Development of Taiwan Ground Motion Model for Crustal Earthquake

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Taiwan SSHAC Level 3 PSHA Study

Taipei, Taiwan

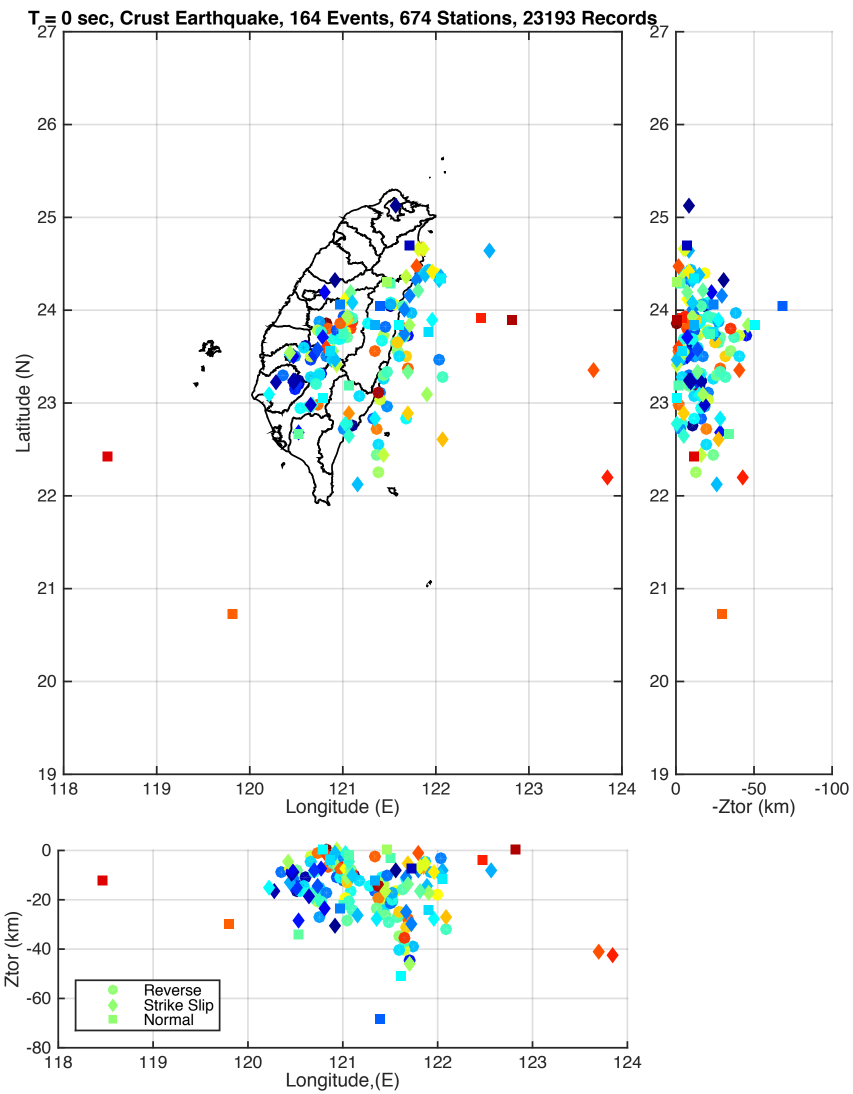
Content

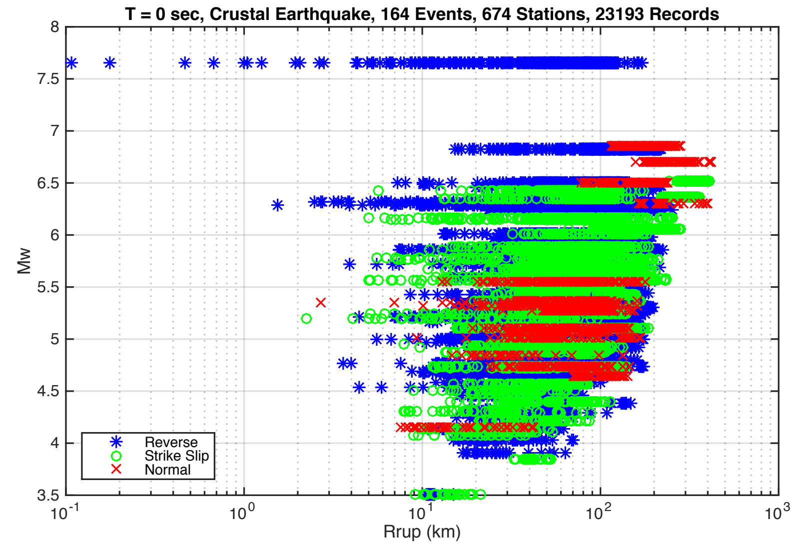
- **Development Approach**
  - Selected Ground Motion Data
  - Median Model
  - Sigma Model
  - Regression Approach
- **Model Prediction Result**
  - Median
  - Sigma
- **Residual Result**
  - Event-Specific Residual
  - Station-Specific Residual
  - Record-Specific Residual

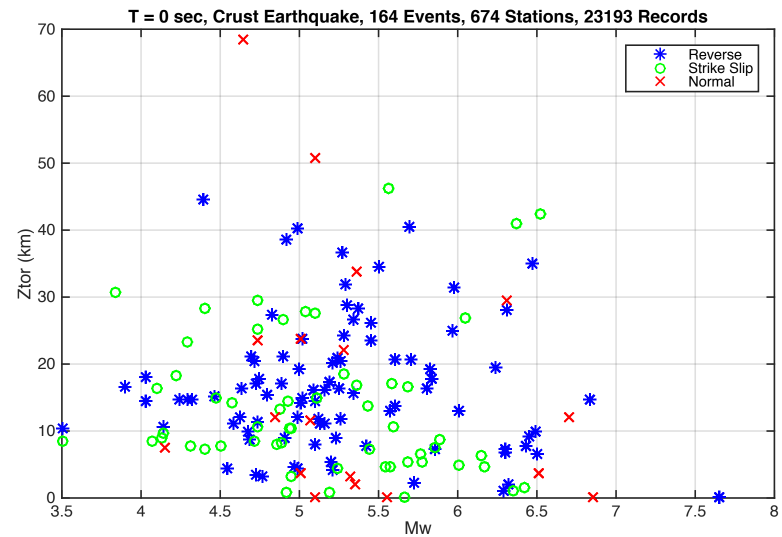
Development Approach – I

- **Selected Ground Motion Data**
  - Use most updated GM database
    - SSHAC_GM_Database_v4 2017.03.31
  - Selection Criteria
    - PGAraw,max > 4 gal
    - Exclude events with less than 10 records
    - Exclude stations with less than 10 records
    - Exclude records from low-resolution RTD station
    - Exclude four crustal events and one subduction event
      - The estimated event terms of them show significant bias from other events
    - Exclude record with T > Tmax

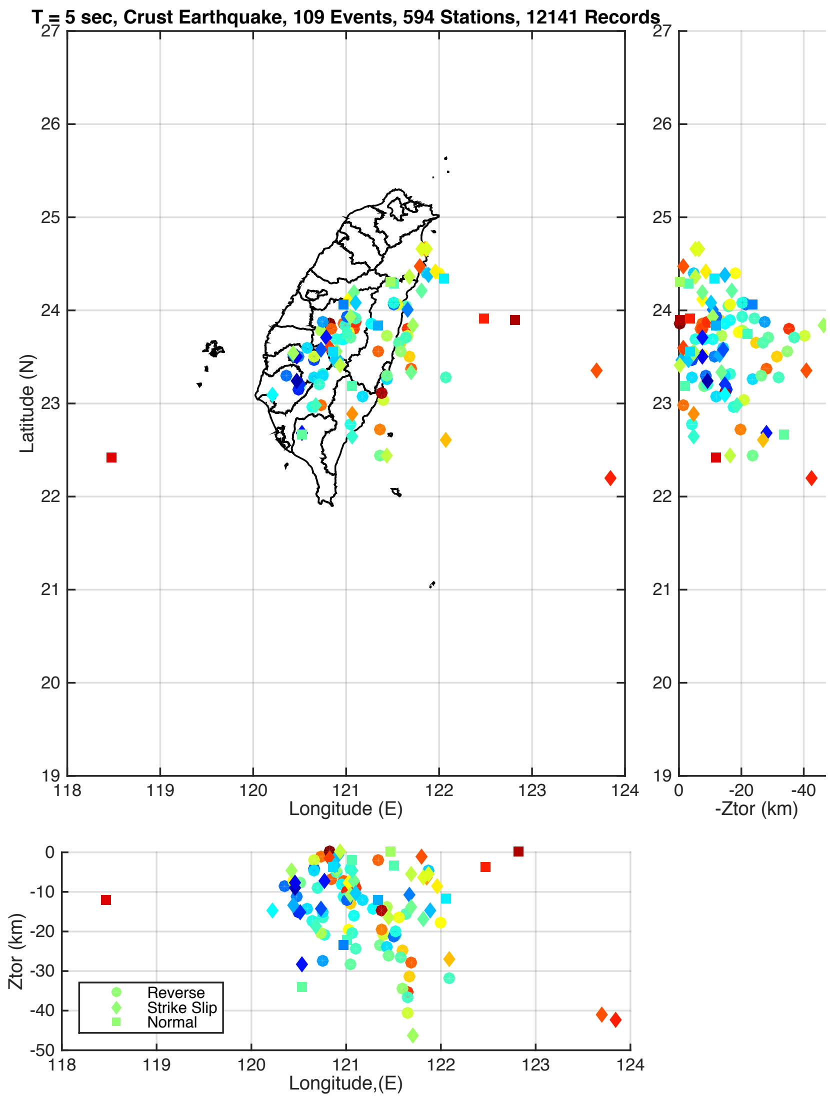
Selected Ground Motion Data for Crustal Source – I

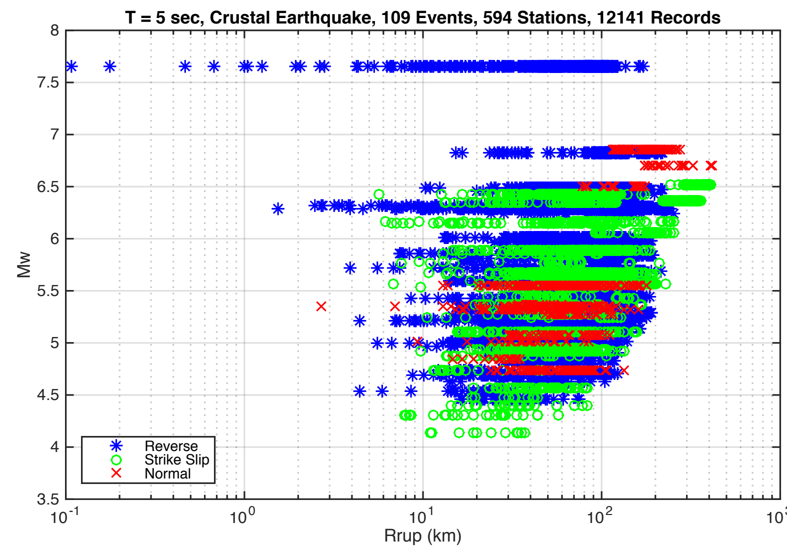


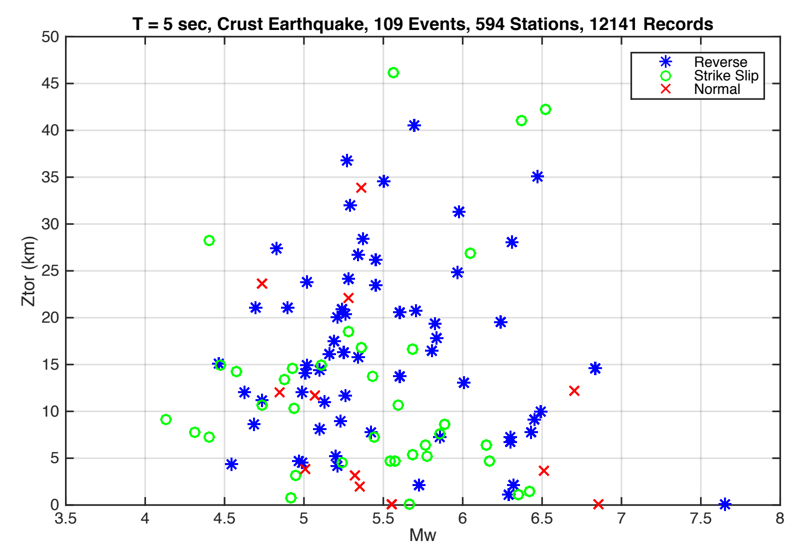




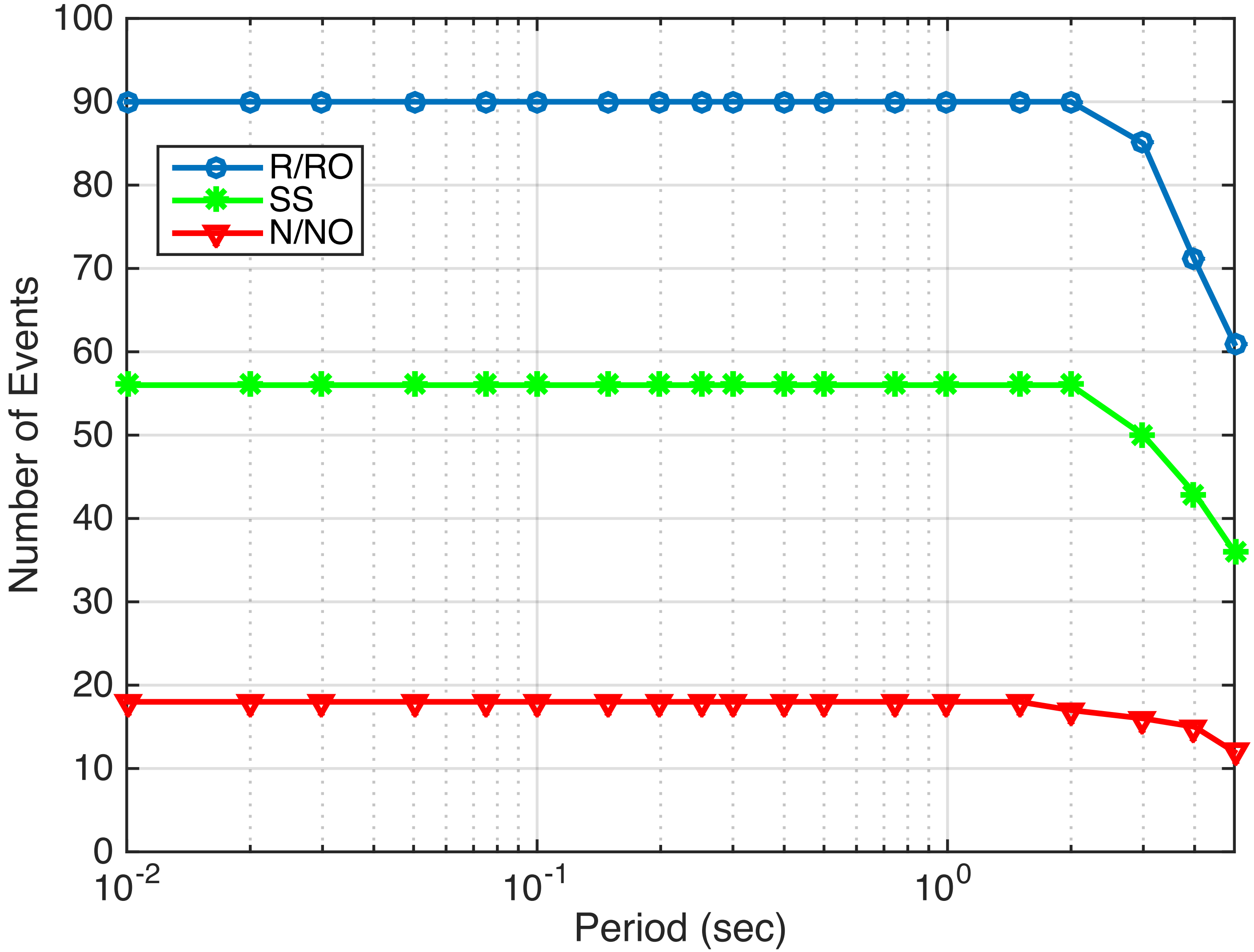
Selected Ground Motion Data for Crustal Source – II



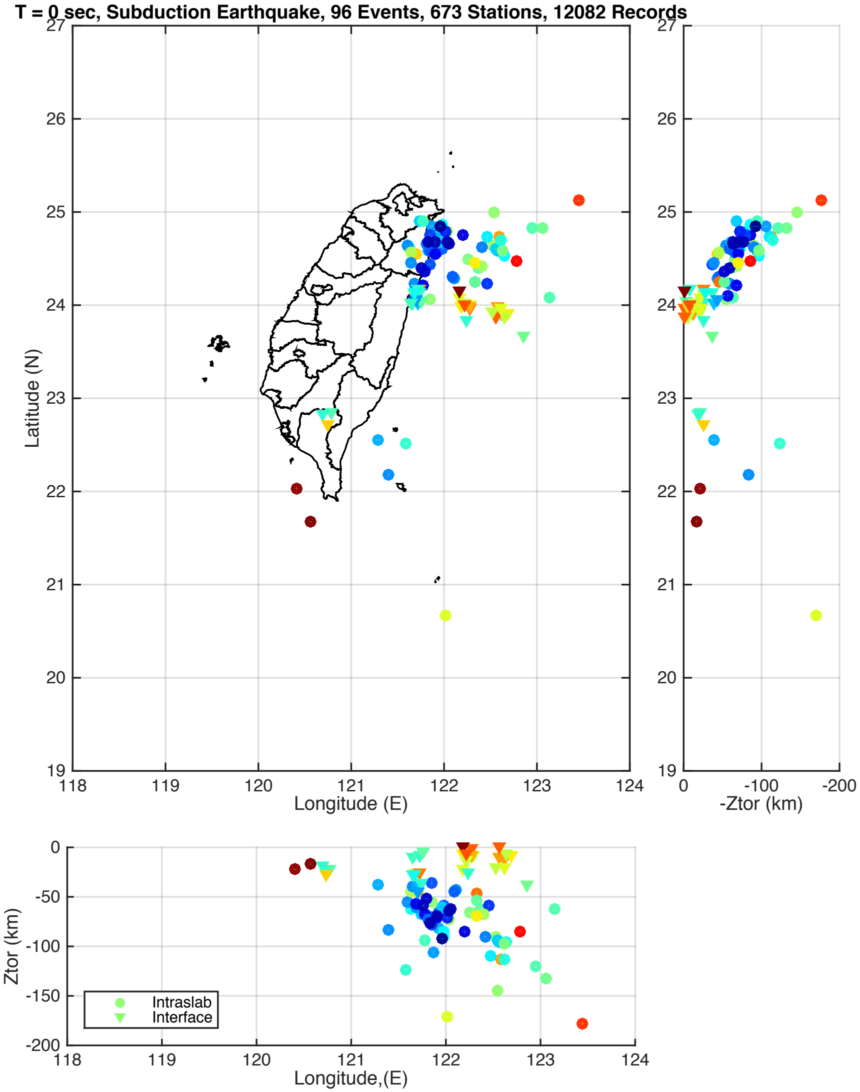


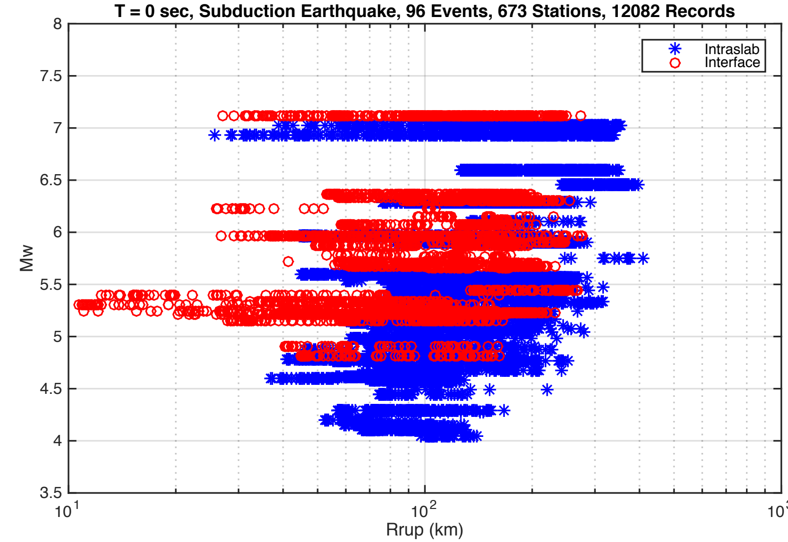


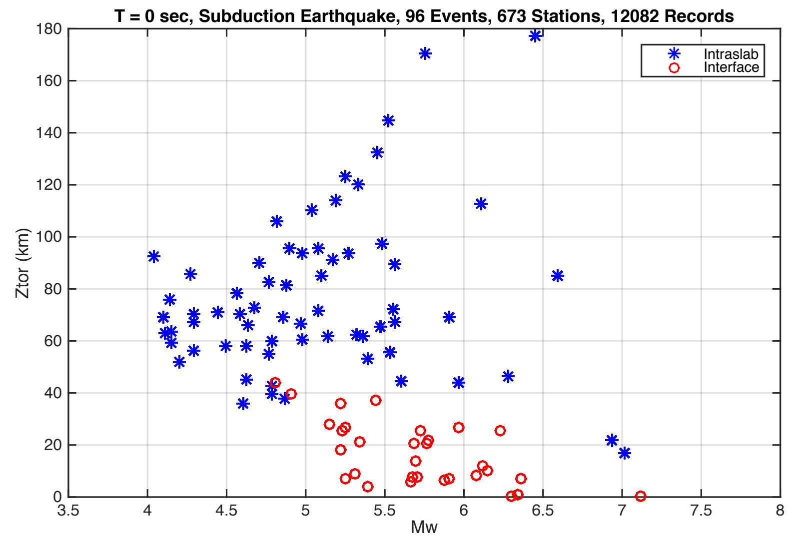
Selected Ground Motion Data for Crustal Source – III



