation receives no support from this study. The results have shown that the observations can be explained just as well – and even slightly better – by the hypothesis that the entire post-seismic transient (thru March 2018) was driven by afterslip.

Even though 7 years of post-seismic observations are significant, the nature of the longer-term transient should become clearer as the time series extends (unless it is interrupted by another great earthquake).

Finally, the results suggest that, in cases where an approximate long-term decay time scale (T_2) is needed, a value ranging from 7 to 11 years seems to be better than the often adopted value of 1 year (at least for the case of Tohoku-Oki earthquake).

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Appendix A: List of station names and locations

Station Code	Latitude (degrees)	Longitude (degrees)	Station Code	Latitude (degrees)	Longitude (degrees)	Station Code	Latitude (degrees)	Longitude (degrees)
G103	40.8975	140.8592	J186	39.9361	140.1324	J911	39.0121	141.4009
G104	39.9421	139.7035	J187	39.7492	140.597	J912	38.9955	141.1485
G105	38.5633	139.546	J188	39.6583	140.2342	J913	38.934	140.8332
G145	38.9019	141.2832	J189	39.5493	140.3866	J914	38.7432	141.3179
G159	39.362	141.0547	J190	39.327	140.5598	J915	38.6861	141.0043
G162	38.5112	139.5338	J191	39.2061	139.9077	J916	38.6606	141.1607
G174	40.5752	140.295	J192	39.1642	140.162	J917	38.5718	140.7277
G175	40.9212	140.9902	J193	39.0519	140.6296	J918	38.5098	141.3044
G179	38.2578	140.7547	J194	39.1856	139.5477	J919	38.1771	140.9437
J026	40.779	140.273	J195	38.7597	139.9574	J921	40.3394	140.0276
J027	40.1334	141.7891	J196	38.594	139.8318	J922	40.1833	140.4082
J028	39.5724	141.94	J197	38.1462	139.7422	J923	40.0997	140.0055
J029	39.1106	141.2039	J199	38.1975	140.0776	J924	39.9214	140.5359
J030	39.9679	139.7761	J231	38.4654	139.2533	J925	39.5276	140.0539
J031	39.3987	140.0482	J232	38.3193	138.5131	J926	39.5081	140.5961
J032	38.8946	139.8089	J537	40.8624	141.1318	J927	39.2967	140.2789
J033	38.7586	140.3187	J538	40.7063	140.5892	J928	39.1462	140.7151
J035	38.331	140.3661	J539	40.6764	141.3762	J929	39.0544	140.4473
J036	38.4492	141.4412	J540	40.6243	140.4785	J930	38.9381	140.1835
J037	38.3175	140.9542	J541	40.6436	140.8033	J931	38.7522	140.4973
J049	38.2307	139.5096	J542	40.9102	140.4516	J932	38.7012	139.6745
J152	40.9682	141.368	J543	39.9531	141.0663	J933	38.6284	140.2205
J153	40.6251	141.1978	J544	39.3513	140.7692	J934	38.1704	140.3939
J154	40.5776	139.9281	J546	39.1431	141.5755	MIZU	39.1352	141.1328
J155	40.5237	140.5781	J547	39.5961	141.6753			
J156	40.5154	141.5113	J548	38.5462	140.8479			
J157	40.2911	141.0765	J549	38.4251	141.2129			
J158	40.4052	141.7131	J550	38.3012	141.5007			
J159	40.2911	141.2937	J551	39.8911	139.8489			
J160	40.0486	141.4619	J552	39.8258	140.0447			
J161	39.9806	141.2251	J553	39.7027	140.7328			
J162	39.8694	141.9505	J554	39.1991	140.5067			
J163	39.8512	141.1649	J555	39.016	139.9275			
J164	39.8492	141.8039	J556	38.4968	140.3652			
J165	39.7011	140.9645	J557	38.1481	140.2711			
J166	39.5966	141.1721	J564	38.0562	139.4617			
J167	39.4582	141.9553	J795	39.849	141.4526			
J169	39.3381	141.5342	J796	39.127	140.9885			
J170	39.2535	141.798	J799	38.4343	140.0946			
J171	39.0238	141.7398	J803	38.289	140.1999			
J172	38.9029	141.5726	J844	40.8344	140.8105			
J173	38.8153	140.9906	J898	40.7306	140.011			
J174	38.7489	140.8016	J899	40.58	141.106			
J175	38.6827	141.4494	J901	40.5088	141.332			
J176	38.5395	141.1475	J902	40.4476	140.9416			
J177	38.4118	140.8514	J903	40.271	141.4849			
J178	38.2057	140.6428	J904	40.1067	141.0465			
J179	38.0297	140.844	J905	39.971	141.6622			
J181	40.325	140.5773	J906	39.739	141.9702			
J182	40.2712	140.2637	J907	39.6394	141.4261			
J183	40.2154	140.7873	J908	39.5545	140.8363			
J184	40.2473	140.0487	J909	39.4647	141.293			
J185	40.0069	140.402	J910	39.2354	141.3117			

Appendix B: Table of jumps

Station Code	Time (Jyear)	Cause
G103	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
G104	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
G105	2007.03267	% EQ M8.1 01/13/2007 04:23:21 UTC 46.243 154.52410 km depth
G105	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
G145	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
G159	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
G162	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
G174	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
G175	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
G179	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
G179	2016.890828	% EQ M6.9 11/21/2016 20:59:49 UTC 37.393 141.3879 km depth
J026	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J027	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J027	2011.472718	% EQ M6.7 06/22/2011 21:50:52 UTC 39.955 142.20533 km depth
J028	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J029	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J029	2011.263808	% EQ M7.1 04/07/2011 14:32:43 UTC 38.276 141.58842 km depth
J029	2011.3	% unknown
J030	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J031	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J032	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J033	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J035	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J036	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J036	2012.05	% unknown
J037	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J049	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J152	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J153	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J154	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J155	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J156	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J157	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J158	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J159	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J160	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J161	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J162	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J163	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J164	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J165	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J166	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J167	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J169	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J170	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J171	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J171	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J172	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J172	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J173	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J174	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J175	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J176	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J177	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J178	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J178	2016.890828	% EQ M6.9 11/21/2016 20:59:49 UTC 37.393 141.3879 km depth
J179	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J179	2012.039	% unknown
J179	2016.890828	% EQ M6.9 11/21/2016 20:59:49 UTC 37.393 141.3879 km depth
J181	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J182	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth

