Appendix L

Glossary of Key Terms and Symbols

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Definitions provided in this glossary were compiled from multiple sources, including the Senior Seismic Hazard Analysis Committee (SSHAC) guidance in NUREG/CR-6372 (Budnitz et al. 1997), NUREG-2117 (NRC 2012), and McGuire (2004). The glossary definitions are consistent with the use of the terms in the Hanford Probabilistic Seismic Hazard Analysis (PSHA) project report and may not correspond exactly to definitions appearing in regulatory documents of the U.S. Nuclear Regulatory Commission (NRC) or the U.S. Department of Energy (DOE). For additional geological terms, the reader is referred to a standard glossary of geology (e.g., Neuendorf KE, JP Mehl Jr, and JA Jackson. 2005. *Glossary of Geology*. Fifth Edition, American Geological Institute, Alexandria, Virginia.).

L.1 Glossary of Key Terms

active fault: A fault that has slipped in geologically recent time, has a clear association with earthquakes, and is likely to slip again in the future. Quaternary faults (i.e., those whose most recent slip was in the past 1.6–1.7 Myr) are generally considered to be active.

active source: A seismic source that is capable of generating moderate- to large-magnitude ($M \geq 5$) earthquakes.

aleatory uncertainty: The uncertainty that is inherent in a random phenomenon and cannot be reduced by acquiring additional data or information. Examples include future earthquake locations and magnitudes.

anelastic attenuation: The diminution of ground motion amplitude due to damping and wave scattering as the waves travel through the Earth's crust. It is often quantified by the quality factor Q and it is parameterized by an exponential decay with distance.

area source: A region of the Earth's crust that is assumed for PSHA to have relatively uniform seismic source characteristics.

backbone ground motion model: A ground motion prediction equation (GMPE), adjusted to local site conditions, selected as the basis for building the logic tree for the prediction of median ground motions. The other branches of this logic tree are populated by scaled versions of the backbone, with the scaling factors corresponding to alternative adjustments for site conditions and/or for host-to-target differences in source and path characteristics.

background source: A regional-scale area source.

Bayesian approach: An approach for determining a maximum magnitude distribution defined by Johnston et al. (1994) that uses a prior distribution for M_{max} developed from the worldwide Stable Continental Region (SCR) database. It assumes that crust with the same characteristics (extension history, age, stress state, angle of structure relative to stress) has the same *prior* distribution of M_{max}. The

approach updates the prior distribution with a likelihood function that includes local information about the maximum observed magnitude and numbers of observed earthquakes of various magnitudes. The result is a *posterior* distribution of M_{max} for an individual seismic source.

***b*-value:** A parameter describing the decrease in the relative frequency of occurrence of earthquakes of increasing sizes. It is the slope of a straight line relating absolute or relative frequency (plotted logarithmically in base 10) to earthquake magnitude. It is referred to as β when using natural logarithms.

center, body, and range of technically defensible interpretations: Terminology given in NRC (2012) to describe the goal of the integration (model-building) phase of a SSHAC process and to replace the terminology of "the informed technical community." The concept requires the incorporation of the full range of uncertainty into the model, but the exclusion of elements that lack technical support in the available data.

cluster: An approach (structure) for grouping ground motion-prediction equations based on similar seismological attributes. This approach (structure) permits evaluation and assessment of within-cluster epistemic uncertainty.

covariance matrix: Represents the extension of the concept of variance from random scalars to random vectors. The covariance matrix contains the variance of each component of the vector (in the main diagonal), as well as the covariances between all pairs of components (off-diagonal terms). Also called *variance matrix*.

coefficient of variation (COV): A statistical term that measures the relative variation of a quantity. It is calculated as the standard deviation of the quantity divided by the mean of the quantity.

conceptual seismic source characterization framework: The seismotectonic and seismic hazard-informed context within which data are evaluated and seismic sources are defined and characterized.

declustering: A statistical approach that removes foreshocks and aftershocks to produce a catalog of independent main shocks consistent with the requirements of a PSHA model. Comparison with a variety of declustering approaches used by the U.S. Geological Survey and others showed that the results are essentially the same.

distance, epicentral: The distance from the epicenter to a specific location (site).

distance, fault: The shortest distance from the fault to a specific location (site).