Selected Ground Motion Data for Subduction Source – I







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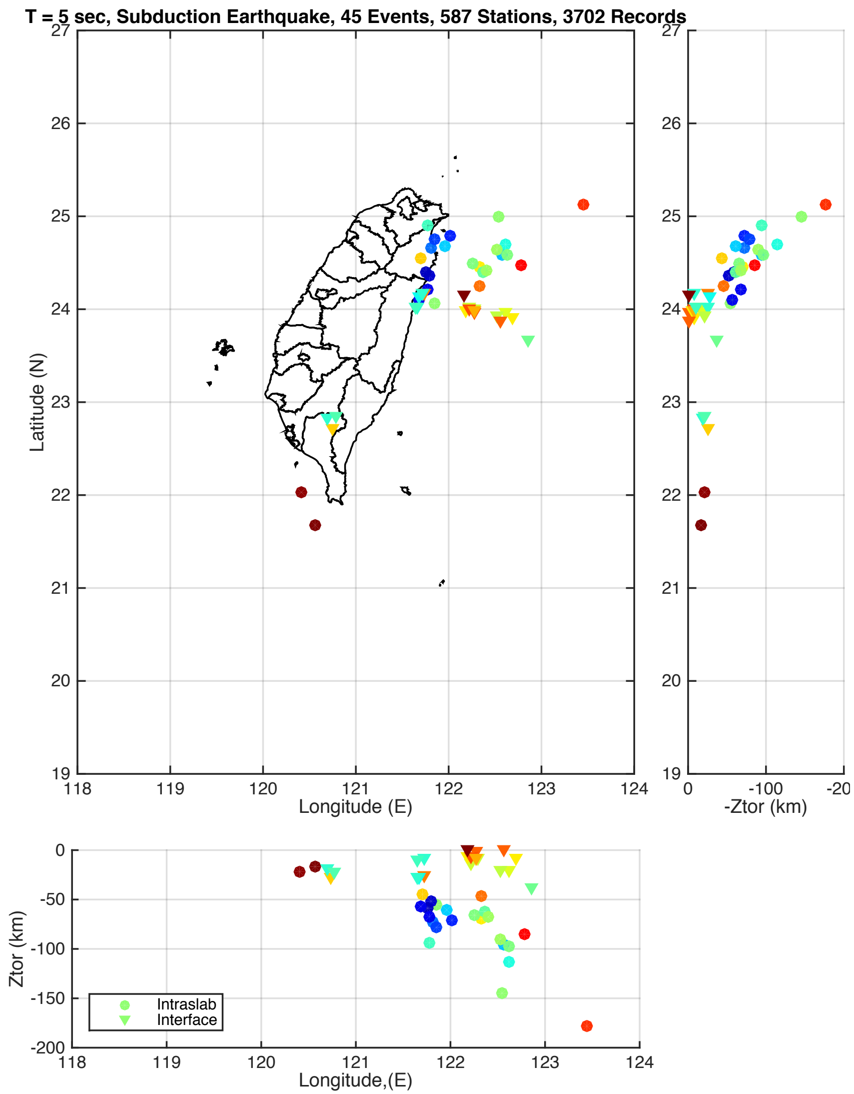
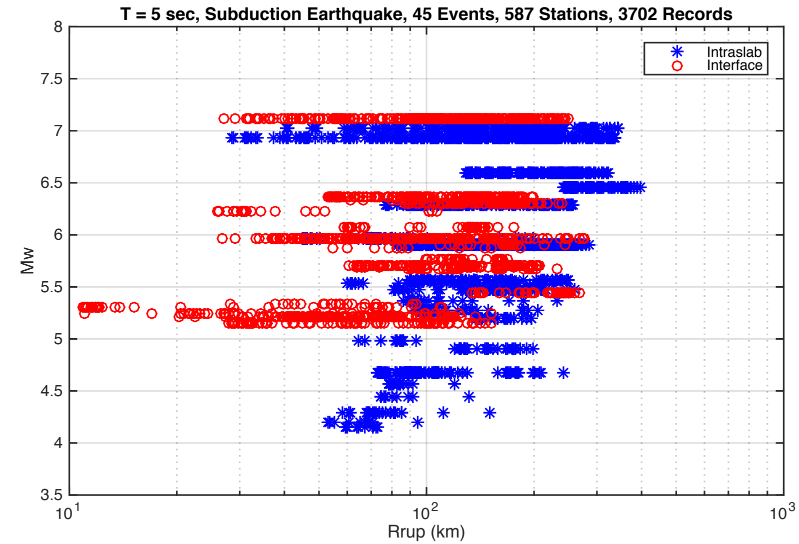
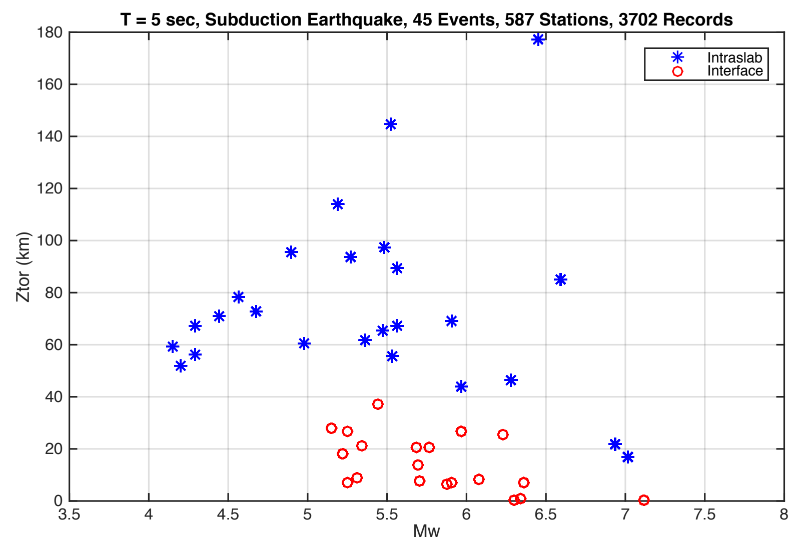
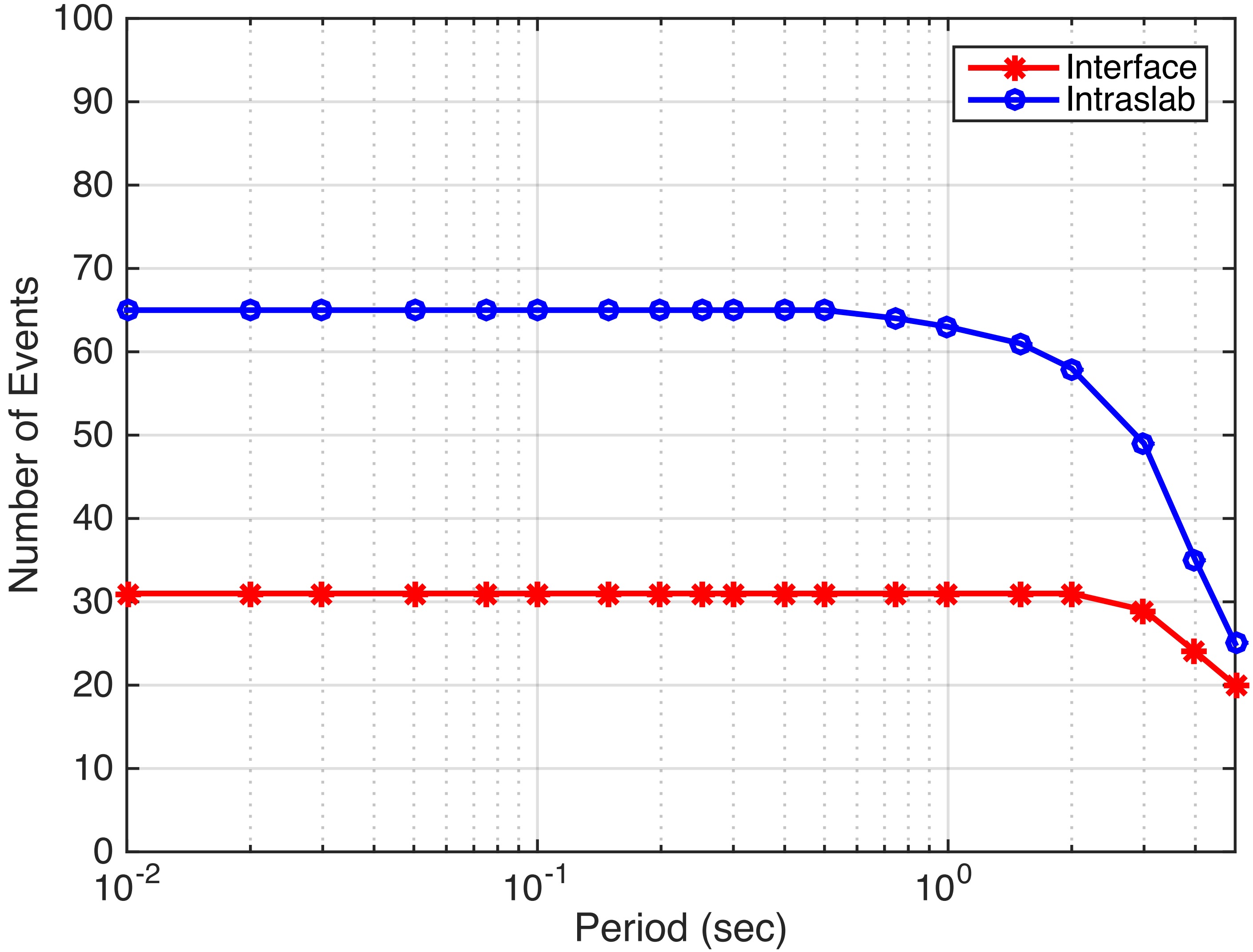






Selected Ground Motion Data for Crustal Source – III



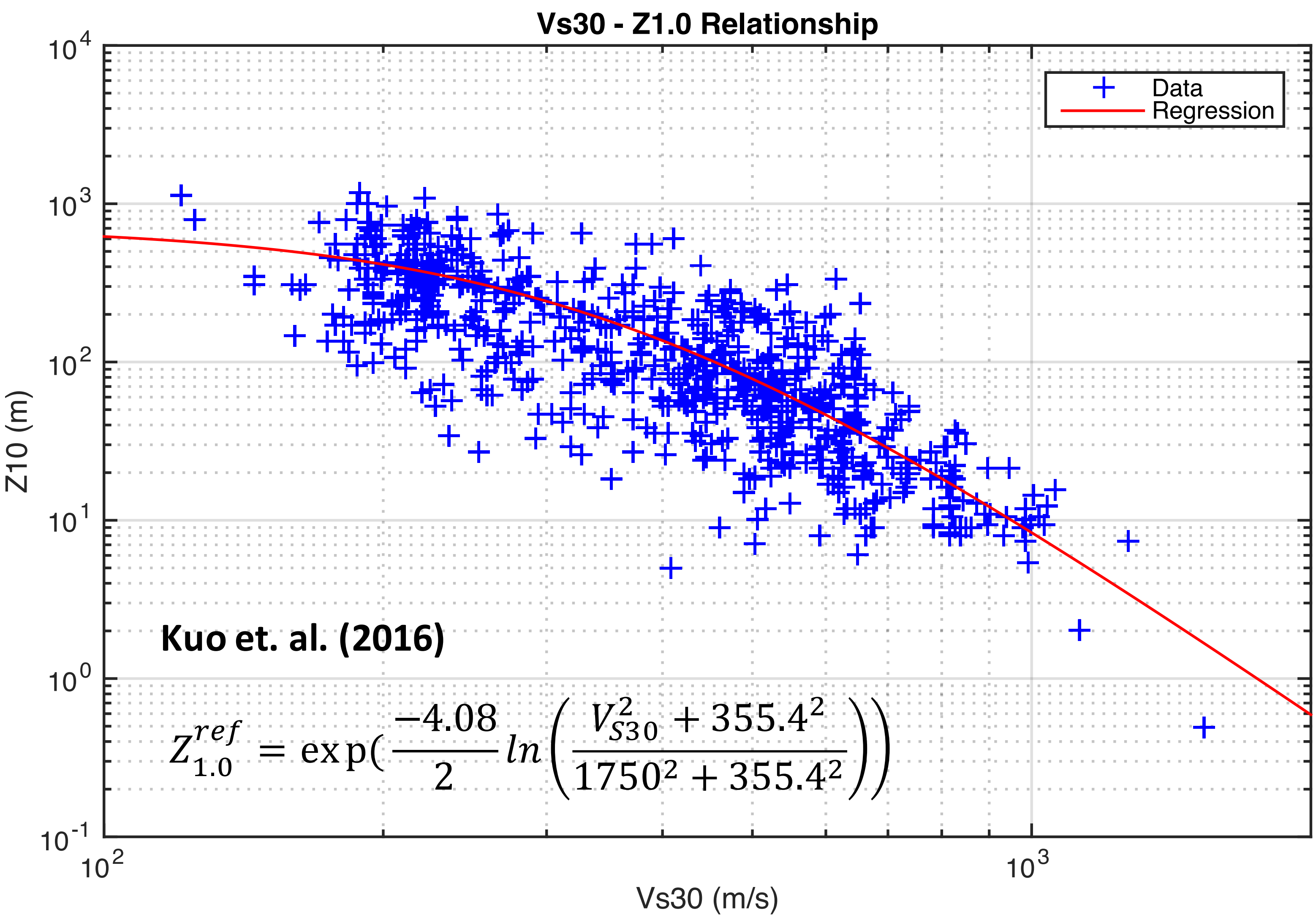
Development Approach – II

- **Features of Median Model**
  - One equation with different source terms, different path terms but same site term for **crustal** and **subduction** source
  - It is constructed by the **reference spectrum** at reference ground motion scenario plus **different scalings** including
    - Source scaling: magnitude, depth, different source types
    - Distance scaling: Rrup-based scaling to describe geometric spreading and anelastic attenuation
    - Site Scaling: linear site effect (shallow soil effect and deep soil effect) and nonlinear site effect
  - Covariance matrix of model coefficients as well as function form of statistical uncertainty are developed

Development Approach – II

- **Reference Ground Motion Scenario**
  - Magnitude Mw 5.5
    - It is selected based on data rich region
  - Reference Ztor
    - It is selected based on the data rich region
      - 15 km for crustal source
      - 50 km for subduction source
  - Reference Rrup 0 km
    - It is selected because it will be easy to constrain the magnitude scaling
  - Reference Vs30 760 m/s
  - Reference Z1.0 is calculated by Vs30-Z1.0 relationship proposed by Kuo. et. al. 2016 with Vs30 760 m/s

Vs30 vs. Z1.0 Relationship in Taiwan



Kuo et. al. (2016)

$$Z_{1.0}^{ref} = \exp\left(\frac{-4.08}{2} ln\left(\frac{V_{S30}^2 + 355.4^2}{1750^2 + 355.4^2}\right)\right)$$

Development Approach – III

- **Reference Spectrum**
  - Mainshok / Aftershock
  - Measured / Inferred Vs30
  - Crustal
    - Strike-Slip
    - Normal / Normal Oblique
    - Revers / Reverse Oblique
  - Subduction
    - Ryukyu Interface
    - Ryukyu Interface
    - Manila Interface
    - Manila Intraslab

Development Approach – IV

- **Magnitude Scaling for Crustal Source**
  - We observed a clear trend of magnitude saturation from the predicted event term of crustal source
    - A second order polynomial function form are used to describe the magnitude scaling of crustal source
  - We also observed a significant change of magnitude scaling from the predicted event term of crustal source with Mw < 5.0
    - A switch on-off function form are used to adjsut the magnitude scaling for the event with Mw < 5.0
  - Large magnitude scaling (Mw > 7.0) is constrained by the conditions including:
    - Ground Motion data of Chi-Chi earthquake
    - The magnitude scaling rate should be larger than zero for the crustal event with Mw < 8.0

Development Approach – IV

- **Magnitude Scaling for Subduction Source**
  - We observed from estimated event terms that the magnitude scaling of interface and intraslab events are similar
    - We use the same magnitude scaling for them with Mw < 7.1
  - We can't observed the magnitude saturation phenomena from the predicted event term of subduction source
    - A first order polynomial function form are used to describe magnitude scaling
  - For Mw > 7.1 event, we use the magnitude scaling of interface and intraslab events (Mw > 7.1) proposed by Zhao et. al. 2016
    - These magnitude scalings are developed by Japan GM data
    - The magnitude scaling of interface and intraslab are different for Mw > 7.1
    - These magnitude scalings are Rrup-independent for Mw > 7.1
      - Based on the reason that for a very large event, only a part of the fault contribute to the ground motion

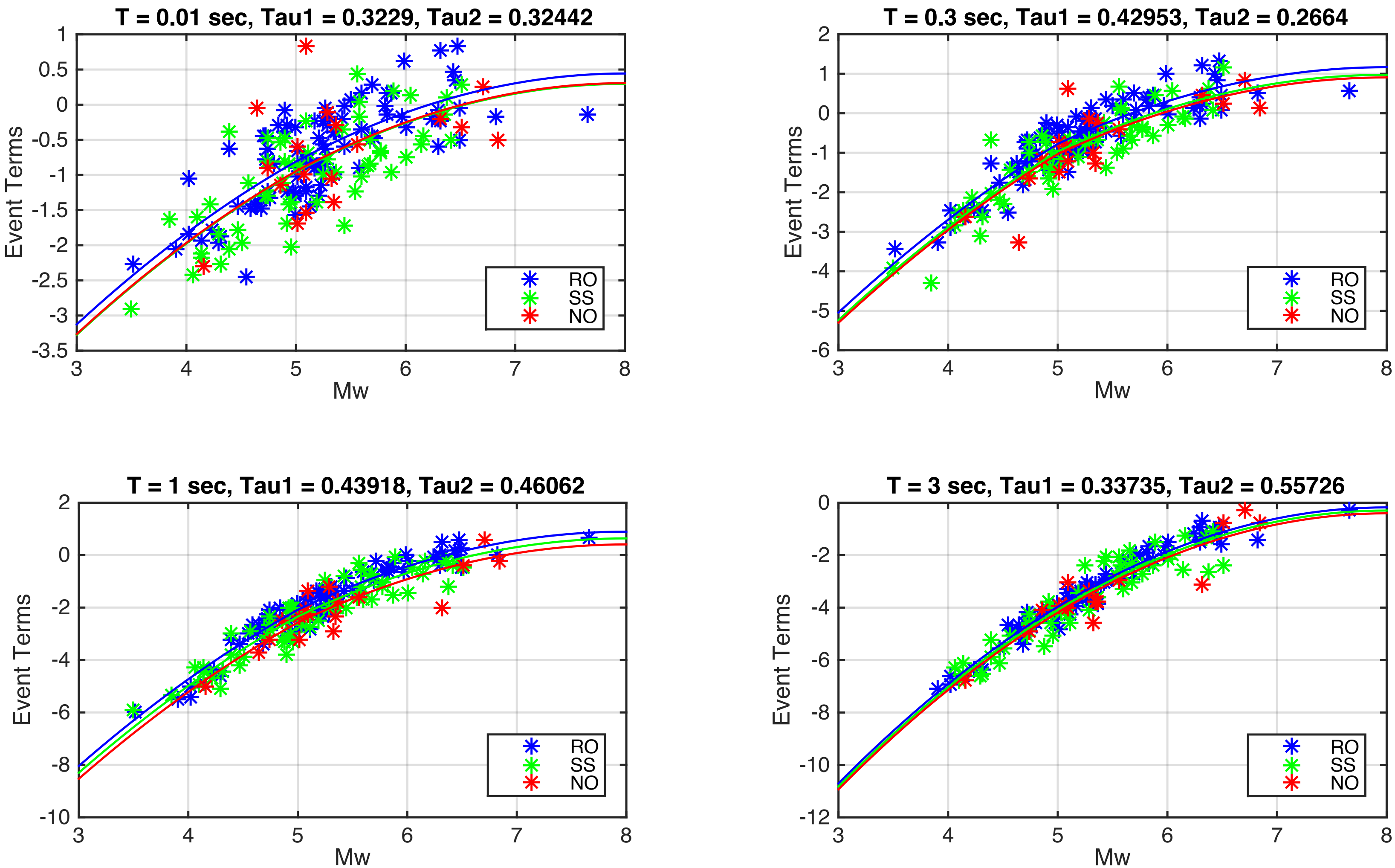
Development Approach – V

- **Depth Scaling for Crustal Source**
  - We found that the predicted event term residual is proportional to depth within available data range (Ztor 0 to 70 km)
  - We found that if the magnitude-dependent reference depth was used, the large magnitude event term will be overestimated
    - As a result, the magnitude-independent reference depth is used
- **Distance Scaling for Crustal Source**
  - We use distance scaling term of CB14 model to describe the geometric spreading the anelastic attenuation
  - The addictive distance is assumed as 10 km for each period
    - This assumption is based on the observation of the Taiwan ground motion data of 4 crustal events in which distance saturation can be observed clearly while Rrup < 10 km