J183	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J184	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J185	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J186	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J187	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J188	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J189	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J189	2011.263808	% EQ M7.1 04/07/2011 14:32:43 UTC 38.276 141.58842 km depth
J190	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J191	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J192	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J192	2012.694	% unknown
J193	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J194	2003.436	% Antenna_Type
J194	2008.450346	% EQ M6.9 06/13/2008 23:43:45 UTC 39.030 140.8817.8 km depth
J194	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J195	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J196	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J196	2012.678	% unknown
J197	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J199	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J231	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J231	2012.675	% unknown
J231	2017.107	% unknown
J232	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J537	2010.506266	% EQ M6.3 07/04/2010 21:55:51 UTC 39.697 142.36927 km depth
J537	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J537	2016.034614	% EQ M6.7 01/14/2016 03:25:33 UTC 41.972 142.78146 km depth
J537	2016.890828	% EQ M6.9 11/21/2016 20:59:49 UTC 37.393 141.3879 km depth
J538	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J538	2011.707899	% EQ M6.7 09/16/2011 19:26:40 UTC 40.273 142.77930 km depth
J538	2012.984	% unknown
J538	2012.235342	% EQ M6.1 03/27/2012 11:00:44 UTC 39.859 142.01715 km depth
J538	2013.392853	% EQ M8.3 05/24/2013 05:44:48 UTC 54.892 153.221598.1 km depth
J539	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J539	2013.815784	% EQ M7.1 10/25/2013 17:10:19 UTC 37.156 144.66135 km depth
J539	2014.775107	% EQ M6.1 10/11/2014 02:35:47 UTC 41.027 143.16522 km depth
J539	2016.034614	% EQ M6.7 01/14/2016 03:25:33 UTC 41.972 142.78146 km depth
J540	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J540	2012.752	% unknown
J541	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J541	2012.086	% unknown
J541	2013.056	% unknown
J541	2013.129	% unknown
J541	2013.156	% unknown
J541	2012.933185	% EQ M7.3 12/07/2012 08:18:23 UTC 37.890 143.94931 km depth
J541	2013.392853	% EQ M8.3 05/24/2013 05:44:48 UTC 54.892 153.221598.1 km depth
J542	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J542	2014.753	% unknown
J543	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J543	2011.707899	% EQ M6.7 09/16/2011 19:26:40 UTC 40.273 142.77930 km depth
J544	2010.613	% unknown
J544	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J544	2012.88	% unknown
J544	2014.64	% unknown
J546	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J546	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J547	2009.222	% unknown
J547	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J547	2012.072595	% EQ M5.6 01/28/2012 00:22:18 UTC 40.177 142.21155.3 km depth
J547	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J548	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J548	2011.248	% unknown
J548	2012.05	% unknown
J548	2012.091	% unknown
J548	2012.460929	% EQ M6.3 06/17/2012 20:32:20 UTC 38.919 141.83136 km depth

J549	2009.307	% unknown
J549	2010.704	% unknown
J549	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J549	2011.263808	% EQ M7.1 04/07/2011 14:32:43 UTC 38.276 141.58842 km depth
J549	2011.363393	% EQ M6.1 05/13/2011 23:35:52 UTC 37.396 141.34135 km depth
J549	2013.815784	% EQ M7.1 10/25/2013 17:10:19 UTC 37.156 144.66135 km depth
J549	2014.025	% unknown
J549	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J549	2016.146	% unknown
J549	2016.896348	% EQ M5.9 11/23/2016 21:23:36 UTC 37.214 141.3219 km depth
J550	2008.450346	% EQ M6.9 06/13/2008 23:43:45 UTC 39.030 140.8817.8 km depth
J550	2008.546504	% EQ M7.0 07/19/2008 02:39:28 UTC 37.552 142.21422 km depth
J550	2010.198053	% EQ M6.5 03/14/2010 08:08:03 UTC 37.745 141.59032 km depth
J550	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J550	2012.179	% unknown
J550	2013.965	% unknown
J550	2016.896348	% EQ M5.9 11/23/2016 21:23:36 UTC 37.214 141.3219 km depth
J551	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J551	2012.226	% unknown
J551	2012.626	% unknown
J551	2013.392853	% EQ M8.3 05/24/2013 05:44:48 UTC 54.892 153.221598.1 km depth
J551	2016.034614	% EQ M6.7 01/14/2016 03:25:33 UTC 41.972 142.78146 km depth
J552	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J552	2011.707899	% EQ M6.7 09/16/2011 19:26:40 UTC 40.273 142.77930 km depth
J552	2012.697	% unknown
J552	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J552	2016.08	% unknown
J553	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J553	2011.219454	% EQ M6.4 03/22/2011 09:44:29 UTC 39.851 143.43713 km depth
J553	2011.251	% unknown
J553	2011.552	% unknown
J553	2011.676	% unknown
J553	2016.034614	% EQ M6.7 01/14/2016 03:25:33 UTC 41.972 142.78146 km depth
J553	2017.712	% unknown
J554	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J554	2011.247087	% EQ M5.9 04/01/2011 11:57:54 UTC 39.323 141.95041 km depth
J554	2011.263808	% EQ M7.1 04/07/2011 14:32:43 UTC 38.276 141.58842 km depth
J554	2012.734	% unknown
J554	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J554	2017.033	% unknown
J555	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J555	2017.258	% unknown
J555	2018.125	% unknown
J556	2011.016	% unknown
J556	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J556	2017.022	% unknown
J557	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J557	2012.64	% unknown
J557	2014.917	% unknown
J564	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J564	2012.659	% unknown
J564	2014.914	% unknown
J795	2010.506266	% EQ M6.3 07/04/2010 21:55:51 UTC 39.697 142.36927 km depth
J795	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J795	2011.472718	% EQ M6.7 06/22/2011 21:50:52 UTC 39.955 142.20533 km depth
J795	2012.072595	% EQ M5.6 01/28/2012 00:22:18 UTC 40.177 142.21155.3 km depth
J795	2012.471	% unknown
J795	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J796	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J796	2011.247087	% EQ M5.9 04/01/2011 11:57:54 UTC 39.323 141.95041 km depth
J796	2012.460933	% EQ M6.3 06/17/2012 20:32:20 UTC 38.919 141.83136 km depth
J796	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J796	2016.606	% unknown
J799	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J799	2011.251	% unknown
J799	2011.363393	% EQ M6.1 05/13/2011 23:35:52 UTC 37.396 141.34135 km depth

J799	2011.219406	% EQ M6.1 03/22/2011 09:19:06 UTC 37.325 141.79131 km depth
J799	2013.815784	% EQ M7.1 10/25/2013 17:10:19 UTC 37.156 144.66135 km depth
J799	2016.991175	% EQ M5.9 12/28/2016 12:38:49 UTC 36.860 140.4427 km depth
J799	2016.896348	% EQ M5.9 11/23/2016 21:23:36 UTC 37.214 141.3219 km depth
J799	2012.24938	% EQ M5.7 04/01/2012 14:04:24 UTC 37.116 140.95748 km depth
J803	2010.198053	% EQ M6.5 03/14/2010 08:08:03 UTC 37.745 141.59032 km depth
J803	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J803	2012.776	% unknown
J803	2012.905	% unknown
J803	2012.933186	% EQ M7.3 12/07/2012 08:18:23 UTC 37.890 143.94931 km depth
J803	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J803	2016.044	% unknown
J844	2010.506266	% EQ M6.3 07/04/2010 21:55:51 UTC 39.697 142.36927 km depth
J844	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J844	2011.895782	% EQ M6.2 11/24/2011 10:25:34 UTC 41.898 142.63938 km depth
J844	2012.391859	% EQ M5.9 05/23/2012 15:02:25 UTC 41.335 142.08246 km depth
J844	2014.605489	% EQ M6.1 08/10/2014 03:43:17 UTC 41.159 142.13141 km depth
J898	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J898	2011.263808	% EQ M7.1 04/07/2011 14:32:43 UTC 38.276 141.58842 km depth
J898	2014.655	% unknown
J899	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J899	2012.08	% unknown
J899	2013.392853	% EQ M8.3 05/24/2013 05:44:48 UTC 54.892 153.221598.1 km depth
J899	2018.064208	% EQ M6.3 01/24/2018 10:51:19 UTC 41.103 142.43231 km depth
J901	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J901	2012.235342	% EQ M6.1 03/27/2012 11:00:44 UTC 39.859 142.01715 km depth
J901	2013.815784	% EQ M7.1 10/25/2013 17:10:19 UTC 37.156 144.66135 km depth
J902	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J902	2014.605489	% EQ M6.1 08/10/2014 03:43:17 UTC 41.159 142.13141 km depth
J903	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J903	2010.506266	% EQ M6.3 07/04/2010 21:55:51 UTC 39.697 142.36927 km depth
J903	2015.527021	% EQ M5.5 07/12/2015 17:52:06 UTC 33.023 131.74953 km depth
J903	2016.588	% unknown
J904	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J904	2017.88	% unknown
J905	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J905	2011.472718	% EQ M6.7 06/22/2011 21:50:52 UTC 39.955 142.20533 km depth
J905	2012.004	% unknown
J906	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J906	2011.707899	% EQ M6.7 09/16/2011 19:26:40 UTC 40.273 142.77930 km depth
J907	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J907	2012.54	% unknown
J907	2016.890828	% EQ M6.9 11/21/2016 20:59:49 UTC 37.393 141.3879 km depth
J907	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J908	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J909	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J909	2014.82	% unknown
J909	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J909	2017.321	% unknown
J910	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J910	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J910	2011.263808	% EQ M7.1 04/07/2011 14:32:43 UTC 38.276 141.58842 km depth
J910	2013.955	% unknown
J911	2011.185192	% EQ M6.5 03/09/2011 21:24:01 UTC 38.296 142.80815 km depth
J911	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J911	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J912	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J912	2012.263	% unknown
J912	2012.471	% unknown
J912	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J912	2017.26	% unknown
J913	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J913	2011.708	% unknown
J913	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J914	2010.506266	% EQ M6.3 07/04/2010 21:55:51 UTC 39.697 142.36927 km depth
J914	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth

J914	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J915	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J915	2011.263	% unknown
J915	2012.057	% unknown
J915	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J915	2017.257	% unknown
J916	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J916	2011.48	% unknown
J916	2012.82	% unknown
J916	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J917	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J917	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J917	2016.890828	% EQ M6.9 11/21/2016 20:59:49 UTC 37.393 141.3879 km depth
J918	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J918	2011.243812	% EQ M6.0 03/31/2011 07:15:30 UTC 38.922 141.82142 km depth
J918	2011.247087	% EQ M5.9 04/01/2011 11:57:54 UTC 39.323 141.95041 km depth
J918	2011.263	% unknown
J918	2011.954	% unknown
J918	2016.890828	% EQ M6.9 11/21/2016 20:59:49 UTC 37.393 141.3879 km depth
J918	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J919	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J919	2010.198053	% EQ M6.5 03/14/2010 08:08:03 UTC 37.745 141.59032 km depth
J921	2010.506266	% EQ M6.3 07/04/2010 21:55:51 UTC 39.697 142.36927 km depth
J921	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J921	2011.519615	% EQ M7.0 07/10/2011 00:57:10 UTC 38.034 143.26423 km depth
J921	2011.725	% unknown
J921	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J922	2010.506266	% EQ M6.3 07/04/2010 21:55:51 UTC 39.697 142.36927 km depth
J922	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J922	2011.226	% unknown
J923	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J923	2015.526	% unknown
J924	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J924	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J925	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J925	2012.697	% unknown
J925	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J926	2008.450414	% EQ M5.5 06/14/2008 00:20:11 UTC 38.882 140.67864 km depth
J926	2008.584	% unknown
J926	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J926	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J927	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J927	2011.775	% unknown
J927	2012.53	% unknown
J927	2012.933186	% EQ M7.3 12/07/2012 08:18:23 UTC 37.890 143.94931 km depth
J928	2011.019	% unknown
J928	2011.062	% unknown
J928	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J928	2011.298	% unknown
J928	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J928	2017.034	% unknown
J929	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J929	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J930	2008.450414	% EQ M5.5 06/14/2008 00:20:11 UTC 38.882 140.67864 km depth
J930	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J930	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J931	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J931	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J931	2016.045	% unknown
J932	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J932	2011.263808	% EQ M7.1 04/07/2011 14:32:43 UTC 38.276 141.58842 km depth
J932	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J933	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
J933	2010.198053	% EQ M6.5 03/14/2010 08:08:03 UTC 37.745 141.59032 km depth
J933	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J934	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth

J934	2015.360394	% EQ M6.8 05/12/2015 21:12:58 UTC 38.906 142.03235 km depth
J934	2016.890828	% EQ M6.9 11/21/2016 20:59:49 UTC 37.393 141.3879 km depth
J934	2017.160371	% EQ M5.7 02/28/2017 07:49:02 UTC 37.567 141.33547 km depth
MIZU	2003.397377	% EQ M7.0 05/26/2003 09:24:33 UTC 38.849 141.56868 km depth
MIZU	2005.53046	% Antenna_Type
MIZU	2008.450346	% EQ M6.9 06/13/2008 23:43:45 UTC 39.030 140.8817.8 km depth
MIZU	2011.188886	% EQ M9.1 03/11/2011 05:46:24 UTC 38.297 142.37329 km depth
MIZU	2014.885695	% Antenna_Type

Appendix C: Results of Log+Log Model

CODE = Station name

T1 = decay timescale of the short-term postseismic transient

T2 = decay timescale of the long-term postseismic transient

Amp1_E = Amplitude of the short-term postseismic transient for the East component

Amp2_E = Amplitude of the long-term postseismic transient for the East component

Amp1_N = Amplitude of the short-term postseismic transient for the North component

Amp2_N = Amplitude of the long-term postseismic transient for the North component

WRMSH = Weighted RMS misfit of combined East and North components (Horizontal components)