distance, hypocentral: The distance from the hypocenter to a specific location (site).

distance, Joyner-Boore or R_{JB}: The horizontal distance from a site to the horizontal projection of the earthquake-rupture plane.

distance, rupture or R_{Rup}: The shortest distance from the earthquake rupture to a specific location (site).

earthquake: A sudden motion or trembling of the Earth caused by the abrupt release of accumulated strain.

epistemic uncertainty: The uncertainty that arises from lack of knowledge about a model or a parameter, which can be reduced by the accumulation of additional information. Epistemic uncertainty is reflected in the different outcomes of viable alternative models, interpretations, and/or assumptions operating on the same data. Examples include geometry of seismotectonic zones and assessed source parameters such as maximum magnitude.

evaluator expert: An expert who is capable of evaluating the relative credibility of multiple alternative hypotheses to explain a set of observations. Requires considering the available data, listening to proponent and other evaluator experts, questioning the technical basis for their conclusions, and challenging the proponent's position.

expert elicitation: A formal expert assessment technique of conventional decision analysis in which experts are led through a series of assessment steps to address narrowly defined questions about specific uncertain quantities within their area of expertise.

expert assessment: The use of expert judgment to address technical questions and their uncertainties.

fault: A fracture surface or zone in the Earth across which there has been relative displacement.

fault, dip-slip: A fault in which the relative displacement is along the direction of the dip of the fault plane; either downdip (normal fault) or updip (reverse fault).

fault, normal: A dip-slip fault in which the block above the fault has moved downward relative to the block below, representing crustal extension.

fault, reverse: A dip-slip fault in which the block above the fault has moved upward relative to the block below, and the fault dip is >45°.

fault slip rate: The amount of displacement on a fault divided by the time period over which the displacement took place.

fault, strike-slip: A fault in which the relative displacement is along the strike of the fault plane, either right- or left-lateral.

fault, thrust: A dip-slip fault in which the block above the fault has moved upward relative to the block below, and the fault dip is <45°, representing crustal compression.

fault zone: The zone of deformation composing a fault, which may be hundreds of meters wide.

focal mechanism: A geometrical representation of earthquake faulting expressed in terms of the strike and dip of the fault plane and the rake angle of the slip vector with respect to the fault plane.

future earthquake characteristics: The expected characteristics of future earthquakes that occur within a particular seismic source. The characteristics identified (e.g., style of faulting, orientation of rupture) are those that are potentially important to ground motion prediction equations.

geometric spreading: The diminution in ground motion amplitude as the wave front expands with distance. It is often parameterized by distance raised to a negative power.

geon: A 100-million-year interval of geologic time starting with the present and continuing backward through time. Geons are named according to the number representing geologic age divided by 100 million. Geologic ages less than 100 million years would be in geon 0. For example, an age of 1,650 million years would belong to geon 16.

ground motion characterization (GMC) model: A model that provides an algorithm to predict ground motions at a particular location, including the associated epistemic and aleatory uncertainties. Elements in a ground motion model include algorithms for the median ground motion, the aleatory variability about the median, the epistemic uncertainty in the median, and the epistemic uncertainty in the aleatory variability. The model may include adjustments of the various GMPEs used to render them more applicable to source, path, and site characteristics of the target region

ground motion prediction equation (GMPE): A formula for estimating values of a specified ground motion parameter, such as response spectral ordinates at a specified oscillator period (or frequency), as a function of independent variables, including magnitude, style of faulting, source-to-site distance, and the characterization of the near-surface layers at the site; other parameters related to the earthquake source, path and site may also be included. The equation predicts a distribution of values of the ground motion parameter, defined by the median value from the equation and the standard deviation (sigma) of the logarithmic residuals.

hazard: A hazard is a situation that poses a threat to life, health, property, or environment**.** Natural hazards are commonly expressed probabilistically as the annual frequency of a particular level or amplitude of hazard, such as the annual frequency of exceeding a particular amplitude of ground motion.

hazard calculation: The calculation of annual frequencies with which seismic ground motion amplitudes will be exceeded as a result of possible earthquakes in the region. The results of this calculation may be represented as mean annual frequencies ("mean hazard curves") or fractile annual frequencies ("fractile hazard curves").

hazard-informed approach: An assessment methodology for characterizing seismic sources or ground motion models that places greatest emphasis and focus on the elements that are most important to the hazard analysis results.