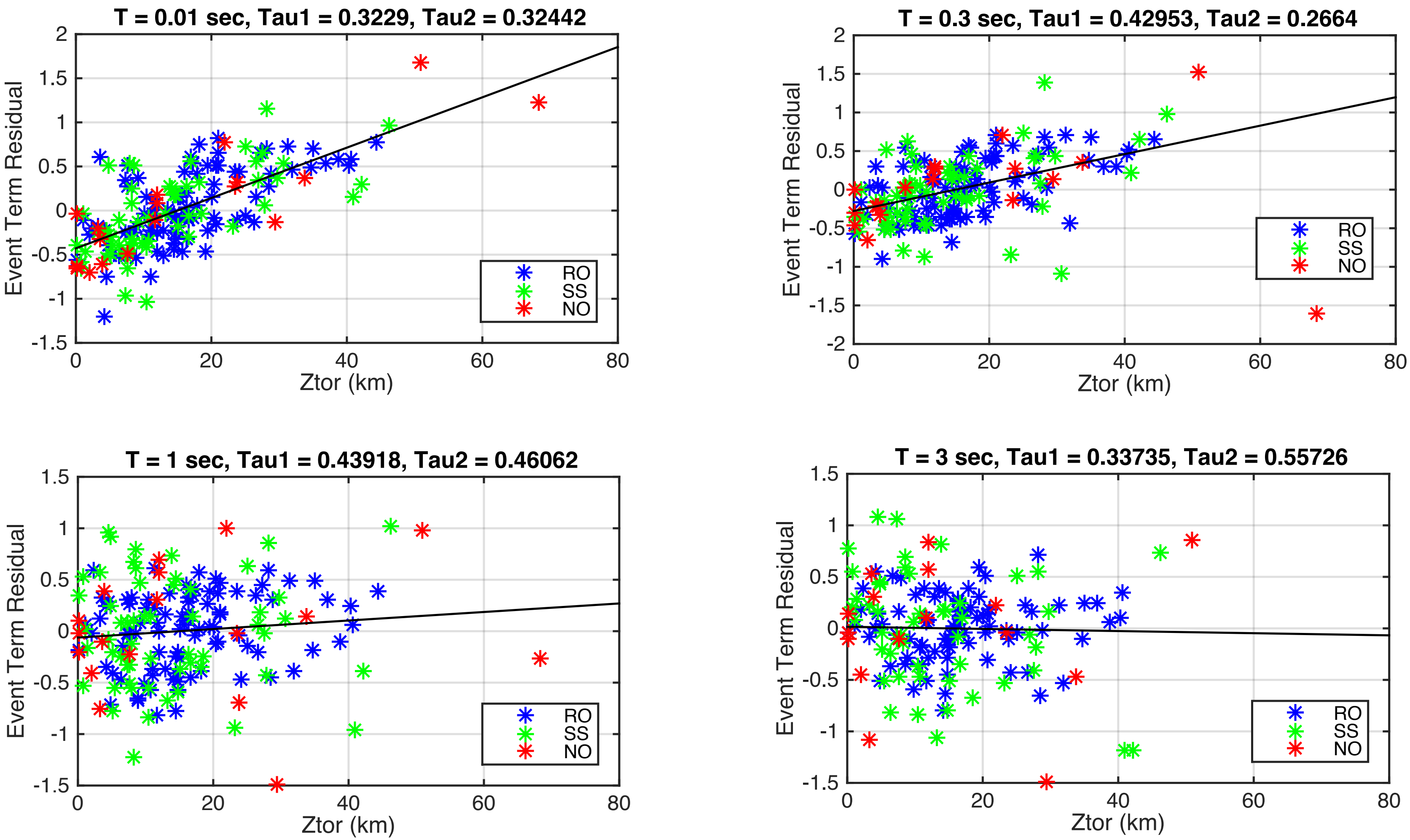
Development Approach – V

- **Depth Scaling for Subduction Source**
  - We observe similar depth scalings for interface and intraslab events from the estimated event terms
    - We use the same depth scalings for them
  - We observed that the predicted event term residual is proportional to depth within available data range (Ztor 0 to 180 km)
- **Distance Scaling for Subduction Source**
  - We use distance scaling term of CB14 model to describe the geometric spreading the anelastic attenuation
  - The addictive distance is assumed as 10 km for each period
    - This assumption is based on the observation of the Taiwan ground motion data of 4 crustal events in which distance saturation can be observed clearly while Rrup < 10 km

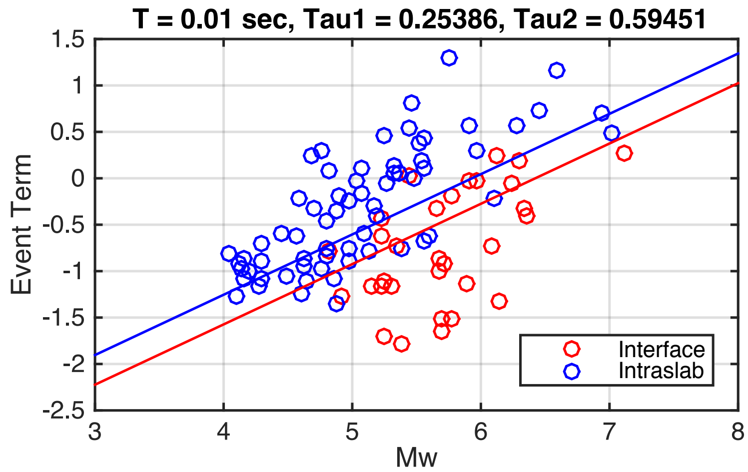
Estimated Event Term and Magnitude Scaling for Crustal Source

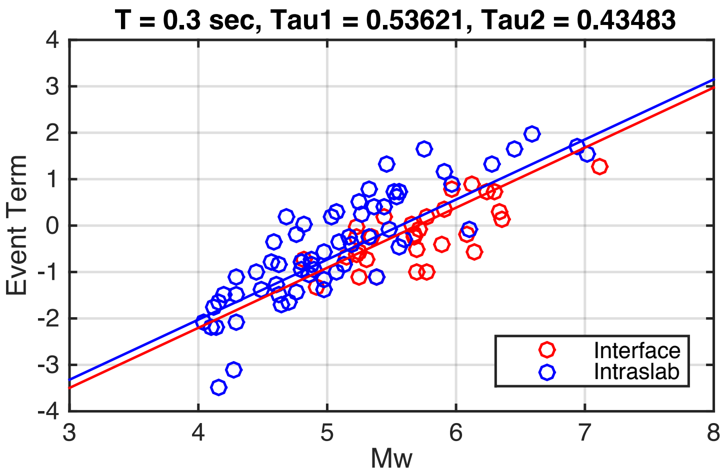


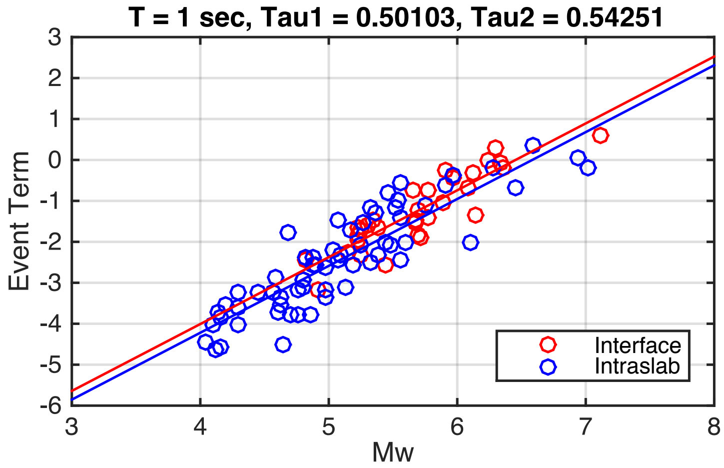
Estimated Event Term and Depth Scaling for Crustal Source

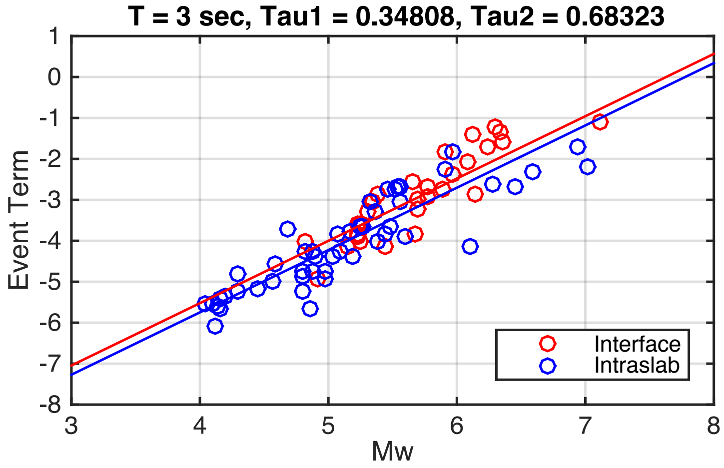


Estimated Event Term and Magnitude Scaling for Subduction Source

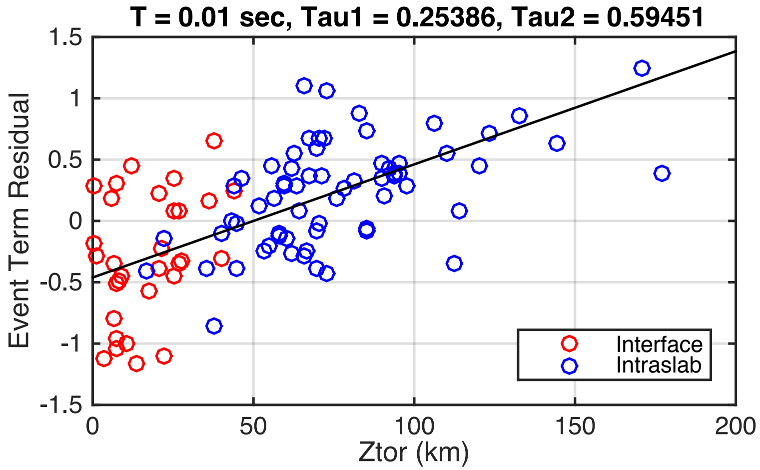


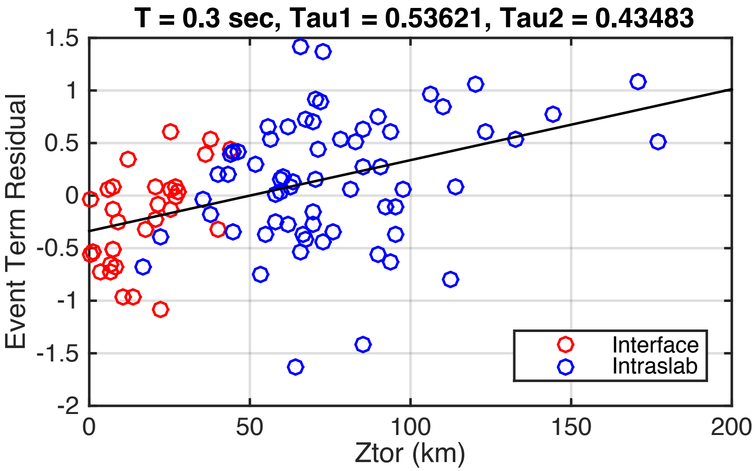


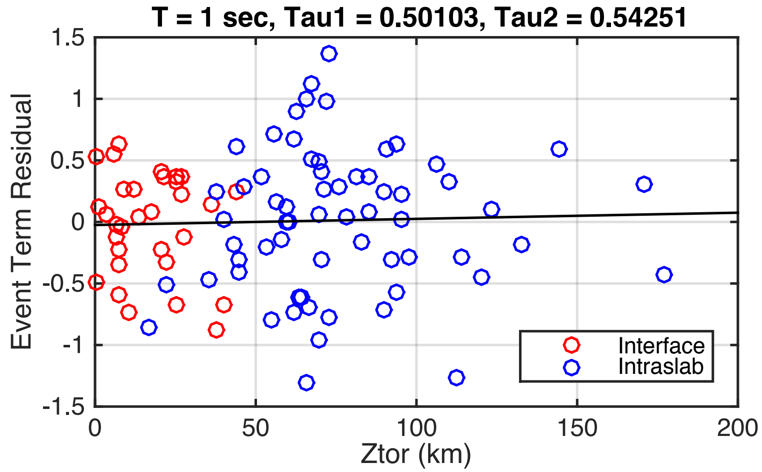


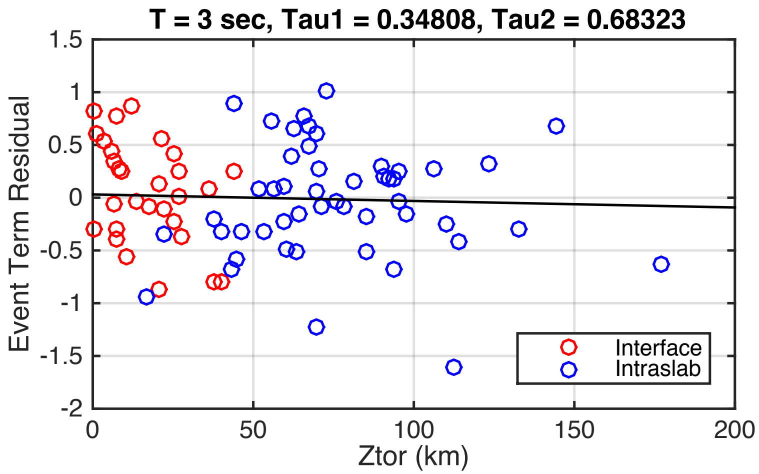


Estimated Event Term and Depth Scaling for Subduction Source









Development Approach – VI

- **Site Scaling**
  - Linear site effect is described by parameters Vs30 and Z1.0
  - Z1.0 scaling is developed based on the difference between Z1.0 and Z1.0ref because of the high correlation between Vs30 and Z1.0
  - We use the function form of nonlinear site effect model proposed by Kamai et. al. (2013)
    - Vs,lin is assumed as 760 m/s for each period
    - The coefficient b is refitted and others remain the same
  - We found that the soil nonlinearity of Taiwan ground motion data is stronger in Taiwan than the NGA-West 2 ground motion data under the same rock motion
    - This maybe due to the difference of the soil profile between Taiwan and California

Development Approach – VII

- **Features of Sigma Model**
  - Model coefficients of median as well sigma including **Tau, PhiS2S, PhiSS** are determined simultaneously through **regression approach**
  - Tau and PhiSS models are developed for crustal and subduction sources, and the same PhiS2S model are developed for crustal and subduction source
  - Magnitude-dependent Tau and PhiSS models are developed
    - The break points are assumed as 4.5 and 6.5
  - Mixture model consisted of two normal distribution with equal weights and different standard deviations are used to describe the probability density function of **PhiSS**
  - Covariance matrix of model coefficients as well as function form of statistical uncertainty of sigma are developed

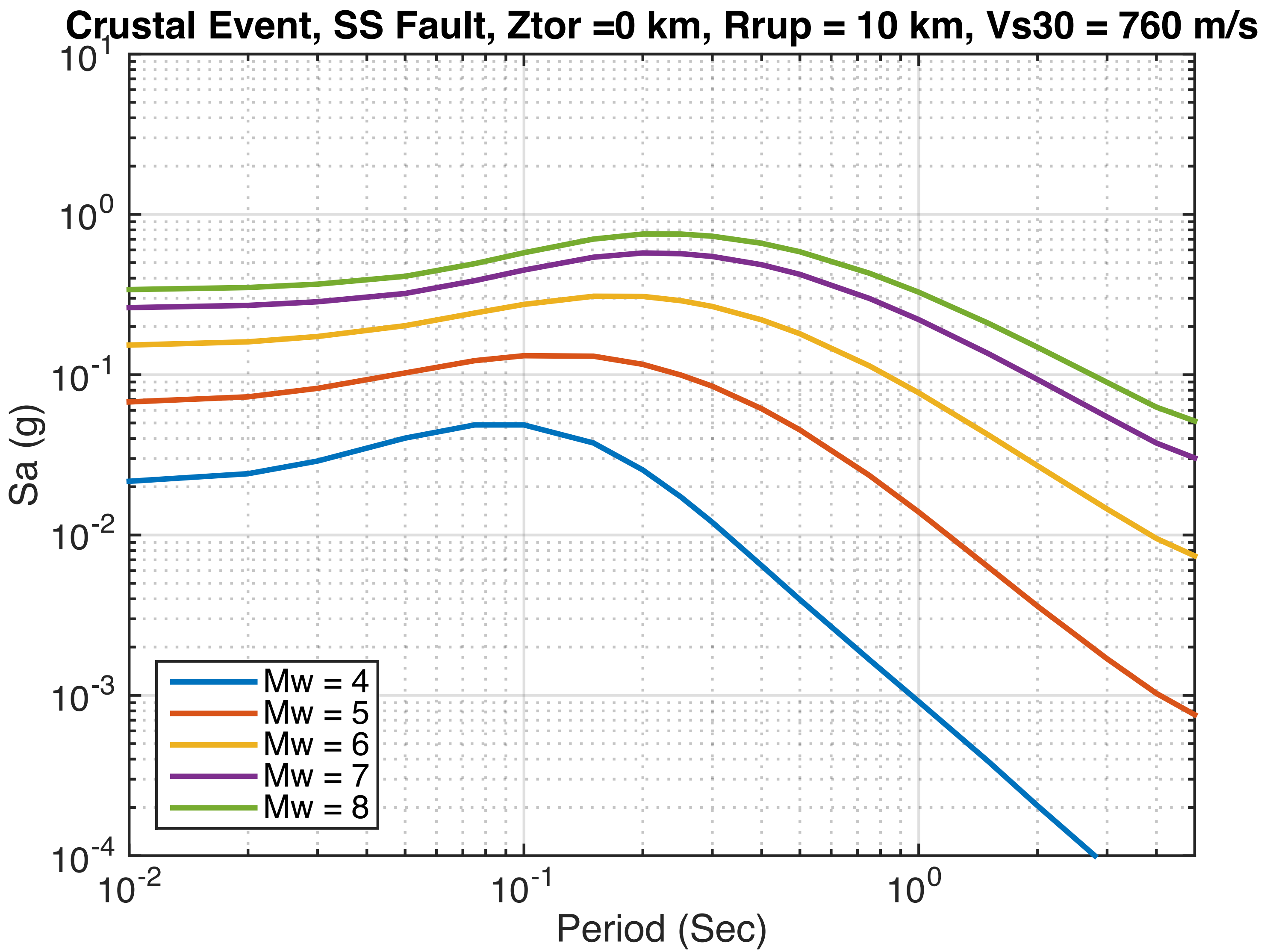
Development Approach – VIII

- **Regression method**
  - Consider the **mixed-effect model** and **random truncation effect simultaneously** by using two-step maximum likelihood method
    - the trigger level CWB strong motion network is PGAraw,max set equal to 0.2% full scale range
      - ~4 gal for $\pm$ 2g instrument
      - ~2 gal for $\pm$ 1g instrument
    - We exclude all ground motion data with PGAraw,max < 4 gal and assumed the the truncation level for PGAraw,max is 4 gal
    - The median and standard deviation of truncation level for RotD50 when PGAraw,max is 4gal are evaluated for each period
  - The proposed regression approach is validated by synthetic ground motion data from assumed ground motion model