CODE	T1[yr]	T2[yr]	Amp1_E[m]	Amp2_E[m]	Amp1_N[m]	Amp2_N[m]	WRMSH[mm]
G103	0.0589	10.2000	0.0322	0.2709	-0.0411	-0.3312	2.6529
G104	0.0627	7.6127	0.0724	0.5400	-0.0377	-0.2409	2.1585
G105	0.0446	4.9296	0.0957	0.5359	-0.0258	-0.0859	2.4352
G145	0.0586	6.9334	0.1947	0.9183	-0.0649	-0.2728	3.8308
G159	0.0389	6.4024	0.1465	0.7353	-0.0801	-0.3951	3.5039
G162	0.0443	6.8716	0.1004	0.6629	-0.0199	-0.1072	2.2726
G174	0.0212	2.3755	0.0370	0.1420	-0.0311	-0.0743	2.7221
G175	0.0702	15.8280	0.0341	0.3716	-0.0434	-0.5109	2.3265
G179	0.0149	1.1664	0.1081	0.2461	-0.0249	-0.0638	2.7448
J026	0.1201	19.7967	0.0507	0.5178	-0.0496	-0.4186	2.1552
J027	0.0510	11.8068	0.1050	0.6274	-0.0637	-0.2560	2.8588
J028	0.0423	11.0601	0.1849	1.0080	-0.0622	-0.2551	3.6253
J029	0.0219	6.3321	0.1602	0.9425	-0.0601	-0.3617	4.0230
J030	0.0606	8.3820	0.0722	0.5862	-0.0371	-0.2724	2.1820
J031	0.0526	6.4679	0.1056	0.6877	-0.0491	-0.2370	2.3863
J032	0.0625	9.4551	0.1185	0.8601	-0.0362	-0.2189	2.3322
J033	0.0383	4.4675	0.1303	0.6363	-0.0408	-0.1653	3.1029
J035	0.0451	4.6150	0.1437	0.5831	-0.0400	-0.0618	2.6642
J036	0.0783	5.5220	0.1701	0.6235	-0.0593	-0.2046	2.9034
J037	0.0142	2.3154	0.1308	0.4445	-0.0439	-0.1037	2.8117
J049	0.0342	3.9648	0.0888	0.4792	-0.0153	-0.0570	2.2000
J152	0.0752	12.3325	0.0301	0.2569	-0.0384	-0.3130	2.3676
J153	0.0559	13.8070	0.0445	0.4370	-0.0551	-0.4964	2.3204
J154	0.0751	11.7561	0.0517	0.4890	-0.0363	-0.3142	2.0476
J155	0.0665	20.0000	0.0590	0.8177	-0.0531	-0.6477	2.5502
J156	0.0620	17.8353	0.0648	0.5110	-0.0563	-0.4904	2.5204
J157	0.0625	10.2550	0.0799	0.5166	-0.0782	-0.5027	2.6601
J158	0.0642	20.0000	0.0780	0.6066	-0.0622	-0.3934	2.6232
J159	0.0423	12.4004	0.0749	0.5831	-0.0689	-0.5561	2.5070
J160	0.0602	14.8787	0.1227	0.7652	-0.0891	-0.4799	2.8891
J161	0.0644	11.2852	0.1228	0.6929	-0.0974	-0.4940	2.9223
J162	0.0388	20.0000	0.1545	1.1817	-0.0658	-0.2622	3.3795
J163	0.0569	8.5689	0.1425	0.6449	-0.0894	-0.4647	3.1867
J164	0.0424	14.5230	0.1573	0.9590	-0.0757	-0.2734	3.3768
J165	0.0531	7.3902	0.1458	0.6915	-0.0902	-0.4386	3.3806
J166	0.0437	7.1648	0.1548	0.7205	-0.0846	-0.4405	3.1127
J167	0.0481	8.8737	0.1941	0.9191	-0.0568	-0.2280	3.7113
J169	0.0100	1.2870	0.1258	0.3771	-0.0371	-0.1514	2.3532
J170	0.0636	11.3461	0.1983	1.2882	-0.0640	-0.3269	5.1703
J171	0.1389	10.5458	0.2314	1.0166	-0.0648	-0.2544	2.4380
J172	0.0812	6.6944	0.1960	0.8411	-0.0570	-0.2370	2.5626
J173	0.0941	8.2427	0.2055	0.8971	-0.0765	-0.2744	3.2875
J174	0.0804	6.3013	0.1831	0.6936	-0.0630	-0.1700	3.0905
J175	0.1176	9.0277	0.2160	0.9530	-0.0670	-0.2451	3.2887
J176	0.0851	7.0340	0.1992	0.7442	-0.0699	-0.1881	2.8421
J177	0.0100	1.0318	0.0929	0.3505	-0.0284	-0.0828	2.9185
J178	0.1538	10.4949	0.2190	0.7098	-0.0529	0.0109	3.5677
J179	0.0446	2.9946	0.1476	0.3943	-0.0419	-0.0835	2.5986
J181	0.0941	10.3103	0.0782	0.5849	-0.0672	-0.3453	2.5944
J182	0.0660	7.8793	0.0681	0.5123	-0.0472	-0.2990	2.1819
J183	0.0577	8.7129	0.0808	0.5379	-0.0687	-0.4327	2.3575
J184	0.0680	6.1095	0.0659	0.4275	-0.0385	-0.2441	2.3376
J185	0.1158	11.0095	0.1163	0.6455	-0.0740	-0.3322	2.4792
J186	0.0620	7.4688	0.0874	0.5966	-0.0439	-0.3098	2.2130
J187	0.0583	7.2530	0.1237	0.7185	-0.0622	-0.3354	2.8098

J188	0.0537	6.7985	0.1061	0.6890	-0.0503	-0.2930	2.2336
J189	0.0389	4.6256	0.1068	0.6026	-0.0465	-0.2488	2.5351
J190	0.0444	5.1126	0.1247	0.6592	-0.0608	-0.2794	2.7664
J191	0.0427	4.9190	0.0943	0.5819	-0.0411	-0.1833	2.5515
J192	0.0571	6.2963	0.1210	0.6869	-0.0502	-0.2266	3.5663
J193	0.0530	4.4428	0.1471	0.5726	-0.0596	-0.3136	3.0484
J194	0.0585	4.9455	0.0859	0.5163	-0.0359	-0.1333	2.4753
J195	0.0411	4.6904	0.1088	0.6011	-0.0352	-0.1519	2.3331
J196	0.0513	5.6755	0.1157	0.6153	-0.0323	-0.1194	2.7676
J197	0.0428	4.2240	0.1042	0.5010	-0.0196	-0.0428	2.6340
J199	0.0387	3.4050	0.1146	0.4623	-0.0226	-0.0375	3.1858
J231	0.0100	1.7442	0.0476	0.3573	-0.0079	-0.0450	3.3842
J232	0.0445	4.2886	0.0565	0.3653	-0.0093	-0.0293	2.5493
J537	0.0718	16.2053	0.0334	0.3981	-0.0479	-0.5112	2.6205
J538	0.0676	8.4635	0.0397	0.3364	-0.0451	-0.2992	2.1843
J539	0.0449	7.2921	0.0371	0.2649	-0.0461	-0.2938	2.1166
J540	0.0836	19.3649	0.0541	0.6857	-0.0519	-0.4975	2.4261
J541	0.0779	17.5404	0.0529	0.6213	-0.0573	-0.5763	2.6948
J542	0.0988	10.7752	0.0358	0.3175	-0.0418	-0.2866	2.1066
J543	0.0603	8.6319	0.1130	0.5967	-0.0924	-0.4765	3.2630
J544	0.0612	7.4107	0.1478	0.8109	-0.0881	-0.3607	3.5530
J546	0.0829	7.2647	0.2140	0.8272	-0.0659	-0.2634	2.6423
J547	0.0637	10.9858	0.2030	0.8552	-0.0832	-0.2796	2.8845
J548	0.0129	1.3625	0.1002	0.3913	-0.0357	-0.0988	2.1150
J549	0.0815	3.6590	0.1758	0.4937	-0.0596	-0.1196	2.1615
J550	0.1338	7.6086	0.1916	0.6419	-0.0748	-0.2421	2.1865
J551	0.0648	7.8877	0.0793	0.5936	-0.0390	-0.2617	2.2144
J552	0.0574	7.4107	0.0901	0.6193	-0.0437	-0.2924	1.9672
J553	0.0463	6.6657	0.1274	0.6996	-0.0594	-0.3471	2.7425
J554	0.0367	3.9266	0.1215	0.5612	-0.0489	-0.2390	2.2186
J555	0.0455	4.1480	0.1017	0.5512	-0.0351	-0.1588	2.7425
J556	0.0339	3.3004	0.1310	0.5403	-0.0394	-0.0916	2.9832
J557	0.0454	4.0728	0.1346	0.4690	-0.0270	-0.0465	2.5235
J564	0.0450	4.3397	0.0933	0.4620	-0.0146	-0.0353	2.2727
J795	0.0476	8.4453	0.1451	0.6364	-0.0837	-0.3474	2.3950
J796	0.0477	4.6715	0.1627	0.5407	-0.0616	-0.3018	3.1636
J799	0.0315	3.5551	0.1099	0.5482	-0.0270	-0.0733	2.5463
J803	0.0313	3.0104	0.1161	0.4596	-0.0252	-0.0742	2.3465
J844	0.0590	11.2852	0.0338	0.3564	-0.0433	-0.3773	2.2548
J898	0.0533	9.1943	0.0391	0.3753	-0.0317	-0.2723	2.1569
J899	0.1024	17.1855	0.0612	0.4933	-0.0667	-0.5772	2.5030
J901	0.0387	8.1071	0.0533	0.3471	-0.0549	-0.3443	2.3220
J902	0.0333	5.9555	0.0557	0.3582	-0.0540	-0.3628	2.8153
J903	0.0774	18.4004	0.0999	0.6382	-0.0803	-0.5468	2.3964
J904	0.0860	13.0069	0.1105	0.6228	-0.1005	-0.6129	2.8410
J905	0.0361	6.0312	0.1164	0.4915	-0.0671	-0.2191	3.2679
J906	0.0456	2.8697	0.1615	0.3084	-0.0591	-0.0758	2.1807
J907	0.0547	7.8793	0.1793	0.6643	-0.0867	-0.3134	2.5157
J908	0.0500	6.7089	0.1369	0.7025	-0.0810	-0.3875	3.8021
J909	0.0491	5.1022	0.1796	0.5598	-0.0762	-0.3182	2.9714
J910	0.0249	3.3378	0.1526	0.6004	-0.0569	-0.2465	2.5929
J911	0.0626	5.7355	0.1977	0.7636	-0.0606	-0.2592	2.6884
J912	0.0914	8.5304	0.2096	0.9165	-0.0705	-0.3572	2.5765
J913	0.1126	9.2608	0.2078	0.7080	-0.0882	-0.1460	3.9363
J914	0.0907	6.0792	0.2128	0.7169	-0.0601	-0.2613	2.5647
J915	0.0169	3.0513	0.1379	0.5653	-0.0438	-0.1856	2.3926
J916	0.0813	7.4187	0.2168	0.7362	-0.0614	-0.2626	2.3041
J917	0.0366	2.9023	0.1360	0.4798	-0.0400	-0.1097	2.5226
J918	0.0278	3.3218	0.1449	0.5586	-0.0380	-0.1889	2.3500
J919	0.0106	1.6350	0.1090	0.3971	-0.0326	-0.1035	2.1164
J921	0.0874	11.7245	0.0711	0.5771	-0.0444	-0.3648	2.0266
J922	0.0627	7.9645	0.0780	0.5398	-0.0495	-0.3511	2.5468
J923	0.0641	8.8928	0.0742	0.5665	-0.0452	-0.3035	1.9226
J924	0.0603	6.4540	0.1045	0.5544	-0.0576	-0.3190	2.3860
J925	0.0613	7.6127	0.1103	0.6978	-0.0488	-0.2629	2.1217
J926	0.0497	4.9349	0.1280	0.5941	-0.0594	-0.2776	2.4471
J927	0.0106	1.8207	0.0746	0.4030	-0.0312	-0.1600	2.0717
J928	0.0401	3.6203	0.1372	0.5083	-0.0549	-0.2788	2.7237
J929	0.0409	4.0512	0.1256	0.5704	-0.0469	-0.2069	2.5204
J930	0.0450	4.6517	0.1206	0.5916	-0.0448	-0.1930	2.6942
J931	0.0324	3.2223	0.1309	0.5518	-0.0336	-0.1207	2.7979