Hazard Input Document (HID): A report that provides the documentation necessary for users to implement the input model (e.g., the seismic source characterization or ground motion characterization model) in PSHA calculations for future applications. The HID includes the logic tree structure (with all branches and weights) for each seismic source, but it does not include the technical basis or justification for the elements of the model.

hypocenter: The point in the Earth at which an earthquake is initiated. Also referred to as the *focus*.

informed technical (scientific) community: A hypothetical construct of the SSHAC guidelines that embodies the community distribution of uncertainty sought by the SSHAC process at any study level. The goal of a SSHAC process is to "represent the center, body, and range of the views of the informed technical community." "Informed" means that the technical community is familiar with the project-specific databases and that the individuals have gone through the interactive SSHAC process. Recent SSHAC implementation guidance (NRC 2012) has replaced the terminology to avoid confusion. In that

guidance, the goal of the SSHAC process is said to be twofold: 1) to consider the data, models, and methods of the larger technical community; and 2) to represent the center, body, and range of technically defensible interpretations.

integration: The process for representing the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods).

intensity: A measure of the effects (e.g., damage) of an earthquake at a particular place. Commonly used scales are Rossi-Forel, Mercalli, and modified Mercalli.

inter-event variability: The portion of the total aleatory variability in ground motions that represents the variability in average level of ground motions from earthquake to earthquake. This is also referred to as between-event variability.

intra-event variability: The portion of the total aleatory variability in ground motions that is common to all recordings from an individual earthquake. This is also referred to as within-event variability.

Inverse Random Vibration Theory: A technique to calculate the Fourier or power spectrum of the ground motion given the response spectrum and the duration of the motion.

kappa: A parameter that characterizes anelastic attenuation or damping through the uppermost part of the Earth's crust that acts as a filter on the high-frequency content of the seismic waves. In this study, kappa is decomposed into several contributing components, which are listed with the symbols at the end of this glossary. **likelihood function:** A measure of the consistency of a set of model parameter values with a set of observations. It is constructed by calculating the probability density function of the observations given the parameters, and then interpreting it as a function of the parameters, given the observations.

liquefaction/paleoliquefaction: The temporary conversion of water-saturated, unconsolidated soils (sediments) into a medium that behaves like a fluid. It can occur as a secondary hazard related to strong shaking from an earthquake. The age, location, and extent of liquefaction can be used to estimate the size and location of prehistoric earthquakes.

logic tree: A series of nodes and branches to sequence the assessments in an analysis by describing alternative models or parameter values or both. At each node, there is a set of branches that represent the range of alternative credible models or parameter values; the branch weights must sum to unity at each node. The weights on the branches of logic trees reflect scientific judgments in the relative confidence in the alternative models.

longevity, hazard studies: The length of time a hazard study is considered adequate for continued use.

magnitude (general): A measure of earthquake size, classically determined by taking the common logarithm (base 10) of the largest ground motion recorded during the arrival of a seismic wave type and applying a standard correction for distance to the epicenter.

magnitude, adjusted (M*): Moment magnitude adjusted to correct for a bias that results from the propagation of uncertainty in magnitude estimates through the magnitude conversion process.

magnitude, body-wave (m_b): Magnitude derived from the largest displacement amplitude of body waves.

magnitude, coda-wave (M_C): Magnitude derived from the amplitude and duration of the seismic coda (latter part of a seismic wave train).

magnitude, duration (M_D): Magnitude derived from the total duration of the measured seismic wave train.

magnitude, Lg (m_{bLg}): Magnitude derived from the displacement amplitude of Lg waves; often used in Eastern North America because it can be accurately measured from typical low-gain seismographs at long distances from the source.

magnitude, moment (M, M_w): Magnitude derived from the scalar seismic moment, M_o; approximately equal to local magnitude for moderate earthquakes, and to surface-wave magnitude for large earthquakes. As discussed by Hanks and Kanamori (1979), M_w is derived from Kanamori's (1977) magnitude scale based on strain energy drop and is given by the relationship $\log(M_o \text{ in dyne-cm}) = 1.5M_w + 16.1$. Hanks and Kanamori (1979) defined the moment magnitude scale **M** using the relationship $\mathbf{M} = \frac{2}{3}\log(M_o \text{ in dyne-cm}) - 10.7$. The result is a 0.03-magnitude unit difference between M_w and **M** for the same value of M_o.