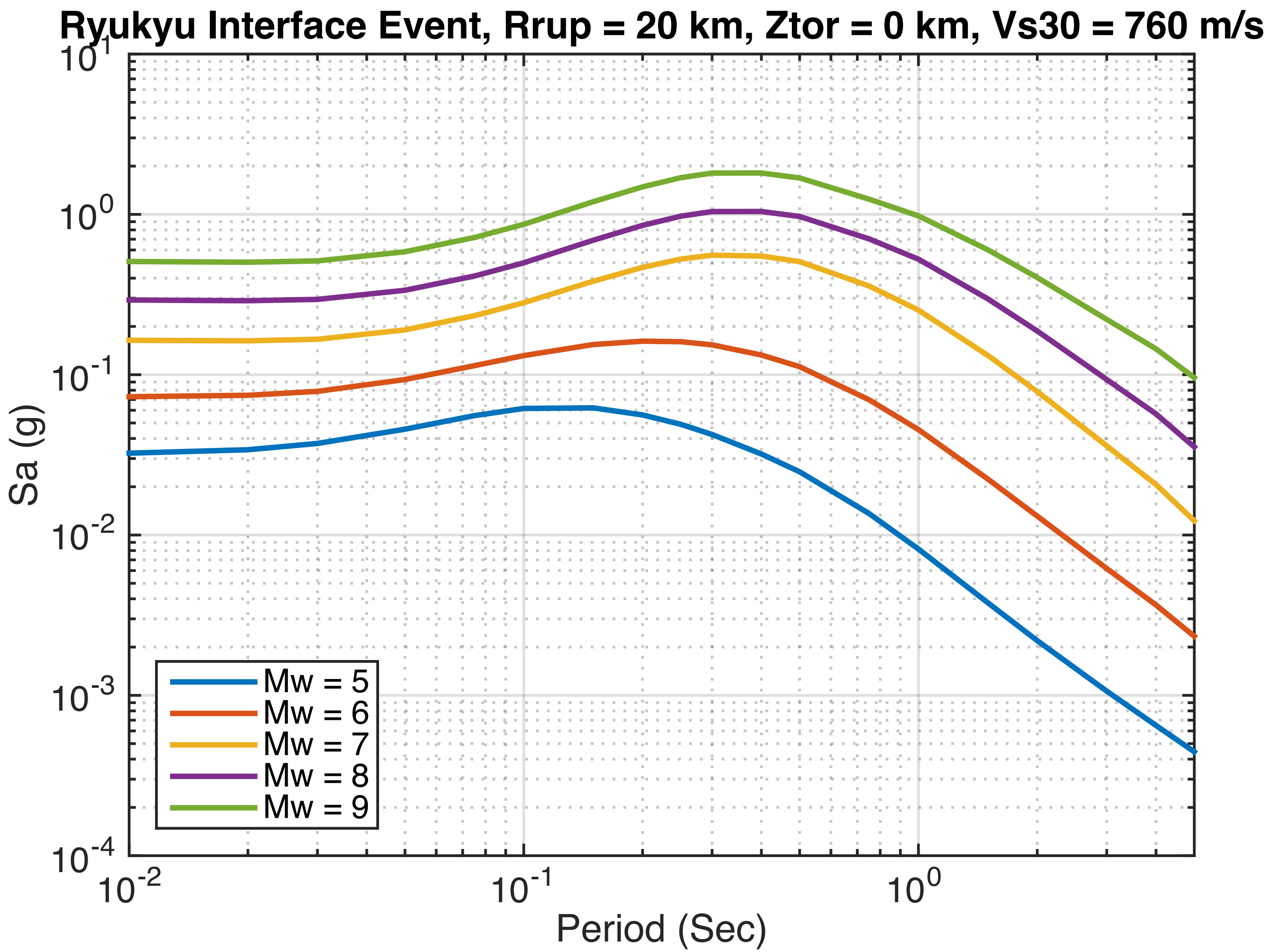
Development Approach – IX

- **Iterations for Nonlinear site effect model**
  - At beginning the ground motion prediction for rock site Sa1100 are unknown, so the iteration is necessary to derive the coefficient of nonlinear site effect model
    - Step A: Solve model coefficients without considering nonlinear site effect and derive initial Sa1100 prediction
    - Step B: Solve model coefficients considering nonlinear site effect with initial Sa1100 prediction and derive updated Sa1100 prediction
    - Step C: Repeat Step B until Sa1100 prediction for each record are converges (MSE $< 10^{-5}$)

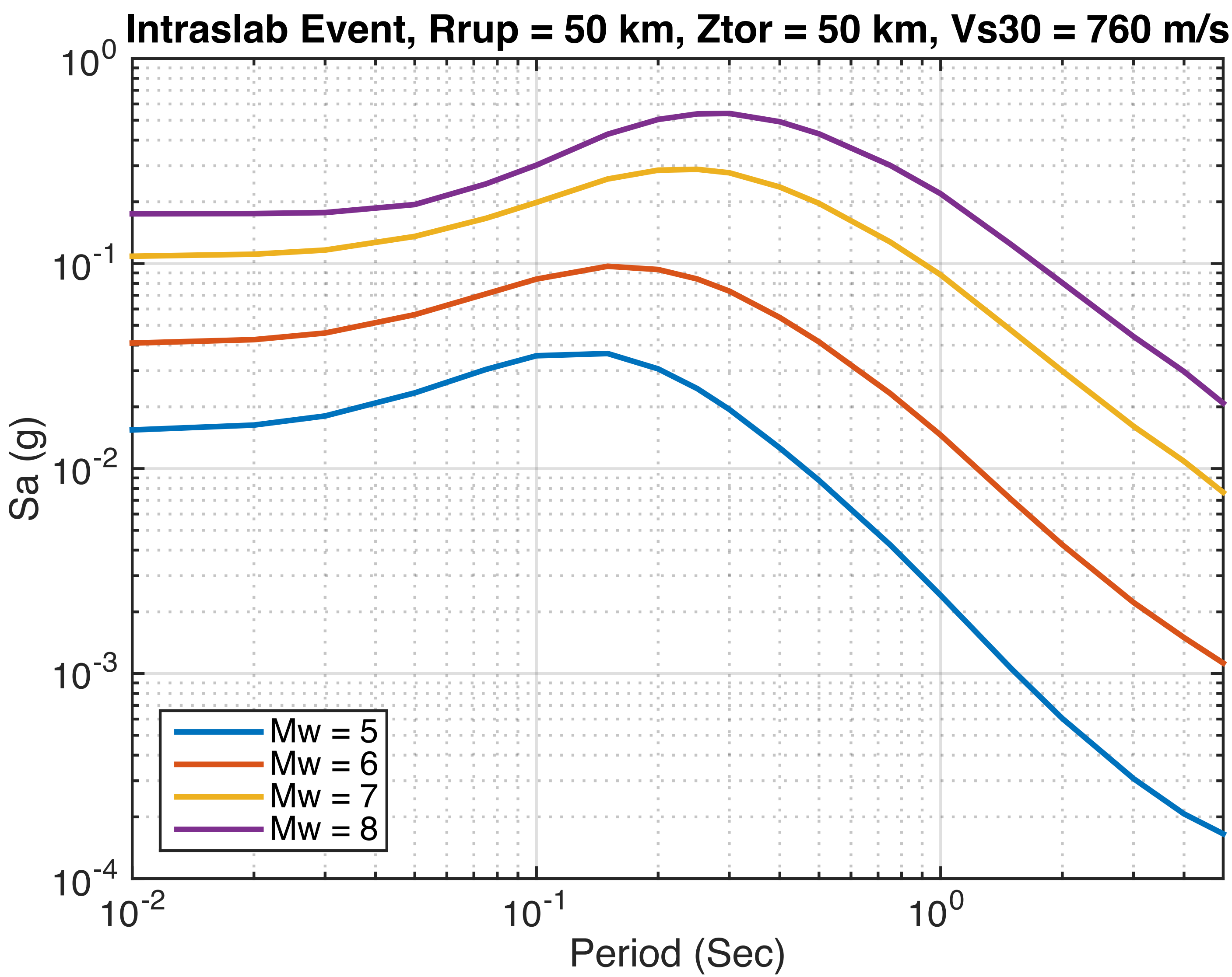
Prediction of Response Spectrum for Crustal Source



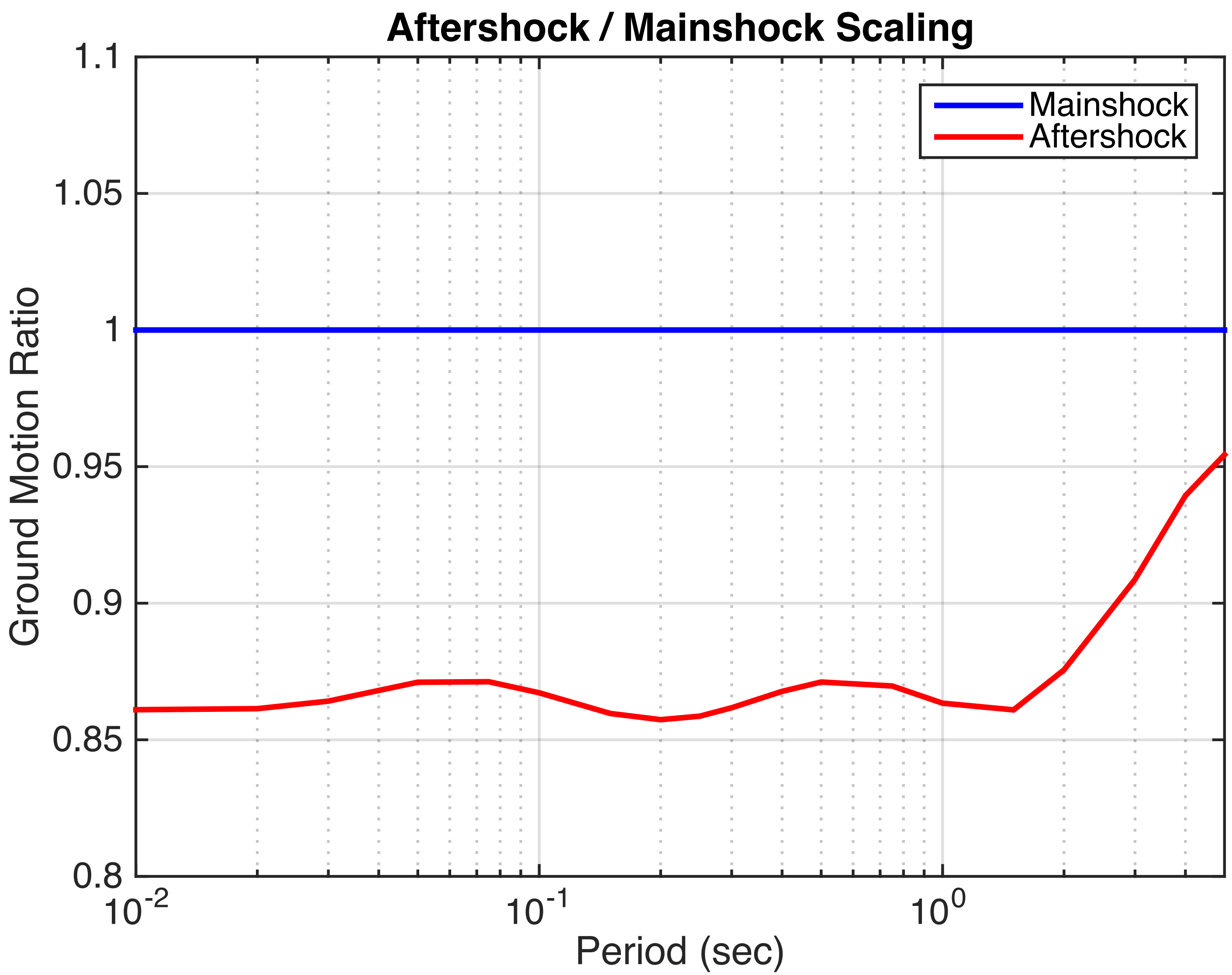
Prediction of Response Spectrum for Interface Source



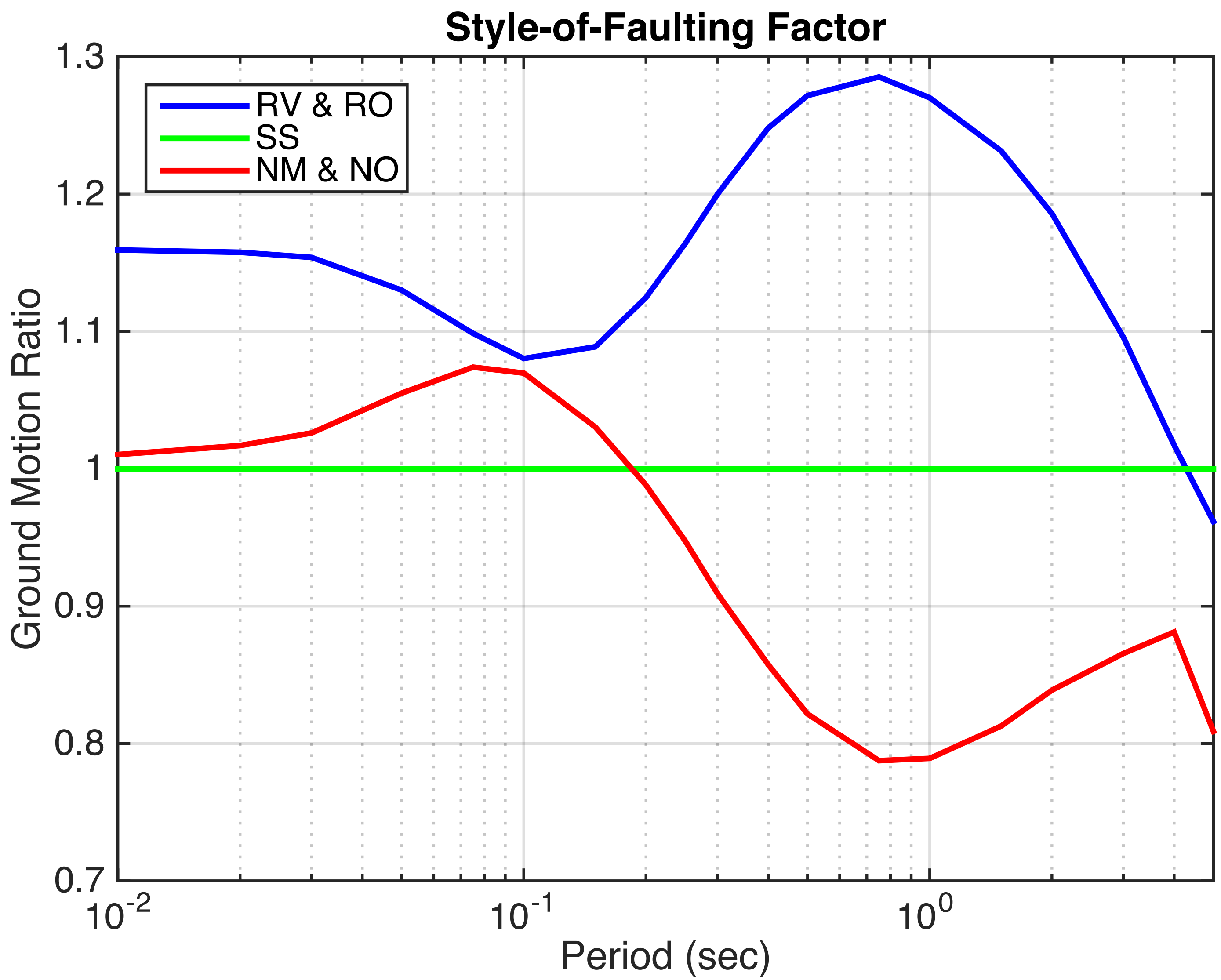
Prediction of Response Spectrum for Intraslab Source