J932	0.0503	5.5337	0.1050	0.5831	-0.0288	-0.1273	2.1330
J933	0.0357	3.9520	0.1243	0.5590	-0.0336	-0.1365	2.9451
J934	0.0251	1.9431	0.1114	0.3715	-0.0310	-0.0547	2.9560
MIZU	0.0735	9.5831	0.1937	0.9781	-0.0783	-0.3913	3.7459

Appendix D: Results of Log+Exp Model

CODE = Station name

T1 = decay timescale of the short-term postseismic transient

T2 = decay timescale of the long-term postseismic transient

Amp1_E = Amplitude of the short-term postseismic transient for the East component

Amp2_E = Amplitude of the long-term postseismic transient for the East component

Amp1_N = Amplitude of the short-term postseismic transient for the North component

Amp2_N = Amplitude of the long-term postseismic transient for the North component

WRMSH = Weighted RMS misfit of combined East and North components (Horizontal components)

CODE	T1[yr]	T2[yr]	AmpT1_E[m]	AmpT2_E[m]	AmpT1_N[m]	AmpT2_N[m]	WRMSH[mm]
G103	0.0697	15.6671	0.0344	0.3780	-0.0436	-0.4608	2.5596
G104	0.0765	12.4591	0.0789	0.7756	-0.0407	-0.3453	2.1933
G105	0.0635	9.5806	0.1102	0.8290	-0.0287	-0.1304	2.4888
G145	0.0718	11.9331	0.2096	1.3513	-0.0696	-0.3997	3.8193
G159	0.0445	10.5608	0.1542	1.0676	-0.0843	-0.5724	3.4798
G162	0.0533	11.2974	0.1077	0.9581	-0.0212	-0.1549	2.2798
G174	0.3597	1.2706	0.1773	-0.1338	-0.2025	0.2283	2.5977
G175	0.0720	20.0000	0.0346	0.4534	-0.0441	-0.6197	2.3567
G179	0.0627	9.3539	0.1720	0.8619	-0.0412	-0.2216	2.8320
J026	0.1084	20.0000	0.0489	0.5420	-0.0480	-0.4390	2.1782
J027	0.0521	15.8536	0.1062	0.8061	-0.0642	-0.3289	2.8500
J028	0.0429	14.7985	0.1864	1.2943	-0.0626	-0.3280	3.5933
J029	0.0242	10.3882	0.1683	1.3705	-0.0632	-0.5259	4.0116
J030	0.0739	13.3255	0.0781	0.8302	-0.0400	-0.3847	2.2035
J031	0.0664	11.2247	0.1164	1.0180	-0.0534	-0.3475	2.4426
J032	0.0722	14.5856	0.1256	1.1992	-0.0382	-0.3033	2.3777
J033	0.0542	8.7317	0.1477	0.9876	-0.0455	-0.2558	3.0611
J035	0.0522	8.5735	0.1549	0.8934	-0.0415	-0.0943	2.6548
J036	0.0944	10.0746	0.1847	0.9360	-0.0643	-0.3059	2.8816
J037	0.0397	6.4132	0.1684	0.7387	-0.0538	-0.1681	2.9751
J049	0.0561	8.4362	0.1066	0.7647	-0.0177	-0.0895	2.2735
J152	0.0844	18.2918	0.0317	0.3500	-0.0404	-0.4267	2.4165
J153	0.0538	17.2040	0.0445	0.5334	-0.0551	-0.6058	2.3576
J154	0.0872	17.2596	0.0548	0.6606	-0.0384	-0.4242	2.0765
J155	0.0594	20.0000	0.0568	0.8447	-0.0512	-0.6713	2.5608
J156	0.0594	20.0000	0.0641	0.5770	-0.0557	-0.5522	2.5322
J157	0.0667	14.7910	0.0823	0.6938	-0.0806	-0.6745	2.6578
J158	0.0607	20.0000	0.0765	0.6254	-0.0611	-0.4074	2.6393
J159	0.0451	16.7229	0.0764	0.7499	-0.0704	-0.7145	2.5407
J160	0.0603	18.5694	0.1232	0.9329	-0.0893	-0.5851	2.8799
J161	0.0659	15.3558	0.1244	0.8979	-0.0986	-0.6398	2.9133
J162	0.0322	20.0000	0.1511	1.2242	-0.0645	-0.2761	3.3123
J163	0.0606	12.8470	0.1464	0.8871	-0.0922	-0.6394	3.1753
J164	0.0385	15.2040	0.1532	1.0449	-0.0742	-0.2997	3.2749
J165	0.0591	11.8329	0.1525	0.9860	-0.0945	-0.6249	3.3763
J166	0.0459	10.9349	0.1589	1.0061	-0.0867	-0.6168	3.0317
J167	0.0503	12.8194	0.1978	1.2394	-0.0577	-0.3078	3.6814
J169	0.0100	2.1978	0.1279	0.5690	-0.0380	-0.2285	2.4300
J170	0.3297	1.3091	0.6910	-0.6530	-0.1863	0.1512	4.9999
J171	0.1531	17.0017	0.2436	1.4495	-0.0682	-0.3590	2.4903
J172	0.0972	11.9385	0.2127	1.2575	-0.0619	-0.3529	2.6010
J173	0.0750	10.9300	0.1978	1.1840	-0.0739	-0.3639	3.3596
J174	0.0906	10.9976	0.1951	1.0267	-0.0663	-0.2495	3.0925
J175	0.4535	1.4704	0.6668	-0.4892	-0.1798	0.1135	3.0298
J176	0.0930	11.5555	0.2086	1.0708	-0.0727	-0.2686	2.8242
J177	0.0157	2.5909	0.1113	0.5962	-0.0334	-0.1384	2.9685
J178	0.1515	13.6740	0.2191	0.8974	-0.0527	0.0129	3.4715
J179	0.0611	7.0613	0.1690	0.6434	-0.0473	-0.1323	2.6410
J181	0.1052	15.6924	0.0827	0.8092	-0.0703	-0.4745	2.6514
J182	0.0820	13.1822	0.0749	0.7451	-0.0514	-0.4329	2.2162
J183	0.0657	13.5668	0.0852	0.7547	-0.0724	-0.6064	2.3979
J184	0.0913	11.2158	0.0756	0.6448	-0.0441	-0.3689	2.3799
J185	0.1279	17.3527	0.1226	0.9113	-0.0777	-0.4654	2.5312
J186	0.0764	12.4927	0.0955	0.8662	-0.0481	-0.4500	2.2488
J187	0.0678	11.9277	0.1321	1.0368	-0.0663	-0.4830	2.8261