magnitude, Richter or local (M_L): Common logarithm of the trace amplitude (in microns) of a standard Wood-Anderson seismograph located on firm ground 100 km from the epicenter. Correction tables are used to account for other distances and ground conditions.

magnitude, surface-wave (M_S): Earthquake magnitude determined from the maximum amplitude of 20-second period surface waves.

magnitude scaling: The dependence of ground motion amplitude on magnitude.

maximum-likelihood method: A statistical technique that estimates the parameters of a model by determining the parameter values that maximize the likelihood function.

maximum magnitude (M_{max}): The largest earthquake that a seismic source is assessed to be capable of generating. The maximum magnitude is the upper bound of recurrence curves.

modeling uncertainty: The epistemic uncertainty that results from the use of various models to explain observed data and predict future phenomena. In principle, it can be reduced or eliminated by further testing, data accumulation, or more detailed modeling. It is one source of epistemic uncertainty.

paleoseismic/paleoseismicity: Term referring to the science of evaluating prehistoric earthquakes through the geological analyses of the surficial strata and landforms that have been created, deformed, and/or offset by earthquakes.

participatory peer review: As defined in SSHAC guidance, an ongoing review throughout an entire project that allows reviewers to observe and comment on the process followed and the technical assessments developed. Reviewers must be recognized experts in the subject matter under review ("peers" in the true sense).

probability of activity: The likelihood that a particular tectonic feature is seismogenic and will localize moderate-to-large ($M \geq 5$) earthquakes.

probabilistic seismic hazard analysis (PSHA): An analytical methodology that estimates the likelihood that various levels of earthquake-caused ground motions will be exceeded at a given location in a given future time period.

project manager (PM): As defined in SSHAC guidance, a dedicated full-time professional who is the point of contact between the project and the project sponsor(s), and who is responsible for ensuring adherence to scope, schedule, budgets, and contractual requirements. The PM organizes workshops and keeps the sponsor(s) apprised of progress.

proponent expert: An expert who advocates a particular hypothesis or technical position.

quarter-wavelength approach: An approach used to quantify the ground motion amplification factor for an arbitrary site by considering the ratio of time-averaged shear-wave velocity and damping between the source and the site, as well as the effect of kappa at the site.

random vibration theory: A technique to calculate peak values of a time series (in this case, the spectral acceleration), given the Fourier or power spectrum and duration of the ground motion.

rate of seismicity: Rate of occurrence of earthquakes above some specified magnitude for a specific region.

recurrence, recurrence rate, recurrence curve: The frequency of earthquake occurrence of various magnitudes often expressed by the Gutenberg-Richter relationship.

recurrence interval: The mean time period between earthquakes of a given magnitude on a fault or in a region.

recurrence model: A model to express the relative number or frequency of earthquakes having different magnitudes. A common recurrence model is the exponential magnitude distribution.

recurrence model (Poisson, Renewal): A model to express the relative number of earthquakes of different magnitudes that occur within or associated with a particular seismic source. Two models that are commonly used to represent the temporal elements of a recurrence model are Poisson and Renewal. In the Poisson model, the time between consecutive earthquakes follows an exponential distribution and there is no dependence of the timing of the next earthquake with the timing or size of earlier earthquakes. In the Renewal model, the time between consecutive events is assumed to be related to the release and accumulation of strain such that there is a relation between the timing of the most recent event and time to the next event.

resource expert: A technical expert who has either site-specific knowledge or expertise with a particular methodology or procedure useful to the evaluator experts in developing the community distribution.

response spectrum: A plot of the maximum response (in terms of absolute acceleration, relative velocity, or relative displacement) of single-degree-of-freedom oscillators of specified damping against their natural period or frequency of vibration, when subjected to a particular earthquake ground motion.

seismicity: The occurrence, intensity, and distribution of earthquakes in a region; also refers to the frequency and depths of these earthquakes.

seismic moment: Scalar measurement of the size of an earthquake. It is the product of the area of rupture, the average slip on the fault, and the shear modulus of the crustal rocks. It is typically expressed in units of dyne-cm.