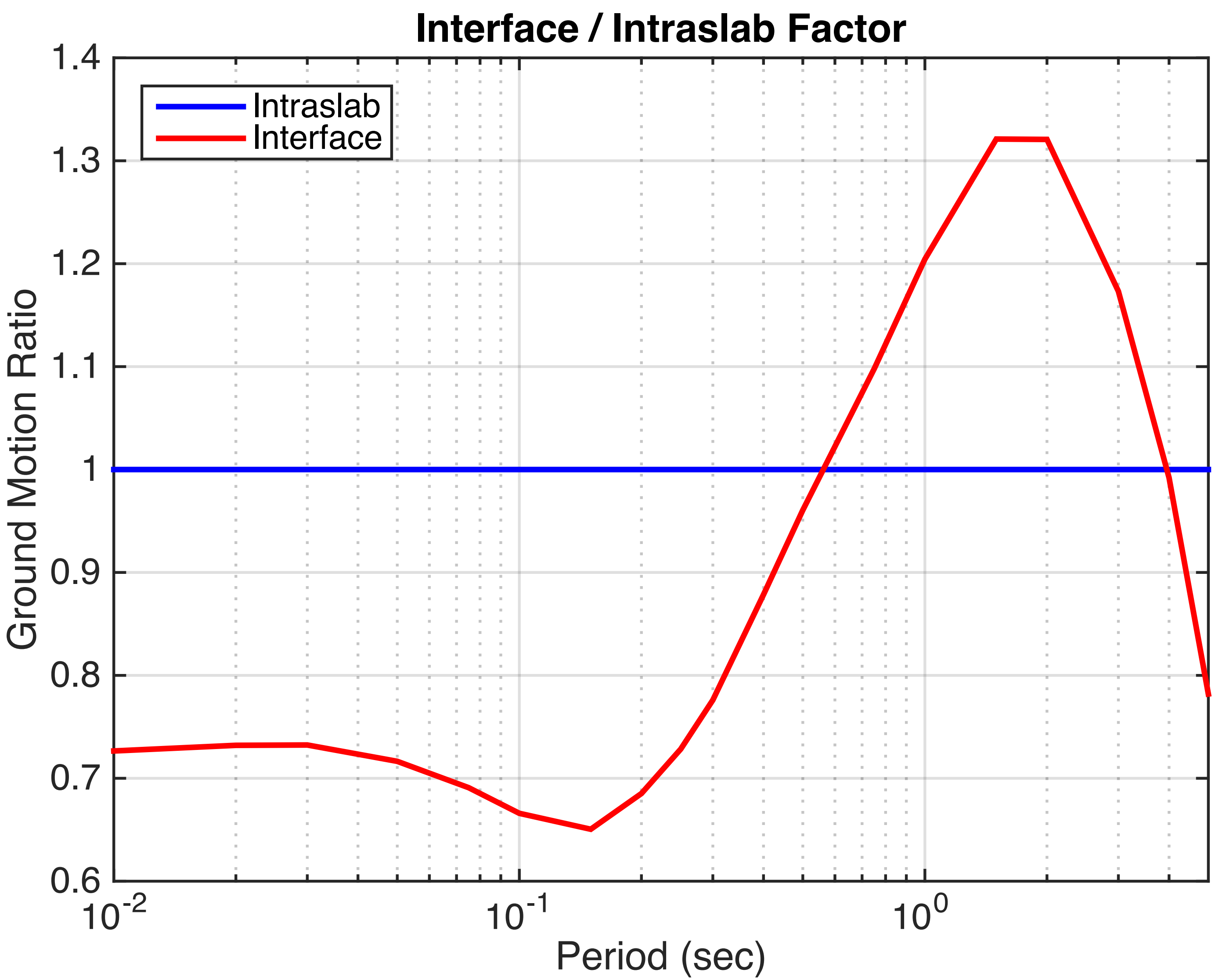
Mainshock / Aftershock Factor



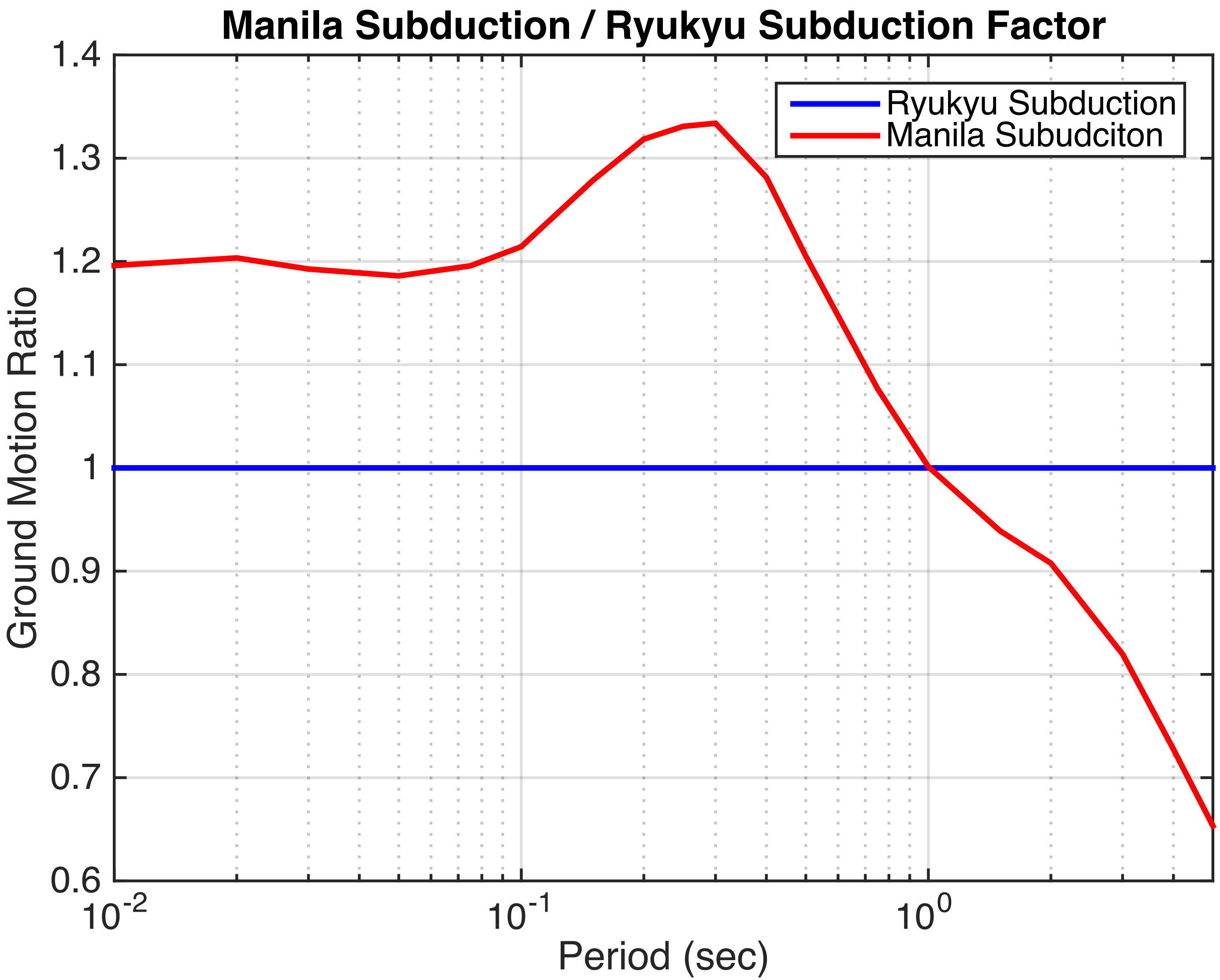
Style-of-Faulting Factors



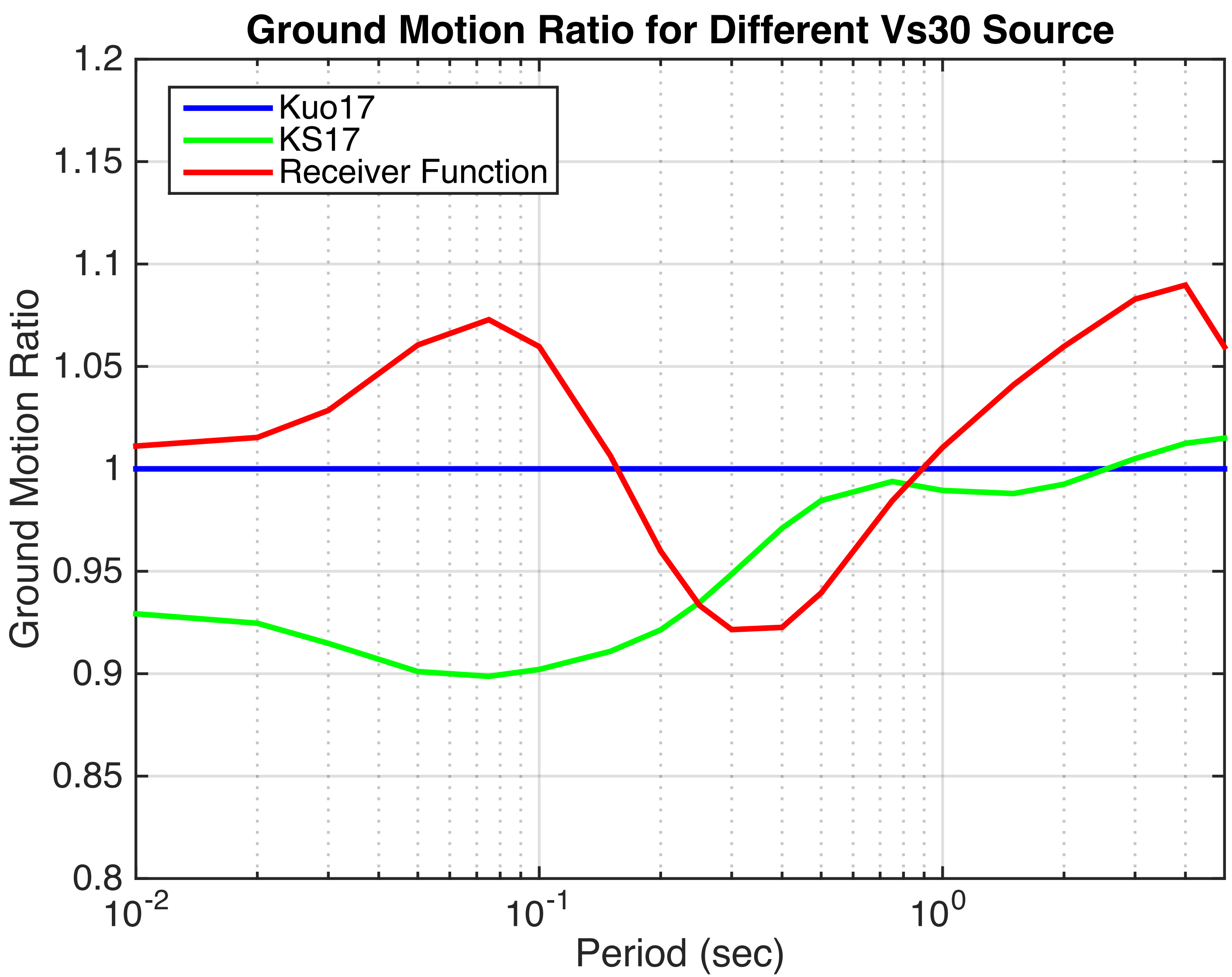
Interface / Intraslab Factor



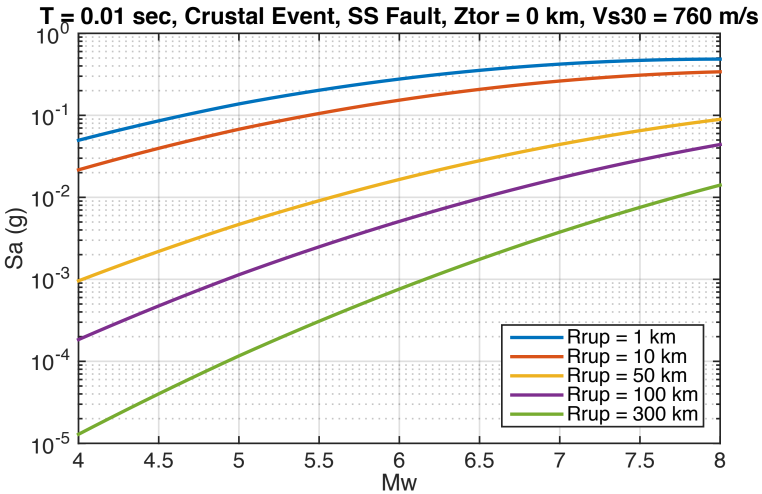
Manila / Ryukyu Subduction Factor

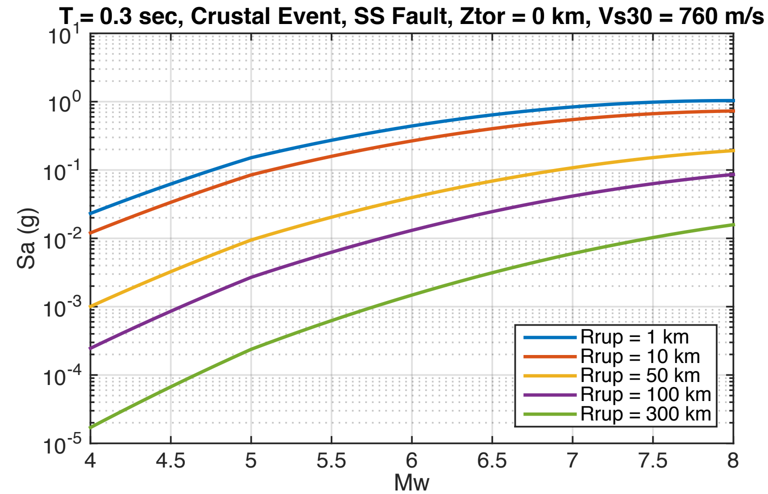


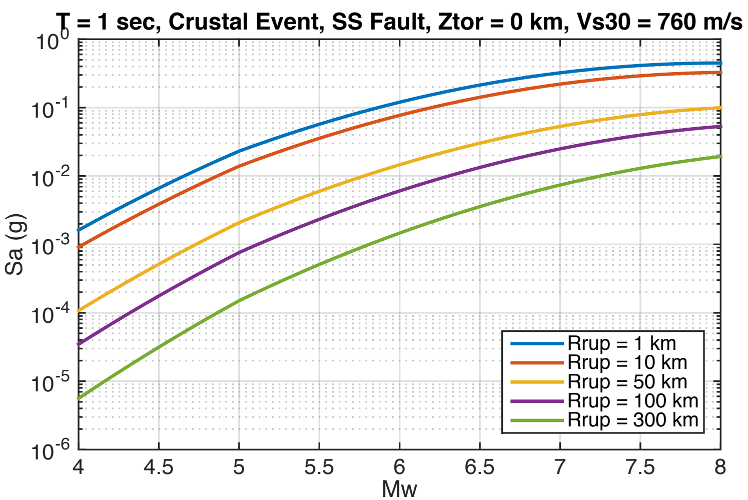
Measured / Inferred Vs30 Value

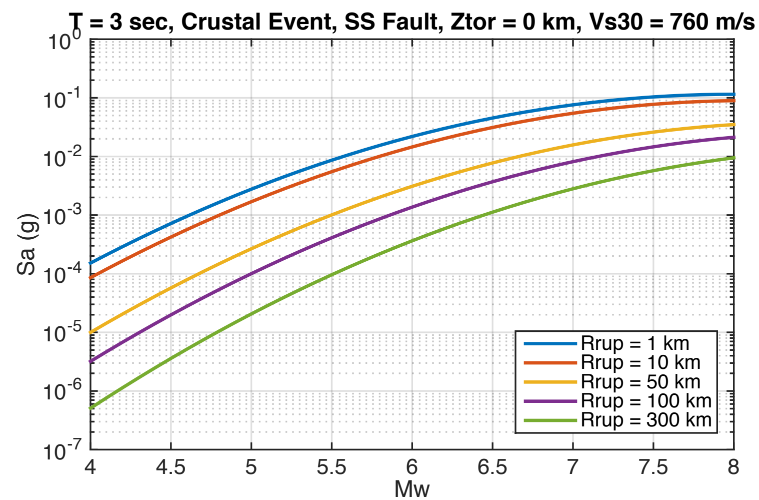


Magnitude Scaling for Crustal Source

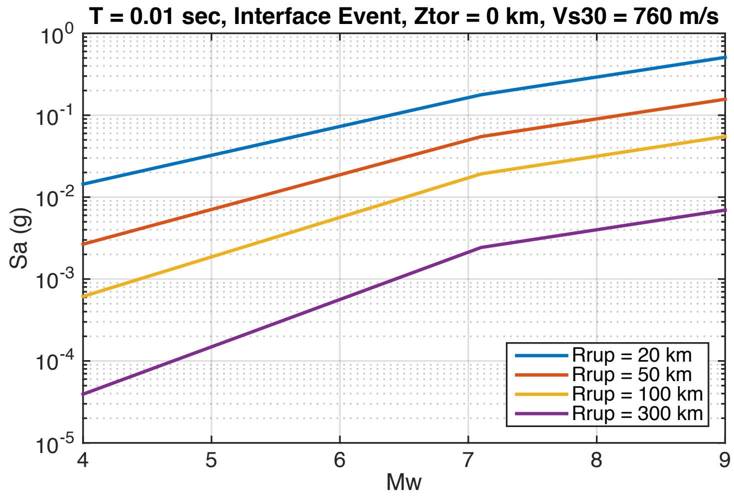


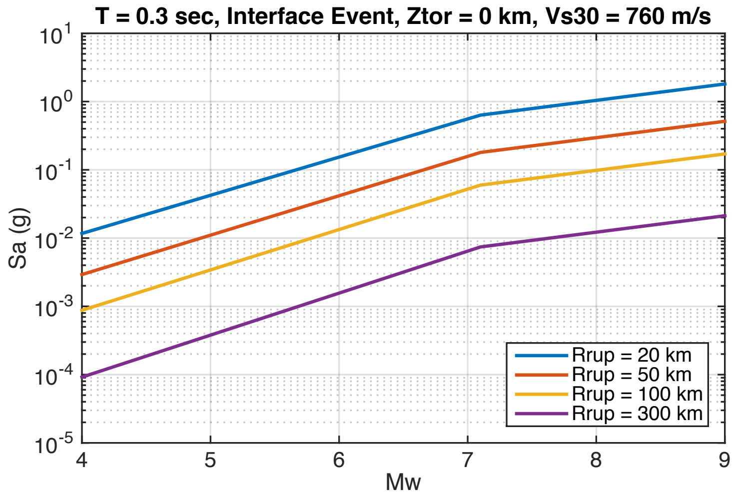


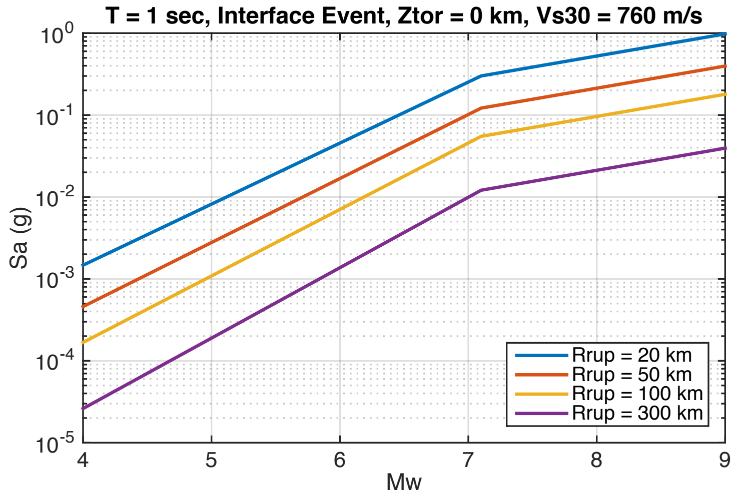