J188	0.0669	11.5673	0.1160	1.0103	-0.0548	-0.4279	2.2713
J189	0.0564	9.0960	0.1233	0.9384	-0.0532	-0.3885	2.5768
J190	0.0575	9.5476	0.1390	1.0079	-0.0672	-0.4248	2.8036
J191	0.0648	9.6711	0.1108	0.9048	-0.0472	-0.2794	2.5898
J192	0.0662	10.9151	0.1304	1.0212	-0.0532	-0.3369	3.4723
J193	0.0754	9.3513	0.1695	0.9062	-0.0712	-0.4981	3.1469
J194	0.0929	10.3103	0.1055	0.8123	-0.0421	-0.2051	2.5428
J195	0.0600	9.3069	0.1261	0.9380	-0.0400	-0.2353	2.4241
J196	0.0648	10.5632	0.1280	0.9416	-0.0351	-0.1806	2.7906
J197	0.0668	8.9941	0.1239	0.7971	-0.0221	-0.0632	2.6922
J199	0.0639	7.9753	0.1396	0.7516	-0.0256	-0.0571	3.2519
J231	0.0467	5.1242	0.0785	0.6045	-0.0108	-0.0809	3.5739
J232	0.0758	9.1058	0.0707	0.5810	-0.0110	-0.0431	2.5934
J537	0.0732	20.0000	0.0338	0.4795	-0.0483	-0.6156	2.6205
J538	0.0906	14.7354	0.0455	0.4960	-0.0508	-0.4386	2.2186
J539	0.0516	11.4073	0.0390	0.3771	-0.0484	-0.4168	2.1299
J540	0.0812	20.0000	0.0530	0.7233	-0.0512	-0.5254	2.4738
J541	0.0755	20.0000	0.0523	0.7093	-0.0567	-0.6588	2.6929
J542	0.1214	17.7110	0.0395	0.4579	-0.0456	-0.4107	2.1450
J543	0.0619	12.5458	0.1152	0.8087	-0.0941	-0.6466	3.1720
J544	0.0661	11.7687	0.1542	1.1583	-0.0913	-0.5115	3.5474
J546	0.0969	13.0560	0.2294	1.2514	-0.0709	-0.3966	2.6766
J547	0.0680	16.1265	0.2078	1.1610	-0.0851	-0.3771	2.8864
J548	0.0156	2.6915	0.1092	0.6266	-0.0382	-0.1573	2.1565
J549	0.1078	8.6104	0.2042	0.8103	-0.0677	-0.1906	2.2117
J550	0.1531	12.6891	0.2047	0.9116	-0.0798	-0.3433	2.2106
J551	0.0775	13.4262	0.0861	0.8771	-0.0424	-0.3847	2.2532
J552	0.0717	12.8630	0.0991	0.9210	-0.0483	-0.4329	2.0043
J553	0.0570	11.5307	0.1387	1.0317	-0.0649	-0.5124	2.7544
J554	0.0589	9.1352	0.1454	0.9364	-0.0590	-0.3992	2.3105
J555	0.0718	8.7882	0.1234	0.8740	-0.0417	-0.2500	2.8312
J556	0.0621	8.0224	0.1636	0.8872	-0.0471	-0.1371	3.1180
J557	0.0644	9.2938	0.1548	0.7714	-0.0301	-0.0707	2.6130
J564	0.0652	9.1995	0.1089	0.7427	-0.0164	-0.0541	2.3455
J795	0.0527	13.7773	0.1512	0.9228	-0.0873	-0.5013	2.4408
J796	0.0586	9.4755	0.1772	0.8626	-0.0689	-0.4849	3.2010
J799	0.0451	7.4908	0.1269	0.8816	-0.0302	-0.1140	2.6155
J803	0.0604	8.4362	0.1488	0.8064	-0.0316	-0.1220	2.4802
J844	0.0566	14.8468	0.0337	0.4554	-0.0435	-0.4803	2.2868
J898	0.0616	13.7182	0.0413	0.5150	-0.0335	-0.3725	2.1823
J899	0.1004	20.0000	0.0608	0.5726	-0.0663	-0.6696	2.5004
J901	0.0467	12.9720	0.0567	0.4933	-0.0581	-0.4904	2.3432
J902	0.0432	10.2660	0.0608	0.5309	-0.0586	-0.5428	2.8198
J903	0.0761	20.0000	0.0994	0.6955	-0.0797	-0.5997	2.4473
J904	0.0908	18.4004	0.1132	0.8250	-0.1031	-0.8114	2.8611
J905	0.2444	1.1937	0.3808	-0.3418	-0.1845	0.1453	3.1938
J906	0.1817	0.7730	0.4257	-0.3520	-0.0879	-0.0065	2.2111
J907	0.0615	13.1688	0.1868	0.9739	-0.0905	-0.4563	2.5894
J908	0.0559	10.9442	0.1441	1.0129	-0.0850	-0.5584	3.7934
J909	0.0606	10.1200	0.1944	0.8858	-0.0842	-0.5050	3.0223
J910	0.0464	7.9258	0.1831	1.0001	-0.0696	-0.4074	2.7488
J911	0.0797	11.1873	0.2185	1.1900	-0.0676	-0.4029	2.7915
J912	0.0662	10.6943	0.1961	1.1844	-0.0662	-0.4584	2.7284
J913	0.1155	13.7540	0.2121	0.9684	-0.0891	-0.2004	3.9365
J914	0.1101	11.7804	0.2335	1.1128	-0.0673	-0.4046	2.6343
J915	0.0435	7.5804	0.1730	0.9360	-0.0562	-0.3029	2.5737
J916	0.0889	12.6686	0.2268	1.0846	-0.0649	-0.3869	2.3451
J917	0.0630	7.4989	0.1688	0.8054	-0.0484	-0.1801	2.6450
J918	0.1338	13.8591	0.2297	1.0846	-0.0637	-0.3849	2.4436
J919	0.0557	4.1748	0.1520	0.6043	-0.0422	-0.1662	2.1827
J921	0.1024	18.3510	0.0766	0.8100	-0.0480	-0.5109	2.0570
J922	0.0752	12.9595	0.0842	0.7744	-0.0535	-0.5057	2.5859
J923	0.0757	14.0316	0.0793	0.8016	-0.0482	-0.4275	1.9493
J924	0.0768	11.7434	0.1156	0.8390	-0.0639	-0.4832	2.4748
J925	0.0708	12.7470	0.1181	1.0220	-0.0521	-0.3829	2.1823
J926	0.0745	10.4721	0.1498	0.9538	-0.0699	-0.4429	2.6001
J927	0.0124	3.3469	0.0802	0.6247	-0.0334	-0.2476	2.1028
J928	0.0636	8.4755	0.1632	0.8367	-0.0678	-0.4659	2.8875
J929	0.0688	9.2356	0.1522	0.9363	-0.0568	-0.3377	2.7022
J930	0.0623	9.3640	0.1378	0.9343	-0.0507	-0.3036	2.7620
J931	0.0589	8.0479	0.1634	0.9283	-0.0404	-0.2067	2.9589