seismic refraction: A method that involves analysis of the travel times of the first energy to arrive at the geophones laid out in a linear array on the surface after acoustic energy is input into the subsurface. Both compressional-wave and shear-wave seismic refraction surveys can be conducted, with compressional-wave refraction being by far the most common. Compressional and shear-wave refraction models can be useful to quantify approximate lateral velocity variation beneath the surface-wave arrays, identify the depth and P-wave velocity of the saturated zone (which is preferably constrained during modeling of Rayleigh wave data), determine depth to bedrock, and estimate the maximum velocities in the near surface.

seismic source: Traditionally, in a probabilistic seismic hazard analysis, a region or volume of the Earth's crust that has uniform earthquake potential or uniform earthquake-generating characteristics. In this project, unique seismic sources (faults, regions) are spatially defined to account for distinct differences in earthquake recurrence rate, maximum earthquake magnitude, expected future earthquake characteristics, and probability of generating earthquakes of magnitude 5 or larger.

seismic source characteristics: The parameters that characterize a seismic source for PSHA, including source geometry, maximum magnitude, earthquake recurrence, and future earthquake characteristics. In ground motion analysis, the term seismic source characteristics refers to the characteristics of the seismic energy release (e.g., seismic moment, stress drop, duration, depth, source mechanism, slip distribution, rupture velocity).

seismic source zones: See "**area source**." Volumes within the Earth where future earthquakes are expected to occur. The geometry of seismic sources is defined by differences in earthquake recurrence rate, maximum earthquake magnitudes, future earthquake characteristics, and the probability of activity of tectonic features.

seismic zone: A region showing relatively elevated levels of observed seismicity.

seismogenic: Capable of generating tectonically significant earthquakes ($M \geq 5$).

seismotectonic province: A region of the Earth's crust having similar seismicity and tectonic characteristics.

sensitivity analysis: The calculation of the effect that a particular input parameter or model has on the output of a seismic hazard analysis. This may be represented as multiple hazard curves for these alternative input assumptions.

shear-wave velocity: An essential parameter used for evaluating the dynamic properties of soils or rock. It represents the propagation speed of shear (i.e., transverse) waves.

sigma: The term generally used to refer to the standard deviation of the logarithmic residuals of a strong-motion data set with respect to the median predictions from a GMPE. Sigma can be decomposed into

inter- and intra-event components, which are also referred to as between-event and within-event components. Further subdivision of sigma is also considered in this project, as reflected in the list of symbols at the end of this glossary.

smoothing: The spatial variation in the rate of activity (*a*-value of the earthquake recurrence relationship) and the *b*-value (slope of the recurrence curve).

source zone: See **area source**.

spatial clustering: Observed or inferred proximity of earthquake occurrences.

spatial stationarity: A model in which the locations of future earthquakes are assessed to follow the spatial distribution of past earthquakes.

SSC Model: A seismic source characterization model to represent the parameters that characterize a seismic source for PSHA, including source geometry, probability of activity, maximum magnitude, and earthquake recurrence.

SSHAC (Senior Seismic Hazard Analysis Committee): A committee sponsored by the NRC, DOE, and Electric Power Research Institute to review the state-of-the-art in PSHA and to develop methodologies for using expert judgment and treating uncertainties in seismic hazard analyses. The report of the SSHAC is given in Budnitz et al. (1997), which is also called the SSHAC guidelines.

SSHAC methodology: The recommended methodology for conducting a PSHA given in Budnitz et al. (1997).

SSHAC Assessment Level: See **SSHAC study level**

SSHAC Study Level: One of four "Study Levels" (also called SSHAC Levels) identified in the SSHAC guidelines, ranging from Level 1 projects, which involve very few participants, to Level 4 projects, which involve multiple participants and workshops.

stability: Characteristic of a hazard input model such as the SSC model that properly quantifies current knowledge and uncertainties such that the identification of new data, models, and methods will not lead to the need to significantly revise the model.

surface-wave techniques: Proven nondestructive seismic methods that can be used to determine the variation of shear-wave velocity with depth. These techniques generally involve the measurement of Rayleigh waves. However, surface-wave testing can also be conducted using Love waves. Examples of active surface-wave techniques (SASW, MASW, and MALW) in which acoustic energy is input to the subsurface by an energy source include spectral analysis of surface waves (SASW) and multi-channel analysis of surface waves (MASW). Examples of passive surface-wave techniques include the array microtremor and refraction microtremor (also referred to as passive MASW or linear array microtremor) techniques.