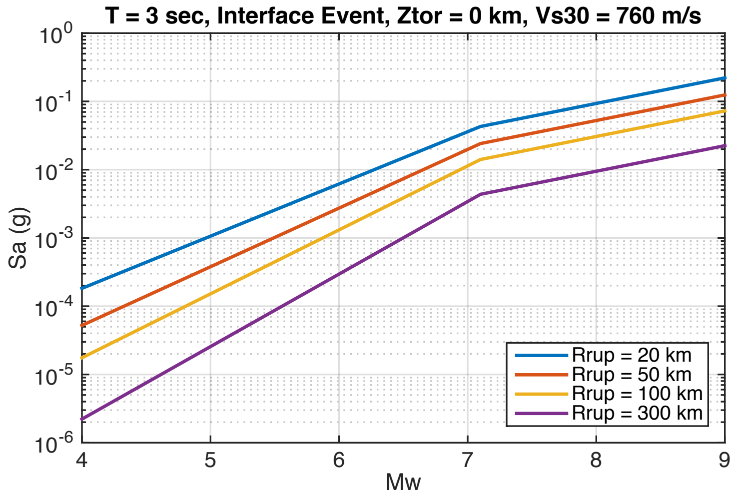


Magnitude Scaling for Interface Source

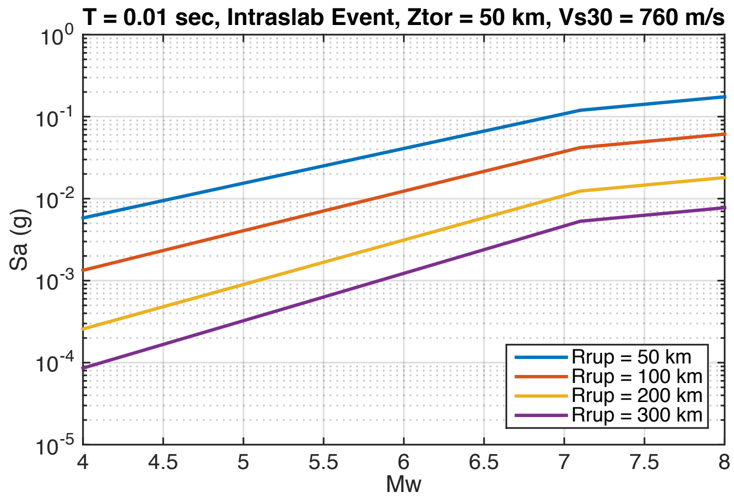


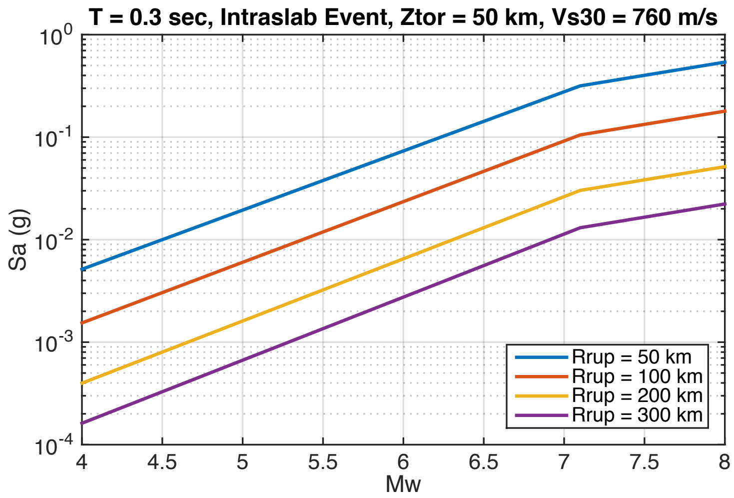


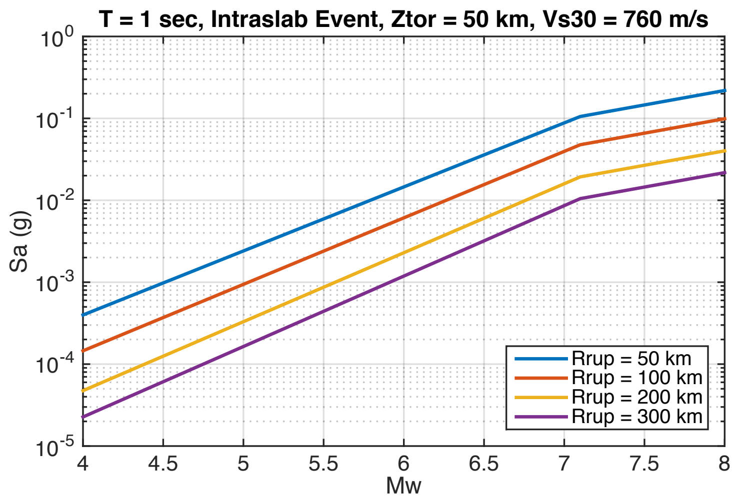


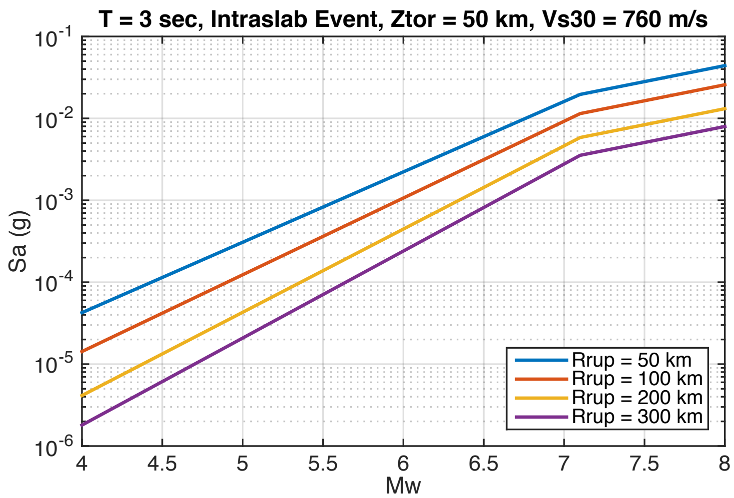


Magnitude Scaling for Intraslab Source

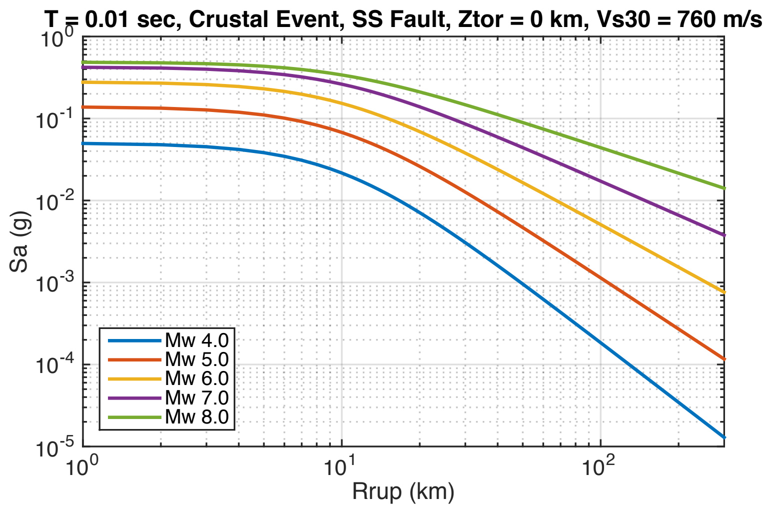


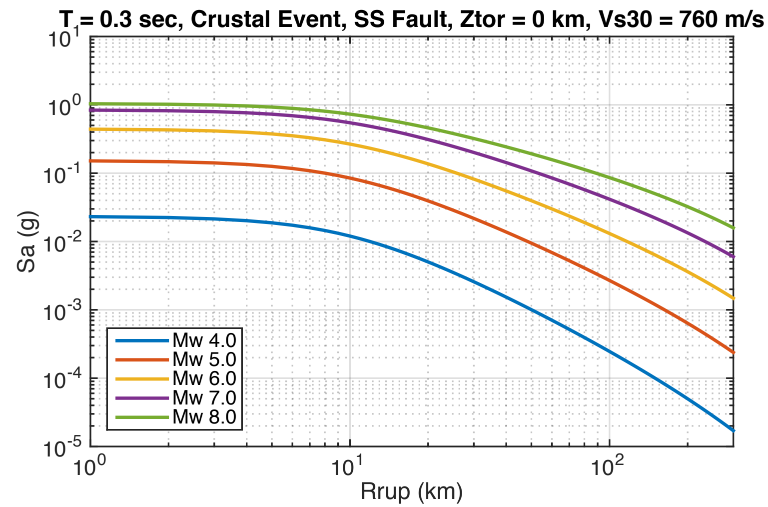


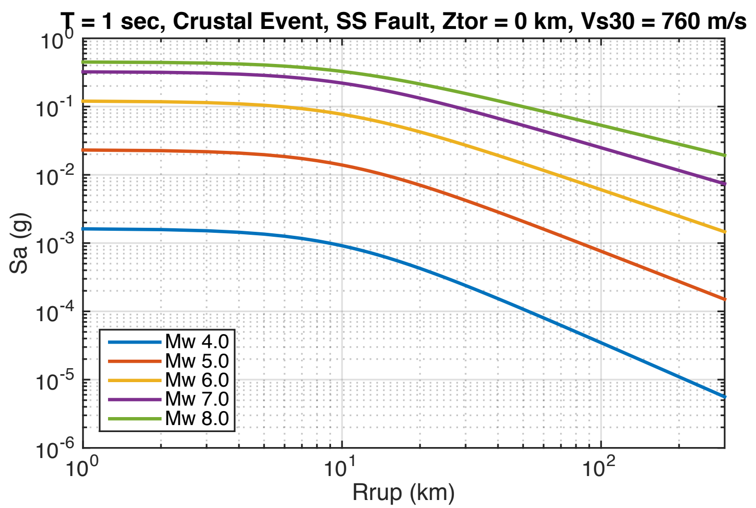


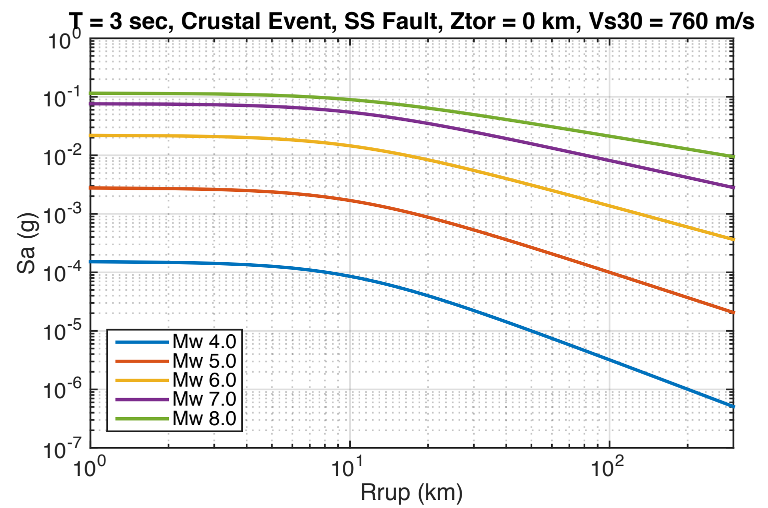


Distance Scaling for Crustal Source

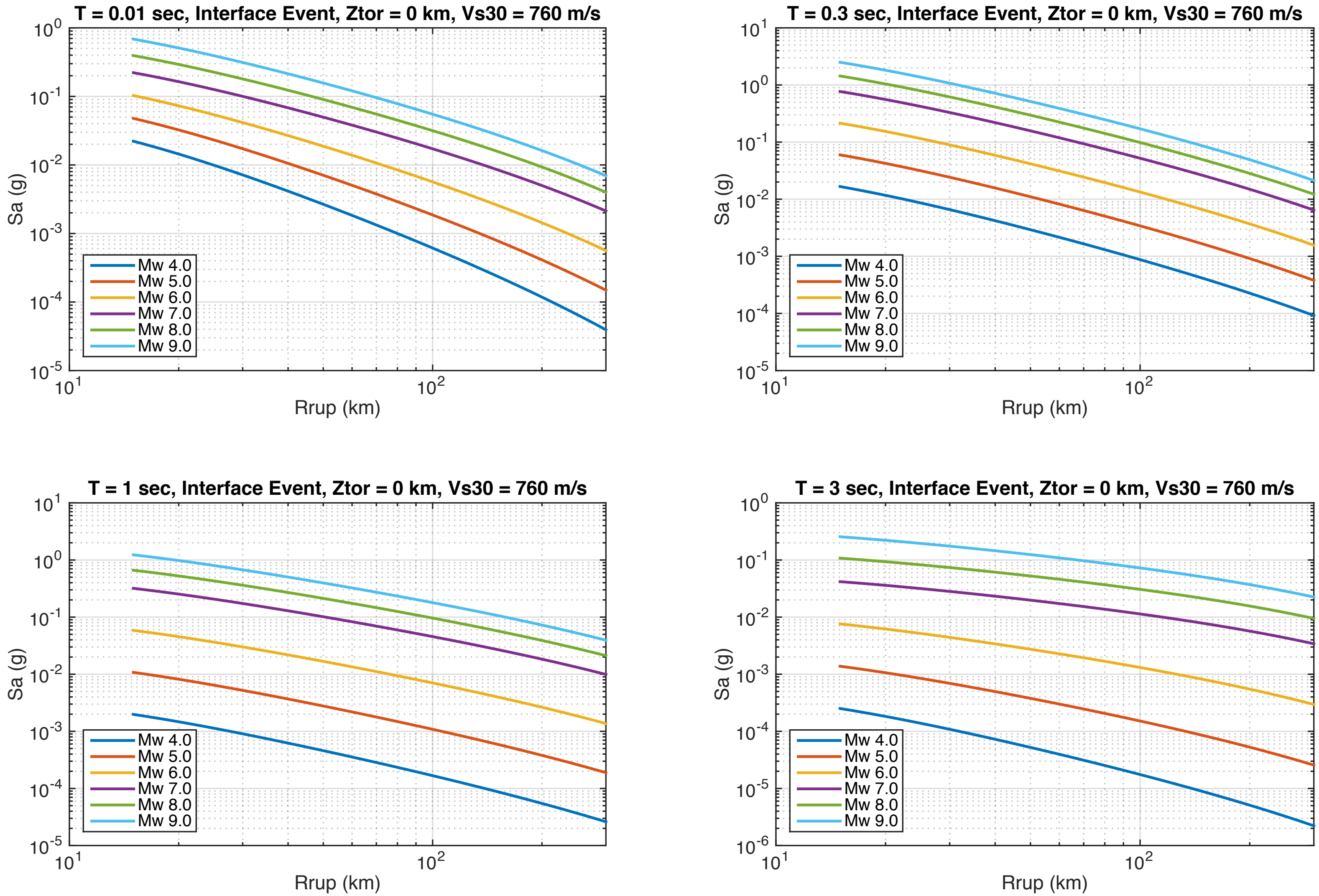




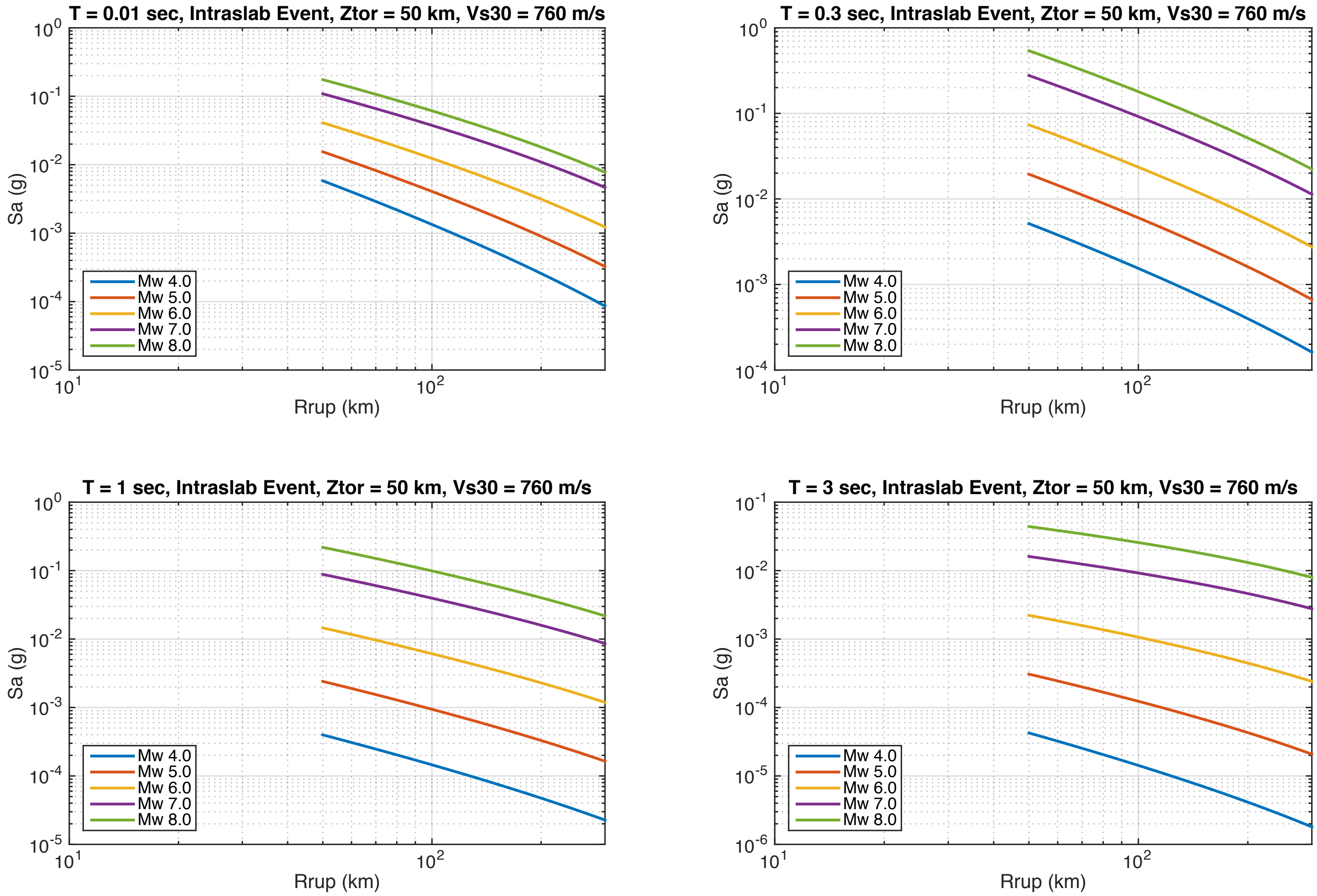




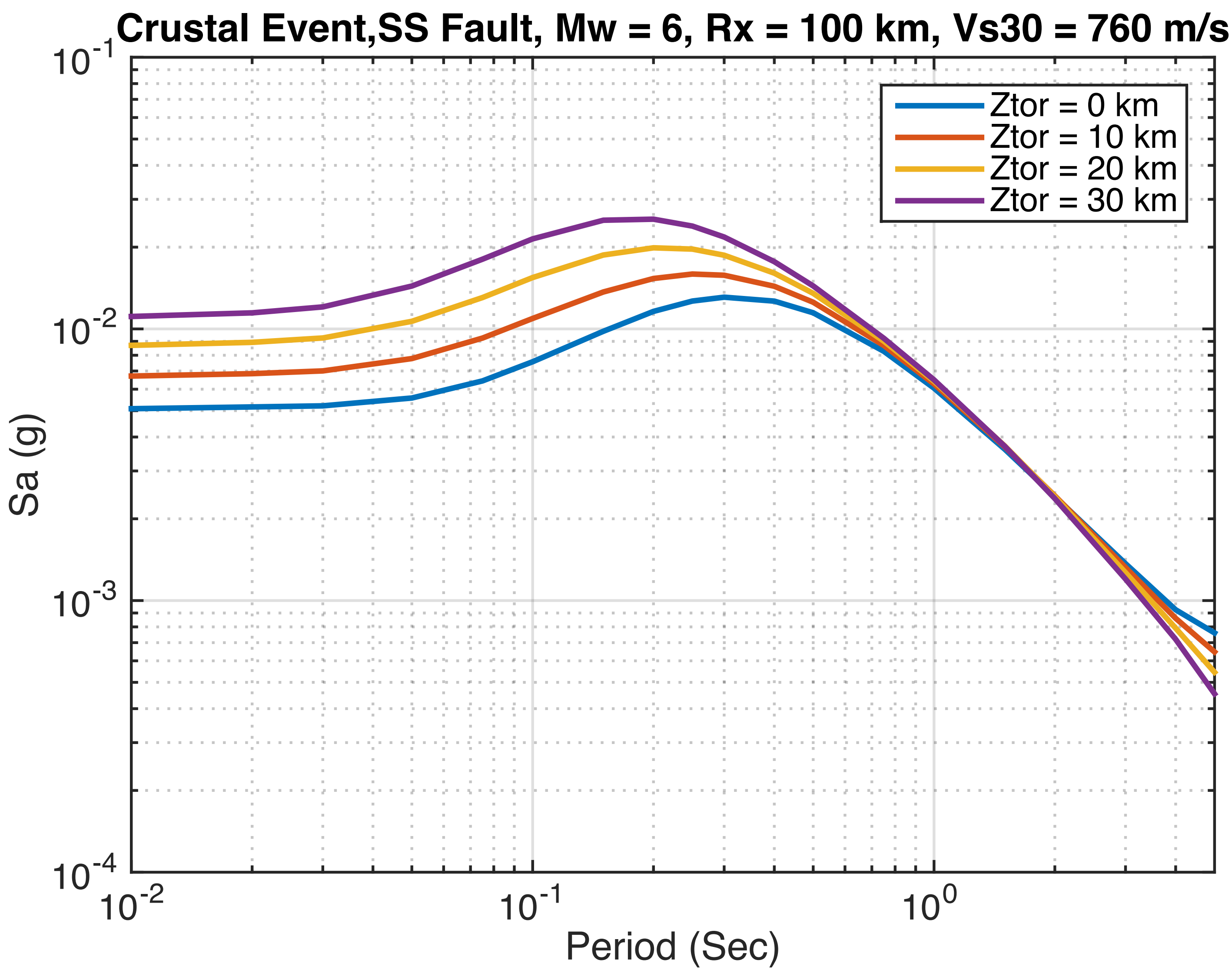