J932	0.0678	10.4744	0.1185	0.8993	-0.0321	-0.1946	2.2048
J933	0.0572	8.7346	0.1470	0.9142	-0.0397	-0.2178	3.0345
J934	0.0686	6.9475	0.1632	0.6447	-0.0421	-0.0773	3.2132
MIZU	0.0767	14.0276	0.1983	1.3321	-0.0803	-0.5316	3.6962

Appendix E: Results of Exp+Exp Model

CODE = Station name

T1 = decay timescale of the short-term postseismic transient

T2 = decay timescale of the long-term postseismic transient

Amp1_E = Amplitude of the short-term postseismic transient for the East component

Amp2_E = Amplitude of the long-term postseismic transient for the East component

Amp1_N = Amplitude of the short-term postseismic transient for the North component

Amp2_N = Amplitude of the long-term postseismic transient for the North component

WRMSH = Weighted RMS misfit of combined East and North components (Horizontal components)

CODE	T1[yr]	T2[yr]	AmpT1_E[m]	AmpT2_E[m]	AmpT1_N[m]	AmpT2_N[m]	WRMSH[mm]
G103	0.3761	7.6291	0.0679	0.3569	-0.0843	-0.4431	2.7248
G104	0.3823	7.2739	0.1502	0.8314	-0.0795	-0.3898	2.4678
G105	0.3651	6.2849	0.2173	1.0226	-0.0600	-0.1997	3.0141
G145	0.3946	6.5076	0.4091	1.6299	-0.1332	-0.5182	5.3012
G159	0.3341	6.1383	0.3381	1.2976	-0.1749	-0.7143	4.5272
G162	0.3486	6.7089	0.2244	1.0751	-0.0482	-0.1868	2.7917
G174	0.3673	7.3324	0.1088	0.5841	-0.0800	-0.3955	2.8742
G175	0.3689	7.9945	0.0703	0.3523	-0.0836	-0.4782	2.5346
G179	0.1943	1.5857	0.2431	0.4723	-0.0592	-0.1151	3.6399
J026	0.4508	8.4950	0.0859	0.4710	-0.0844	-0.4219	2.3456
J027	0.3328	6.5272	0.2398	0.8153	-0.1559	-0.4100	3.1904
J028	0.3772	6.4931	0.3991	1.3831	-0.1358	-0.4159	4.5711
J029	0.4015	6.8987	0.3623	1.6660	-0.1325	-0.6347	6.7875
J030	0.3718	7.4321	0.1502	0.8513	-0.0778	-0.4110	2.5662
J031	0.3578	6.6262	0.2274	1.1395	-0.1027	-0.4526	3.3274
J032	0.3973	7.5385	0.2398	1.2292	-0.0745	-0.3384	3.2669
J033	0.3661	5.9917	0.3151	1.2843	-0.0944	-0.3648	4.6629
J035	0.3474	5.4950	0.3273	1.1915	-0.0885	-0.2238	4.3912
J036	0.4759	6.3063	0.3218	1.3017	-0.1026	-0.4469	3.1188
J037	0.3343	4.7685	0.3699	1.1598	-0.1177	-0.3203	5.1447
J049	0.3428	5.8225	0.2147	0.9820	-0.0392	-0.1333	3.0190
J152	0.3892	7.7875	0.0591	0.3085	-0.0751	-0.3840	2.5465
J153	0.3552	7.6654	0.0953	0.4657	-0.1144	-0.5560	2.4814
J154	0.3910	8.0819	0.1008	0.5938	-0.0714	-0.3946	2.2952
J155	0.3838	8.9788	0.1223	0.6919	-0.1057	-0.5887	2.7367
J156	0.3649	7.1484	0.1311	0.5120	-0.1132	-0.4648	2.6793
J157	0.3615	6.9202	0.1649	0.7100	-0.1564	-0.6965	3.1767
J158	0.3837	7.2805	0.1617	0.5753	-0.1284	-0.4284	2.8116
J159	0.3227	6.9436	0.1694	0.6884	-0.1504	-0.6516	2.9446
J160	0.3551	6.4977	0.2520	0.8738	-0.1804	-0.6048	3.5212
J161	0.3642	6.5559	0.2474	0.9376	-0.1939	-0.7142	3.7251
J162	0.3747	6.8228	0.3278	1.1076	-0.1511	-0.3753	3.4584
J163	0.3601	6.3349	0.3017	1.0684	-0.1765	-0.7303	4.1746
J164	0.3619	6.3958	0.3462	1.1011	-0.1785	-0.4335	4.9891
J165	0.3688	6.3900	0.3080	1.1958	-0.1863	-0.7540	4.4277
J166	0.3460	6.1801	0.3434	1.2574	-0.1758	-0.7394	4.2988
J167	0.3770	6.3623	0.4181	1.4590	-0.1209	-0.4008	4.9128
J169	0.0702	1.2034	0.2931	0.8236	-0.0865	-0.2902	3.5241
J170	0.3907	7.1083	0.4074	1.6923	-0.1289	-0.4947	5.6713
J171	0.4753	7.0765	0.3580	1.6323	-0.0976	-0.4422	3.1755
J172	0.4091	6.4925	0.3707	1.5860	-0.1039	-0.4593	3.9356
J173	0.4296	6.5249	0.3745	1.5185	-0.1389	-0.5207	5.0532
J174	0.4180	6.1578	0.3544	1.3500	-0.1210	-0.4033	4.8205
J175	0.4990	6.8110	0.3458	1.5633	-0.1088	-0.4447	3.0593
J176	0.4026	6.0387	0.3644	1.4009	-0.1279	-0.4327	3.6547
J177	0.1770	2.1227	0.2301	0.8829	-0.0790	-0.2262	3.7339
J178	0.4876	5.9893	0.3122	1.2080	-0.0865	-0.1651	3.4811
J179	0.2926	4.3712	0.3083	1.0261	-0.0924	-0.2514	3.6489
J181	0.3866	7.0342	0.1402	0.7511	-0.1169	-0.5445	3.2182
J182	0.3825	7.2822	0.1391	0.7732	-0.0943	-0.4880	2.7169
J183	0.3582	6.9019	0.1704	0.7860	-0.1412	-0.6542	2.9119
J184	0.3860	6.8491	0.1340	0.7409	-0.0795	-0.4266	2.7777
J185	0.4428	7.2175	0.1974	0.9192	-0.1267	-0.5326	3.1841
J186	0.3758	7.0886	0.1805	0.9455	-0.0904	-0.4859	2.9002
J187	0.3830	6.8093	0.2572	1.1903	-0.1248	-0.5810	3.7973