technical integrator (TI): A SSHAC term for an individual or team responsible for considering the data, models, and methods of the larger technical (scientific) community and for assessing and representing the

center, body, and range of technically defensible interpretations in a seismic hazard model. In this project, this was done using a SSHAC Level 3 assessment process.

tectonic province: See **seismotectonic province**.

temporal clustering: Occurrences of multiple closely timed earthquakes separated by longer periods of quiescence. Events that tend to cluster represent a deviation from a stationary Poisson process.

upper-bound magnitude: See **maximum magnitude**.

uncertainty: A general term. See **epistemic uncertainty** and **aleatory uncertainty**.

variance: The expected value, taken with respect to its probability distribution, of the squared deviation of an aleatory variable from its expected value.

weight: A numerical value ($\leq$1.0 or 100%) assigned to alternative credible models or parameter values. Weights reflect scientific judgments that any particular model or parameter value is the correct model or parameter.

zonation: The process of developing seismic source maps (or a set of seismic zones).

L.2 Symbols

$\boldsymbol{k_{obs}}$**:** Source, site, and distance-dependent spectral decay parameter controlling the rate of amplitude fall-off at high frequency.

$\boldsymbol{k_{source}}$: Source contribution to the high-frequency spectral decay parameter.

$\boldsymbol{k_{path}}$: Path-dependent spectral decay parameter reflecting the incremental attenuation due to the horizontal propagation of shear waves through the crust.

$\boldsymbol{k_{site}}$**:** Site-dependent spectral decay parameter at zero epicentral distance representing the effects of intrinsic material damping and scattering in the shallow crust.

$\boldsymbol{k(0)}$**:** kappa at zero epicentral distance reflecting the combined source and site effects on the high-frequency spectral decay.

$\boldsymbol{k_{baserock}}$**:** Spectral decay parameter representing intrinsic material damping in the competent baserock.

$\boldsymbol{k_{profile}}$**:** Spectral decay parameter representing intrinsic material damping and scattering in the shallow subsurface profile beneath the site.

$\boldsymbol{k_{scattering}}$**:** Spectral decay parameter caused by the scattering and reflection of high-frequency ground motion in the presence of velocity contrasts and layering in the shallow crustal layers beneath the site.

$\boldsymbol{k_{damping}}$**:** Spectral decay parameter representing intrinsic material damping in the shallow subsurface profile beneath the site or in the baserock.

$\boldsymbol{k_{scattering-b}}$**:** Scattering kappa in the baserock, typically negligible.

$\boldsymbol{k_{scattering-p}}$**:** Scattering kappa in the shallow subsurface profile beneath the site.

$\boldsymbol{k_{damping-b}}$**:** Damping kappa in the competent baserock.

$\boldsymbol{k_{damping-p}}$**:** Damping kappa in the shallow subsurface profile beneath the site.

$\boldsymbol{k_1}$**:** Short-distance spectral decay parameter k averaged for scenarios with magnitude 5, 6, and 7 and R_{jb} distances of 5, 10, and 20 km, respectively. This parameter is used in the IRVT approach to approximate $\boldsymbol{k(0)}$.

$\boldsymbol{Q}$**:** Quality factor or energy loss parameter.

ξ: Intrinsic material damping.

σ_{epi}: Epistemic uncertainty on the median

σ_{Region}: Component of the epistemic uncertainty of the median corresponding to region-to-region variability

σ_{μ}: Component of the epistemic uncertainty of the median corresponding to inherent epistemic uncertainty in the median ground motion model

$\sigma_{epi,min}$: Minimum epistemic uncertainty that needs to be applied to the site term in downstream site response analyses

$\sigma_{ergodic}$: Total or ergodic standard deviation

τ: Between-event (or inter-event) standard deviation

ϕ: Within-event (or intra-event) standard deviation

ϕ_{S2S}: Site-to-site variability

ϕ_{ss}: Event-corrected single-station standard deviation

σ_{ss}: Single-station standard deviation

σ: Aleatoric standard deviation used in the model, computed from the event-corrected single-station standard deviation and the between-event standard deviation.

L.3 References

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