Distance Scaling for Interface Source



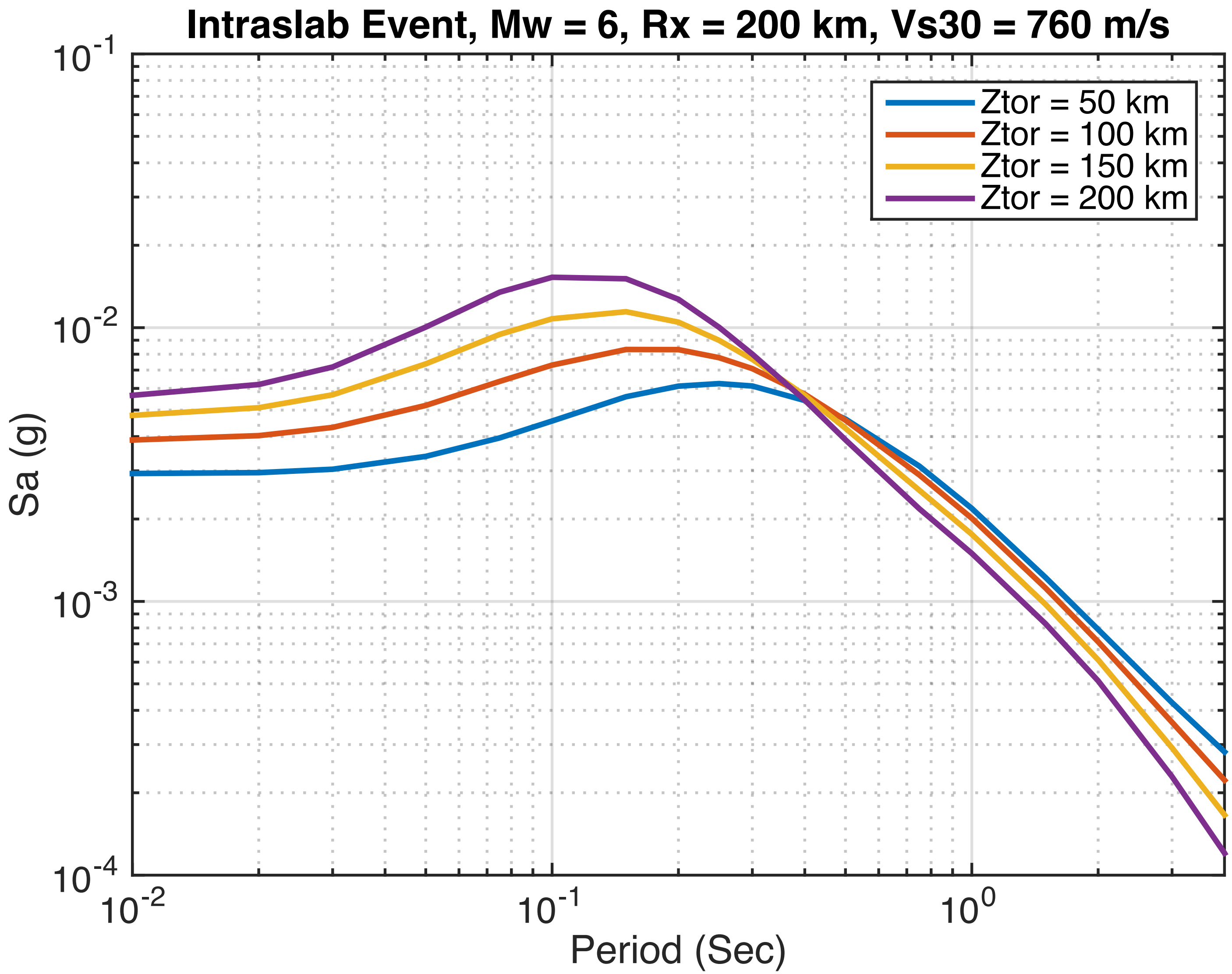
Distance Scaling for Intraslab Source



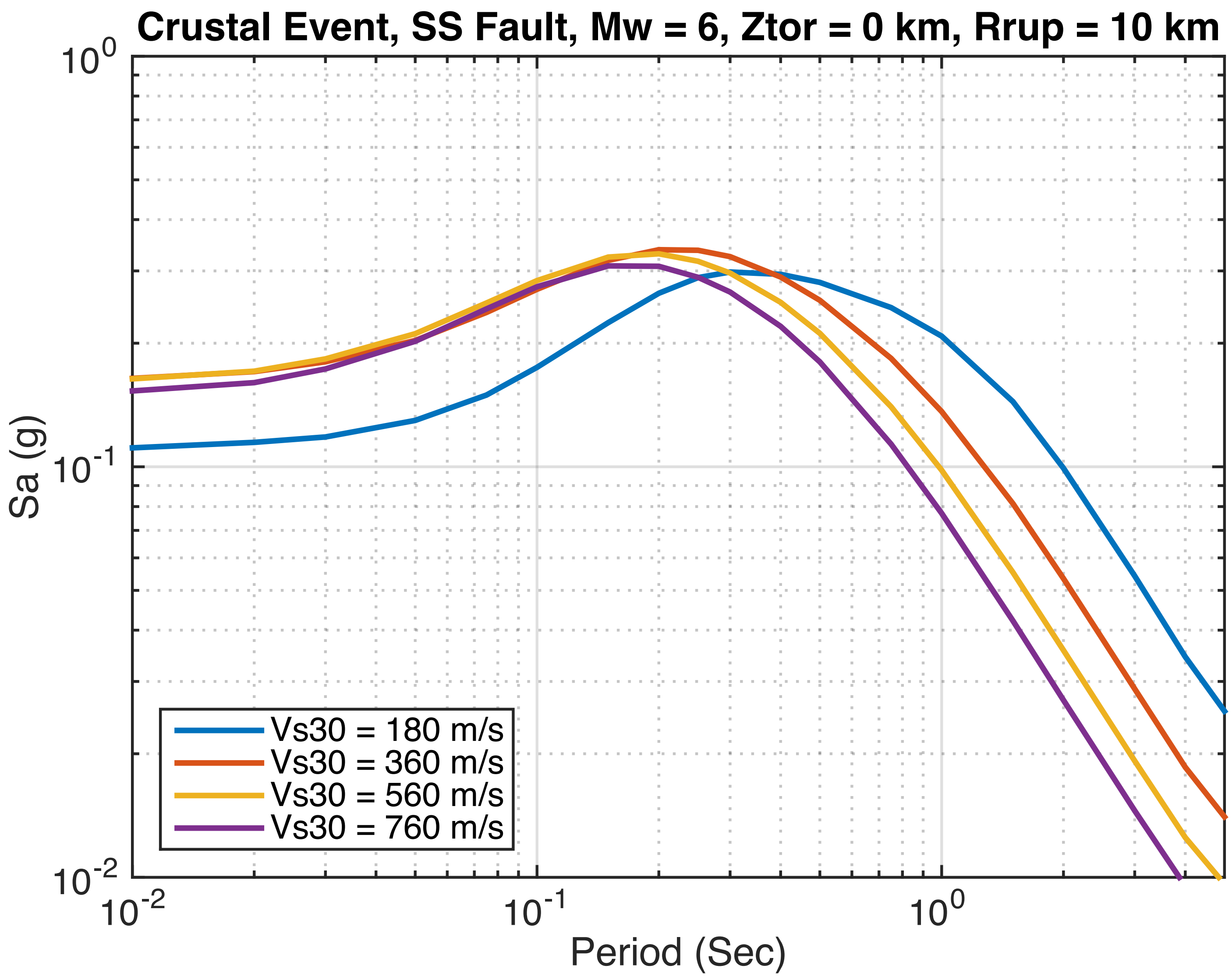
Depth Scaling for Crustal Source



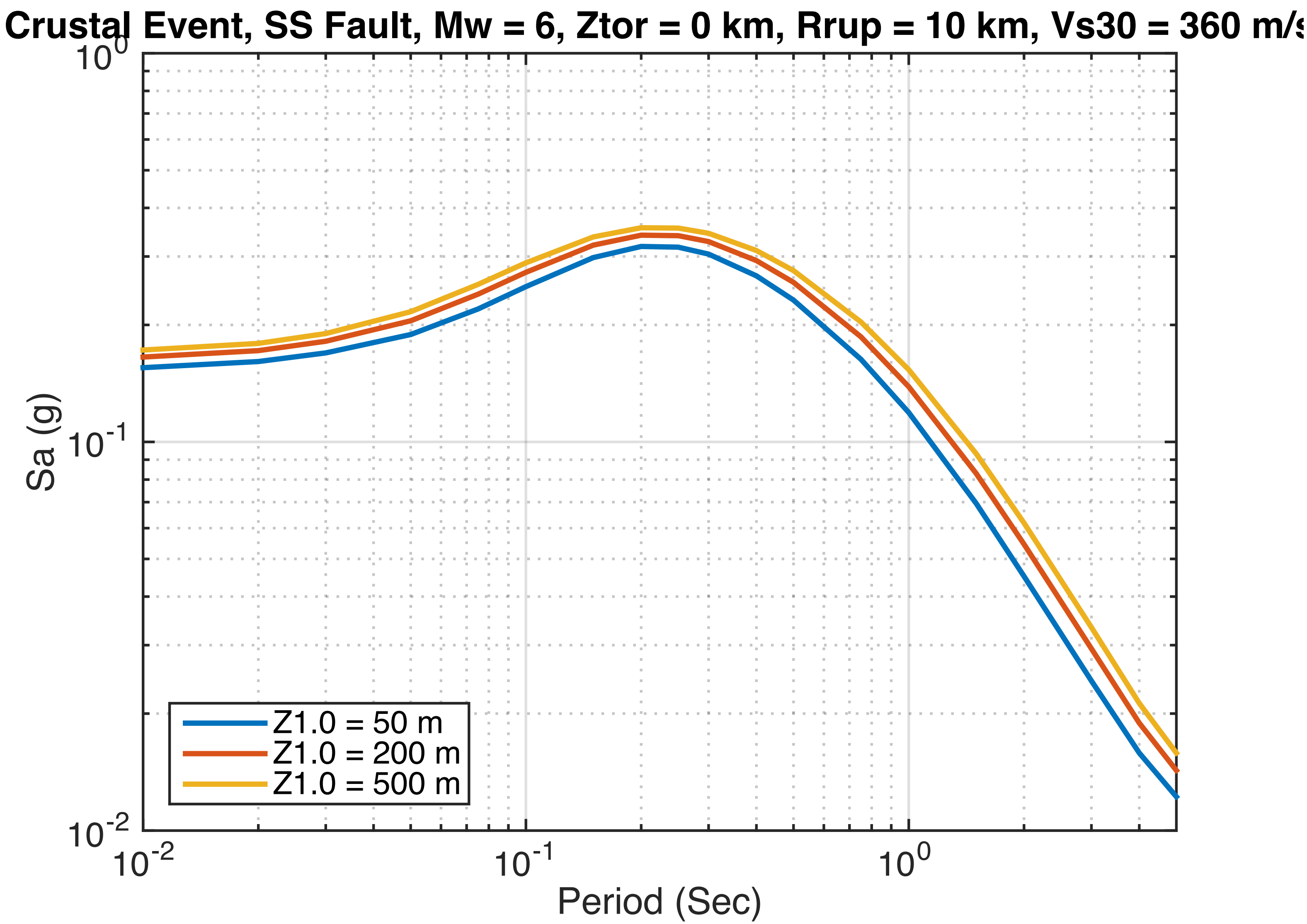
Depth Scaling for Subduction Source



Vs30 Scaling
– Linear and Nonlinear Site Effect

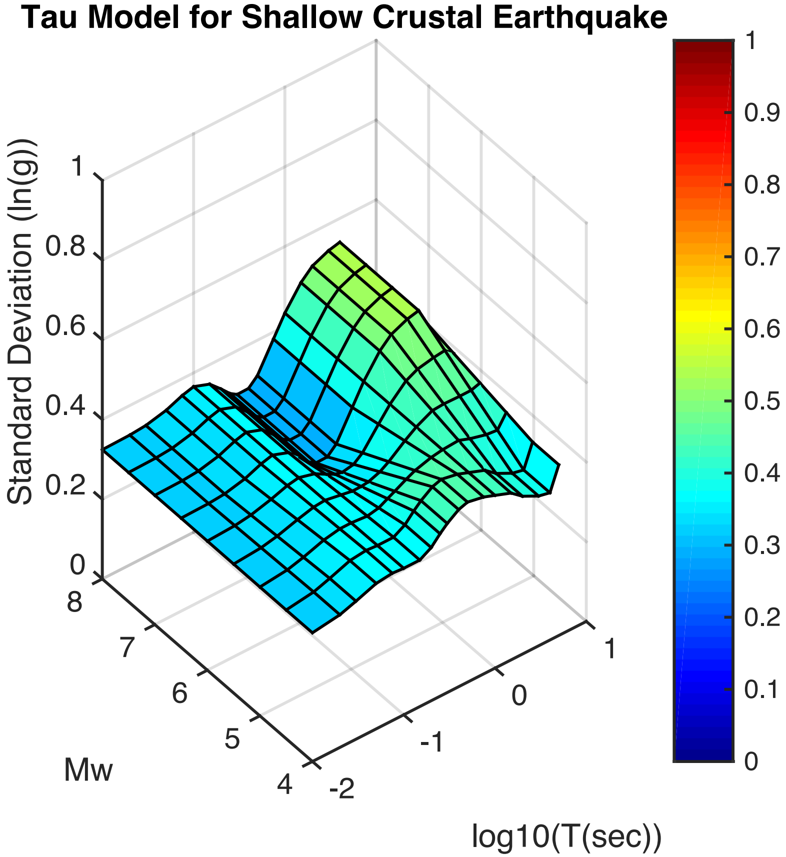


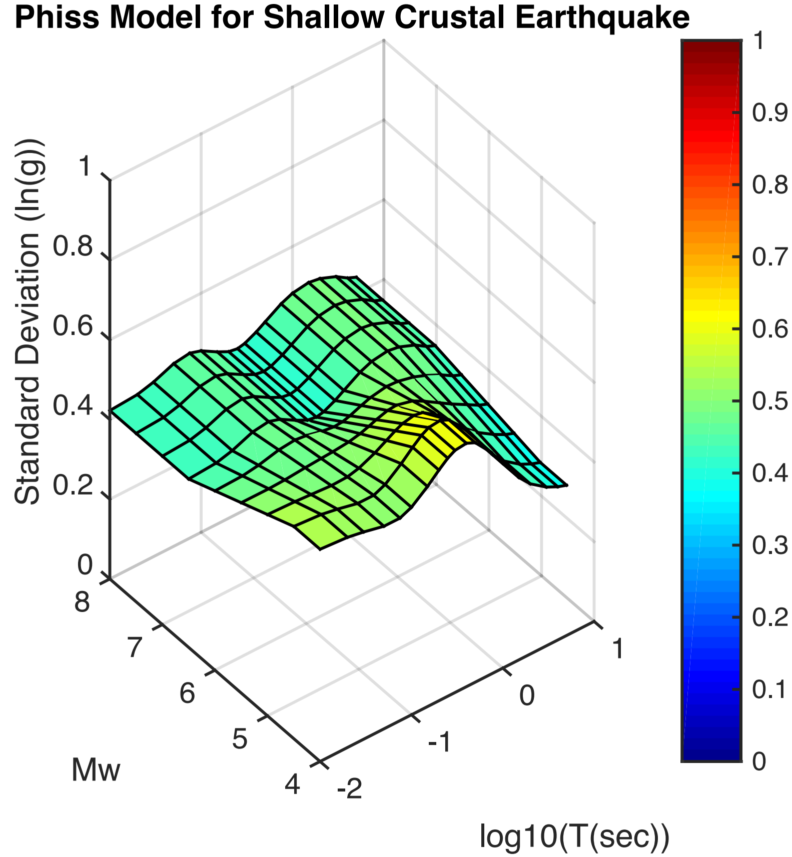
Z1.0 Scaling



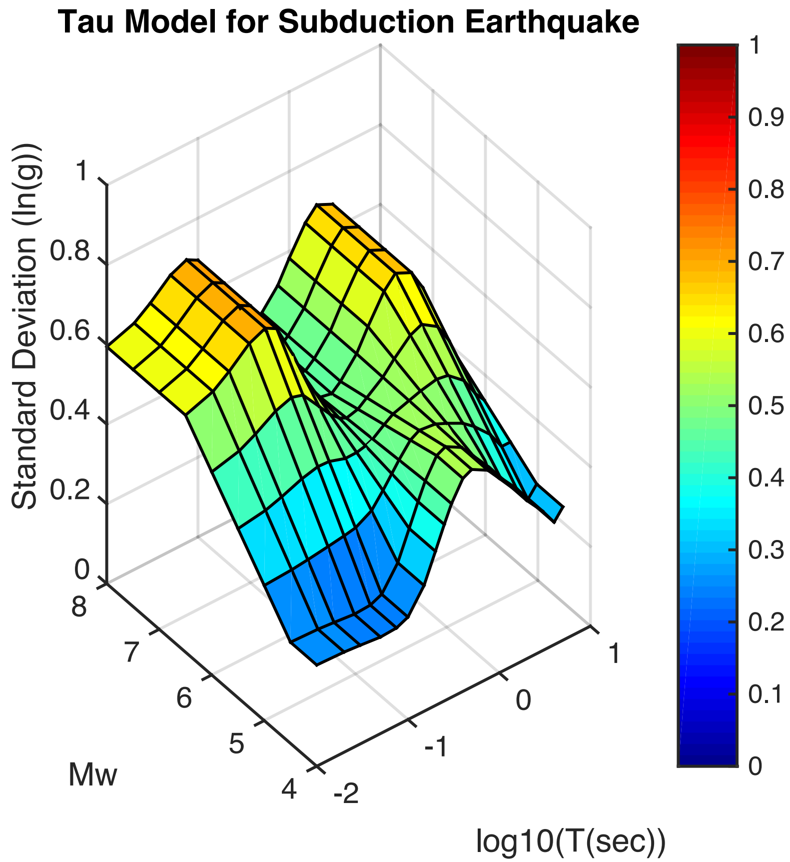
Crustal Event, SS Fault, Mw = 6, Ztor = 0 km, Rrup = 10 km, Vs30 = 360 m/s
Sa (g)
Period (Sec)
10^0
10^{-1}
10^{-2}
Z1.0 = 50 m
Z1.0 = 200 m
Z1.0 = 500 m