J188	0.3606	6.7515	0.2278	1.1298	-0.1049	-0.5072	3.1464
J189	0.3652	6.2124	0.2475	1.1756	-0.1032	-0.5002	3.6319
J190	0.3618	6.1061	0.2907	1.2344	-0.1339	-0.5632	4.3905
J191	0.3621	6.3471	0.2169	1.0863	-0.0884	-0.3963	3.4574
J192	0.3601	6.9308	0.2599	1.2179	-0.1023	-0.4427	3.9609
J193	0.3972	6.0448	0.3354	1.2564	-0.1310	-0.6173	4.7577
J194	0.4017	6.5977	0.1842	0.9793	-0.0765	-0.3003	3.0263
J195	0.3660	6.1843	0.2484	1.1700	-0.0769	-0.3304	3.4503
J196	0.3463	6.7013	0.2582	1.1476	-0.0670	-0.2621	3.4613
J197	0.3740	5.9299	0.2467	1.0332	-0.0430	-0.1326	3.8766
J199	0.3631	5.4218	0.2776	1.0542	-0.0530	-0.1320	4.6076
J231	0.3224	4.6340	0.1600	0.8344	-0.0329	-0.1053	4.0379
J232	0.3774	6.3886	0.1317	0.7176	-0.0196	-0.0797	2.9980
J537	0.3635	7.9507	0.0679	0.3675	-0.0911	-0.5077	2.8006
J538	0.3768	8.4846	0.0908	0.5058	-0.0945	-0.4852	2.3784
J539	0.3000	6.4147	0.0819	0.4121	-0.0935	-0.4857	2.2991
J540	0.3804	9.1585	0.1069	0.6077	-0.0971	-0.5029	2.6634
J541	0.3655	9.8306	0.1067	0.6247	-0.1103	-0.6153	2.8772
J542	0.4141	7.8264	0.0639	0.4006	-0.0722	-0.4121	2.3520
J543	0.4013	6.9755	0.2599	0.9549	-0.2069	-0.7758	3.8083
J544	0.3660	6.8149	0.3202	1.3354	-0.1830	-0.6967	4.8407
J546	0.3819	5.8393	0.3816	1.5134	-0.1166	-0.4763	3.9322
J547	0.3380	6.0073	0.3865	1.3172	-0.1461	-0.5067	3.8955
J548	0.0761	1.5938	0.2372	0.8789	-0.0839	-0.2566	2.5777
J549	0.3486	4.9883	0.3109	1.2773	-0.1098	-0.3690	2.9270
J550	0.4990	6.2459	0.2956	1.2238	-0.1178	-0.4685	2.3622
J551	0.3307	8.3734	0.1685	0.9563	-0.0826	-0.4368	2.5019
J552	0.3662	7.8151	0.2039	1.0358	-0.0966	-0.4945	2.5139
J553	0.3644	6.5849	0.3209	1.2091	-0.1432	-0.5886	3.4696
J554	0.3427	6.2307	0.2929	1.2443	-0.1155	-0.5222	3.3211
J555	0.3646	5.7667	0.2248	1.0974	-0.0734	-0.3421	3.6804
J556	0.3449	5.0568	0.3208	1.1999	-0.0885	-0.2710	4.9118
J557	0.3453	5.8251	0.3165	1.0948	-0.0584	-0.1607	3.9711
J564	0.3321	6.2191	0.2143	0.9651	-0.0347	-0.1003	2.8546
J795	0.2777	6.4074	0.3315	1.0953	-0.1776	-0.6245	3.3588
J796	0.3307	5.8430	0.3706	1.2437	-0.1413	-0.5933	4.9944
J799	0.2970	5.1022	0.2730	1.1301	-0.0665	-0.1908	4.0077
J803	0.3573	6.0378	0.3144	1.1437	-0.0632	-0.2151	3.9385
J844	0.3042	7.8414	0.0752	0.4221	-0.0877	-0.4872	2.4430
J898	0.3647	7.7168	0.0807	0.5108	-0.0674	-0.3841	2.2909
J899	0.4088	7.7155	0.1033	0.5083	-0.1145	-0.5751	2.5750
J901	0.3187	6.8251	0.1179	0.5303	-0.1228	-0.5295	2.4761
J902	0.3079	6.2364	0.1262	0.6212	-0.1249	-0.6141	3.0745
J903	0.3647	6.6871	0.1921	0.6746	-0.1471	-0.5693	2.9198
J904	0.3951	6.8016	0.2084	0.8034	-0.1799	-0.7694	3.4600
J905	0.3412	5.8931	0.2757	0.9340	-0.1490	-0.4773	3.4108
J906	0.1579	1.4850	0.2094	0.6782	-0.0762	-0.2222	2.2120
J907	0.3265	5.9815	0.3663	1.2172	-0.1729	-0.5847	3.3717
J908	0.3589	6.3149	0.2941	1.2157	-0.1692	-0.7001	4.7319
J909	0.3443	5.6454	0.3777	1.3026	-0.1524	-0.6492	4.5242
J910	0.3365	5.4396	0.3842	1.4397	-0.1410	-0.5733	5.2562
J911	0.3923	6.3163	0.4078	1.5889	-0.1224	-0.5180	4.8405
J912	0.3274	6.1822	0.3720	1.5201	-0.1163	-0.5573	3.7508
J913	0.4193	6.0798	0.3686	1.2618	-0.1399	-0.4437	4.7096
J914	0.4232	6.3092	0.3956	1.5376	-0.1023	-0.5062	4.1354
J915	0.2663	4.9652	0.3516	1.3234	-0.1105	-0.4306	4.1136
J916	0.3627	6.3734	0.4305	1.4671	-0.1128	-0.4754	3.2766
J917	0.3525	5.1423	0.3296	1.2009	-0.0939	-0.3071	4.2019
J918	0.4891	6.7632	0.3550	1.4543	-0.0959	-0.4523	3.1045
J919	0.2899	2.9772	0.2279	0.9559	-0.0674	-0.2616	2.2885
J921	0.4019	8.1732	0.1503	0.7509	-0.0901	-0.4765	2.3193
J922	0.3711	7.1393	0.1617	0.8307	-0.0993	-0.5433	3.0496
J923	0.3637	7.4481	0.1513	0.8235	-0.0899	-0.4698	2.4255
J924	0.3661	6.7096	0.2156	1.0103	-0.1178	-0.5715	3.4110
J925	0.3475	7.3734	0.2320	1.1456	-0.1001	-0.4637	2.9664
J926	0.3769	6.3321	0.2906	1.2190	-0.1310	-0.5729	4.2607
J927	0.0806	2.0047	0.2013	0.7508	-0.0849	-0.3027	2.7662
J928	0.3497	5.3955	0.3214	1.1871	-0.1362	-0.5727	4.8589
J929	0.3548	6.0264	0.2920	1.2620	-0.1034	-0.4681	3.9523
J930	0.3488	6.1272	0.2717	1.2126	-0.0950	-0.4218	3.7636
J931	0.3610	5.7293	0.3355	1.3177	-0.0850	-0.3074	4.8476

J932	0.3545	6.4991	0.2282	1.0997	-0.0615	-0.2667	3.0514
J933	0.3634	5.9427	0.3058	1.2243	-0.0766	-0.3221	4.6340
J934	0.3443	4.6366	0.3084	1.0259	-0.0764	-0.2015	4.8929
MIZU	0.3760	6.4314	0.3705	1.4924	-0.1391	-0.6093	4.3618