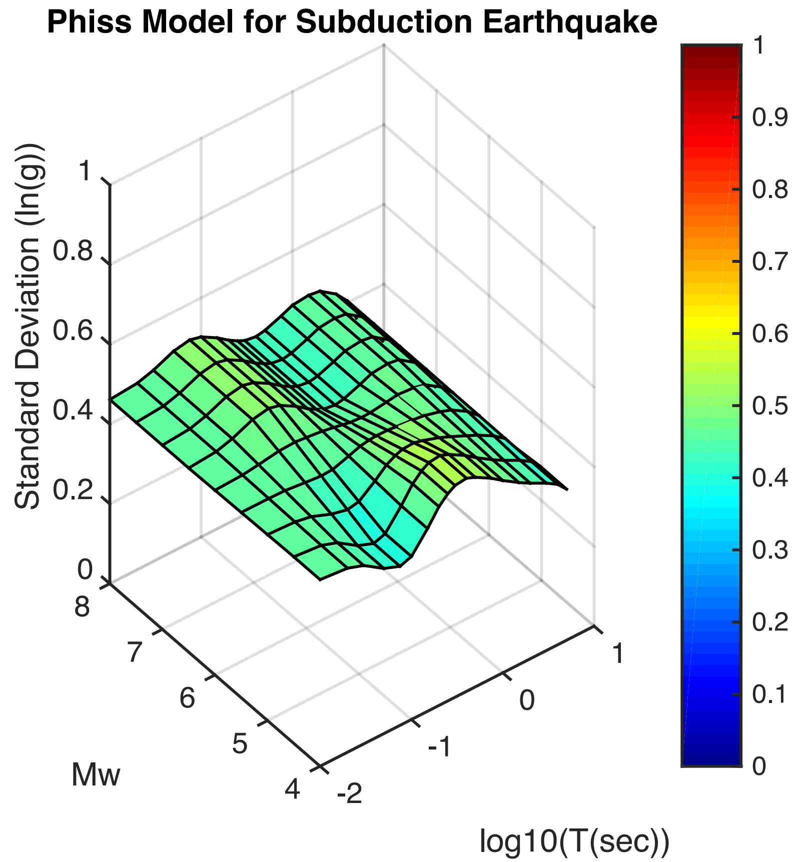
Tau and PhiSS Models for Crustal Source



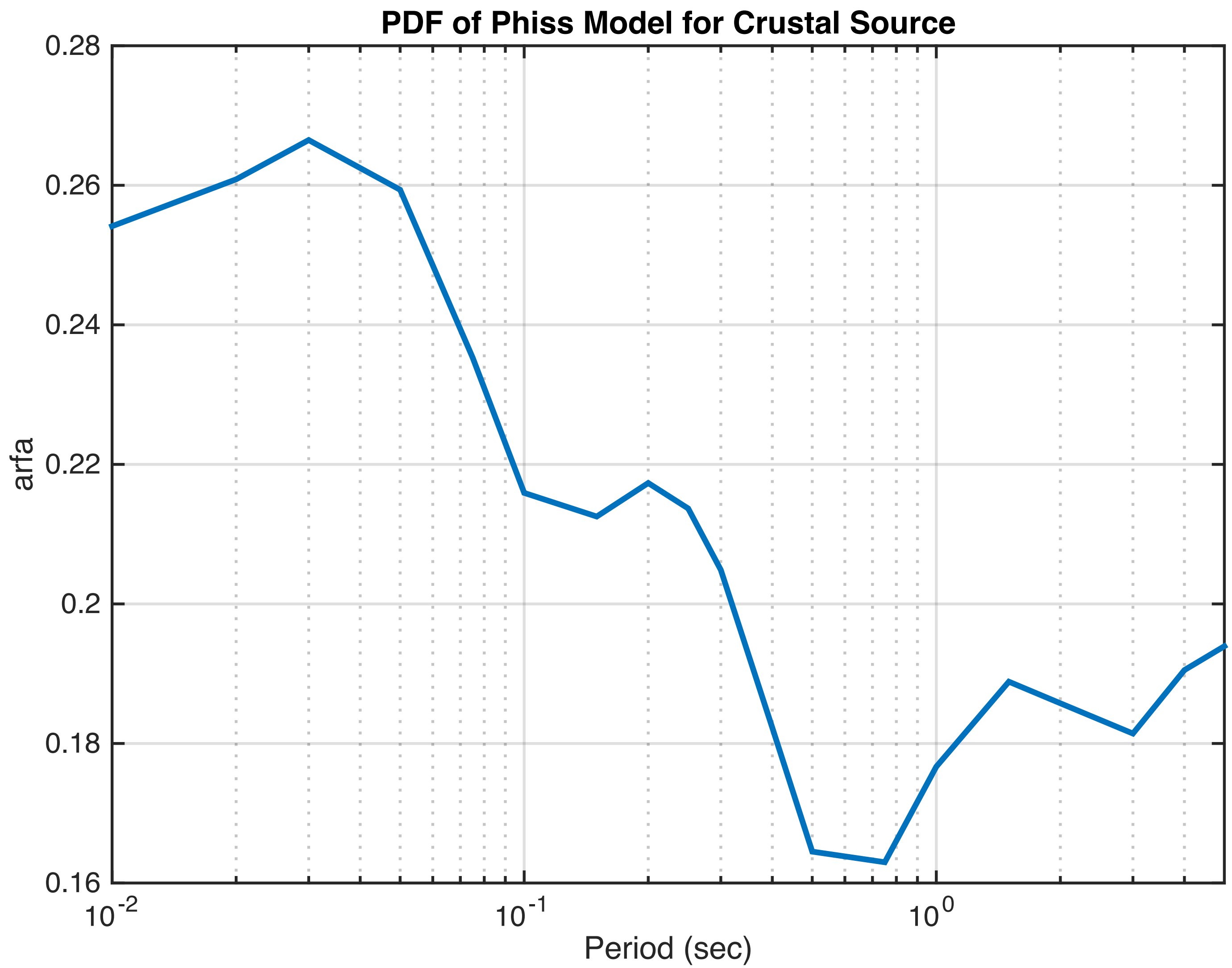


Tau and PhiSS Models for Subduction Source

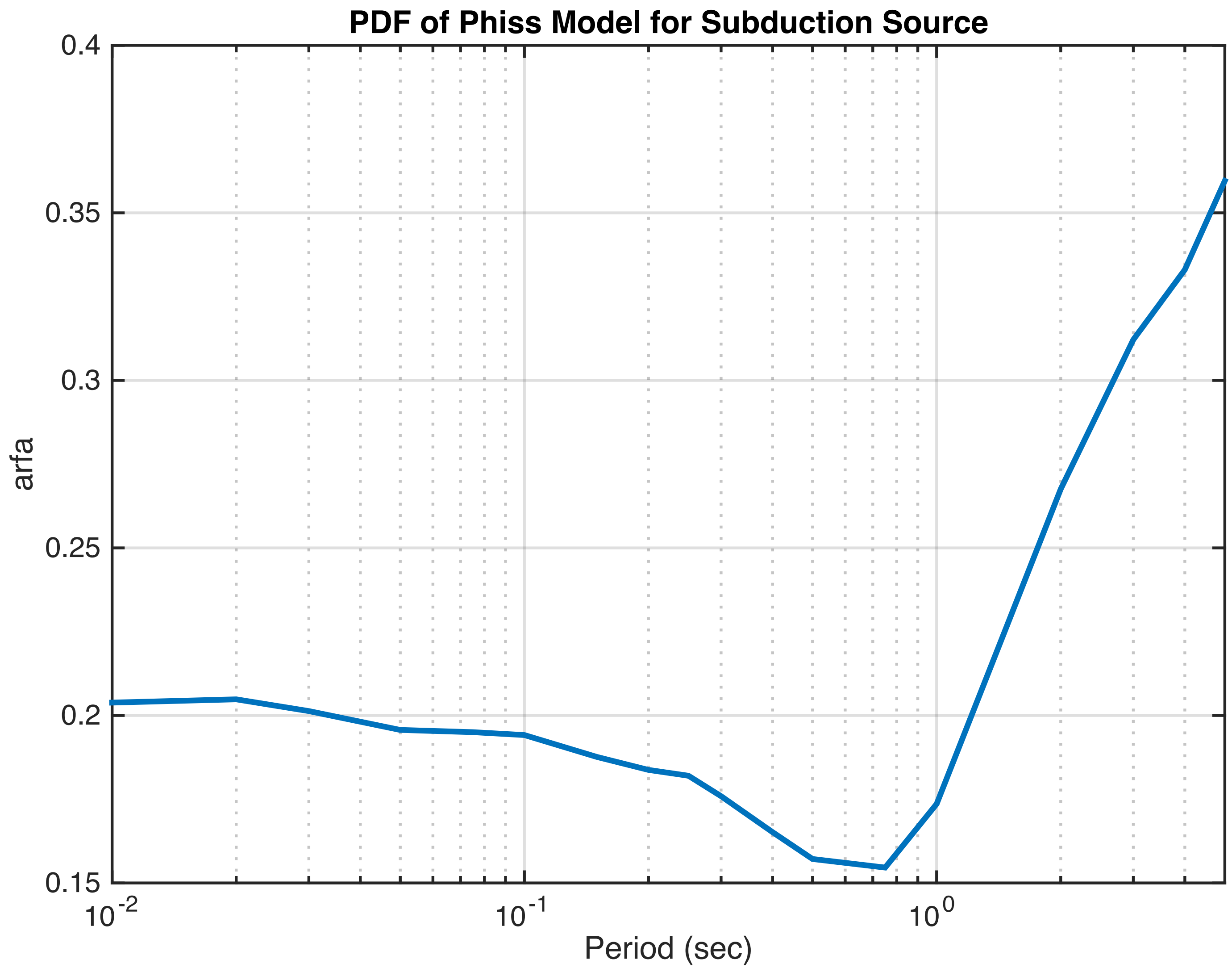




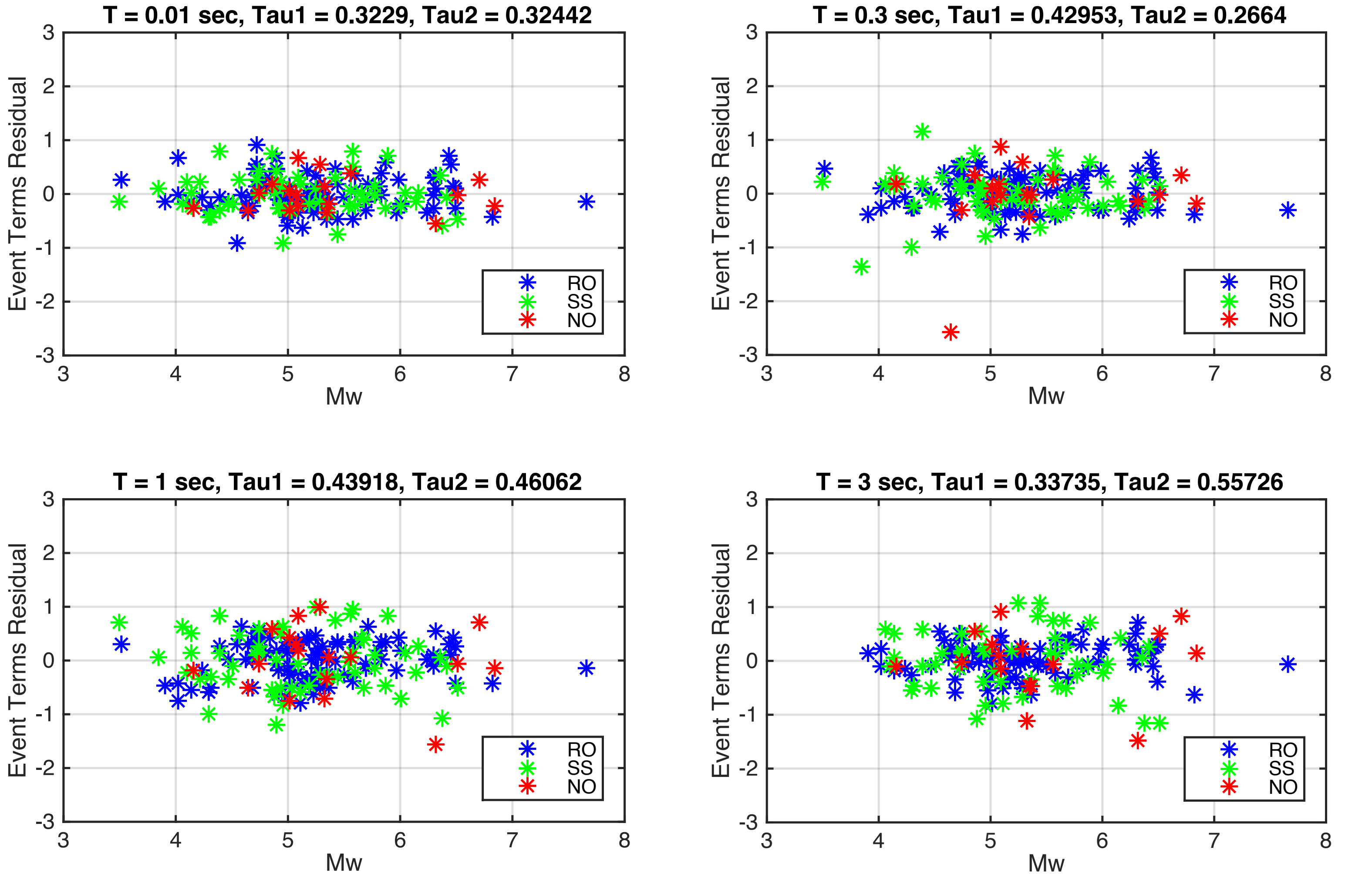
Mixture Model of PhiSS for Crustal Source



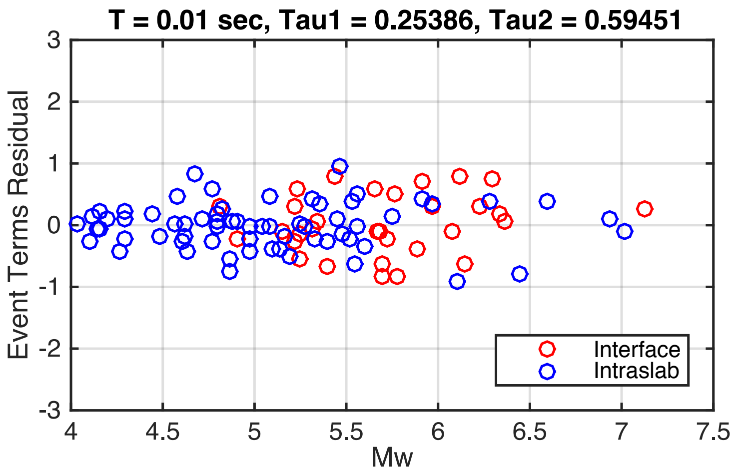
Mixture Model of PhiSS for Subduction Source

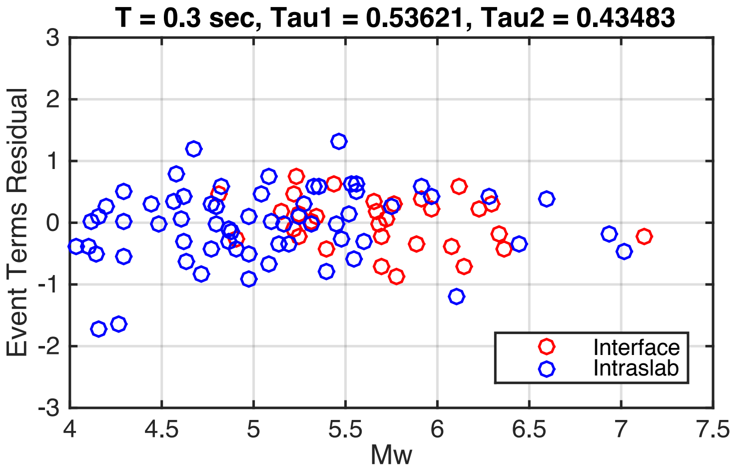


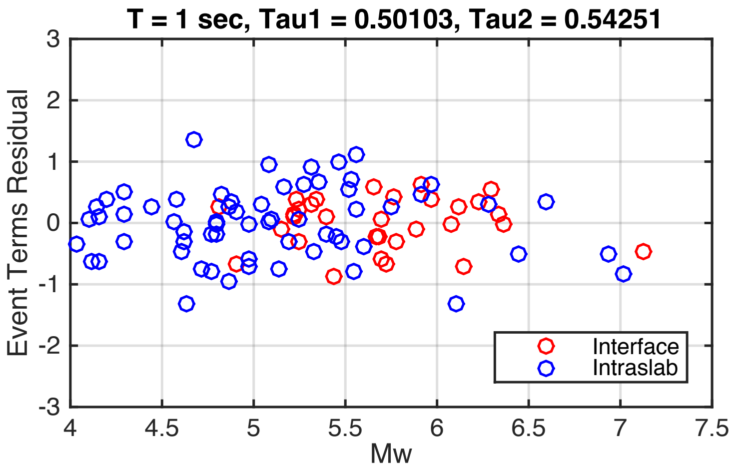
Event-Specific Residual of Crustal Source – I

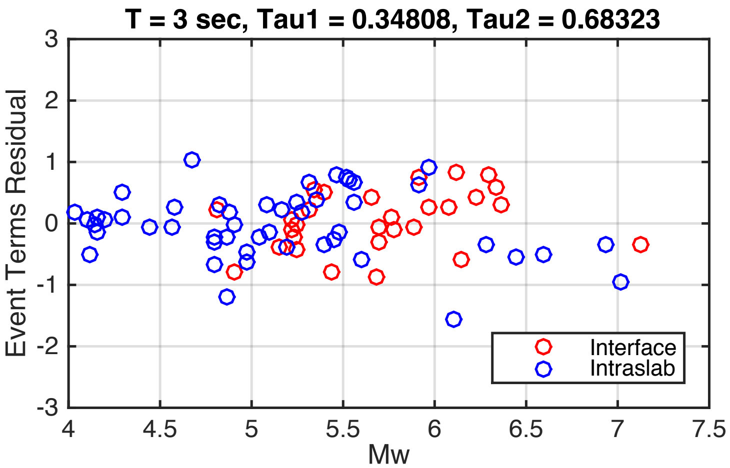


Event-Specific Residual of Subduction Source – I

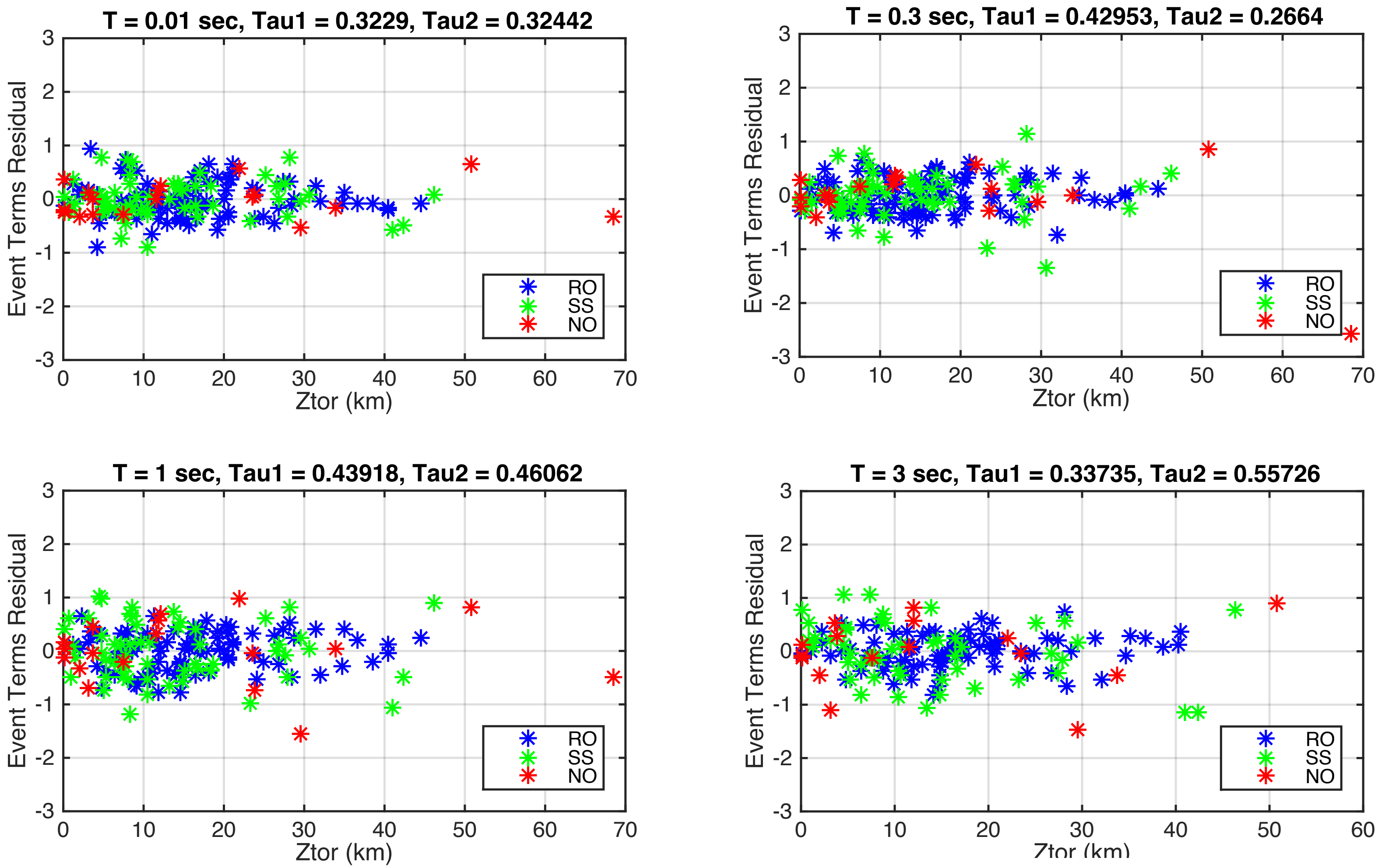




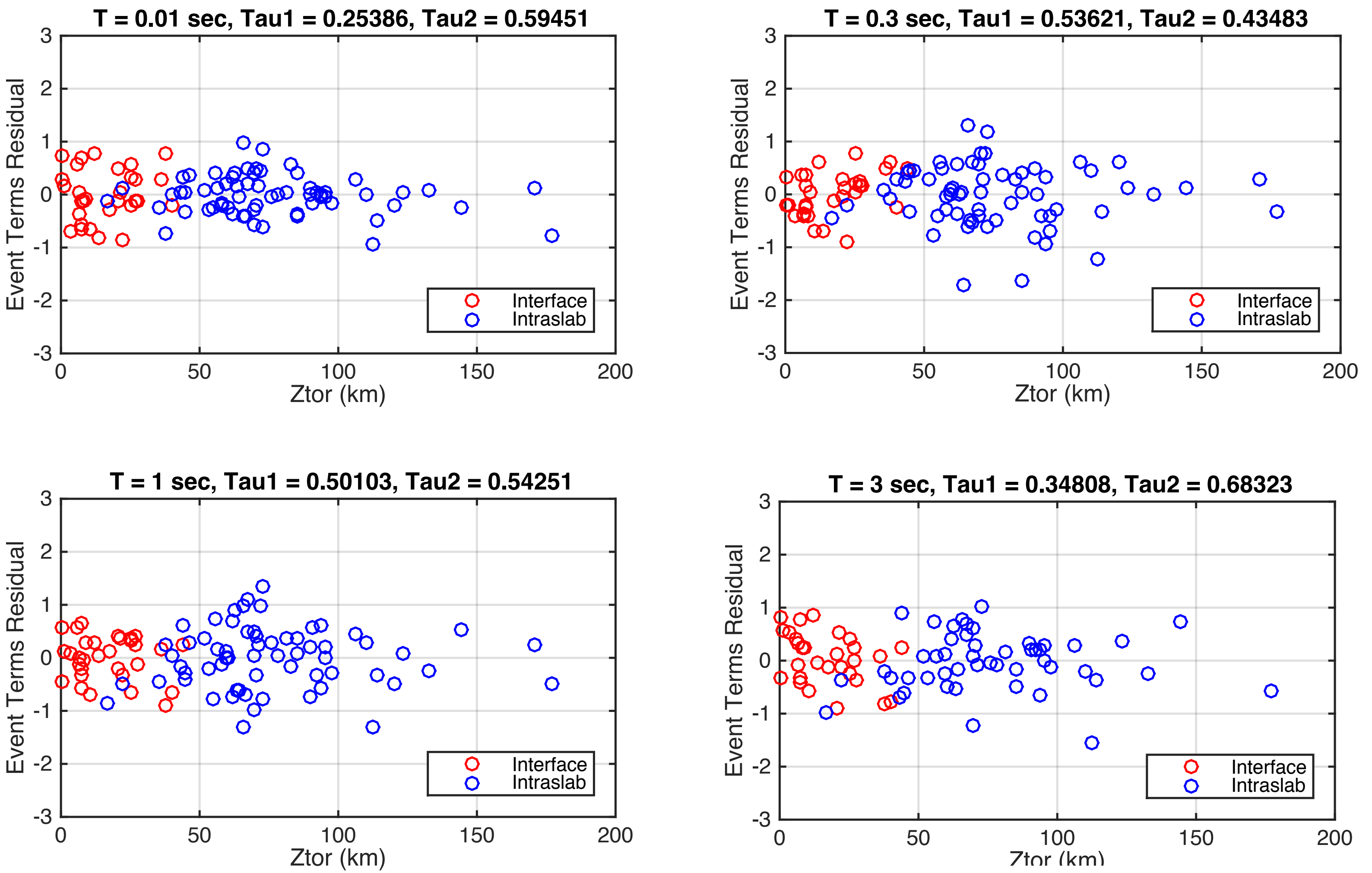




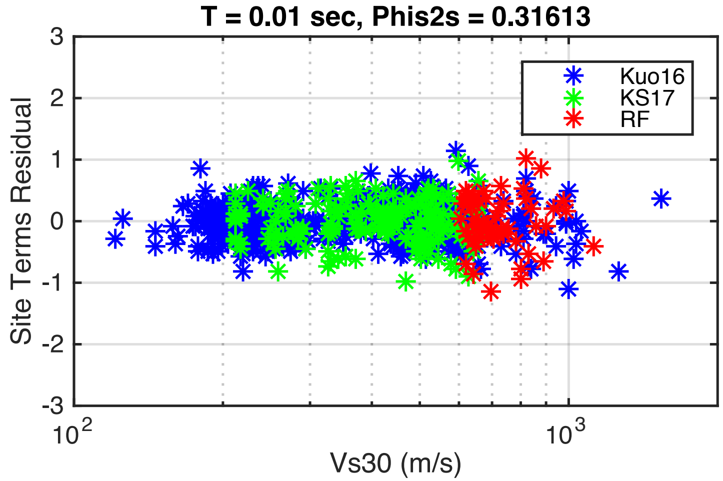
Event-Specific Residual of Crustal Source – II

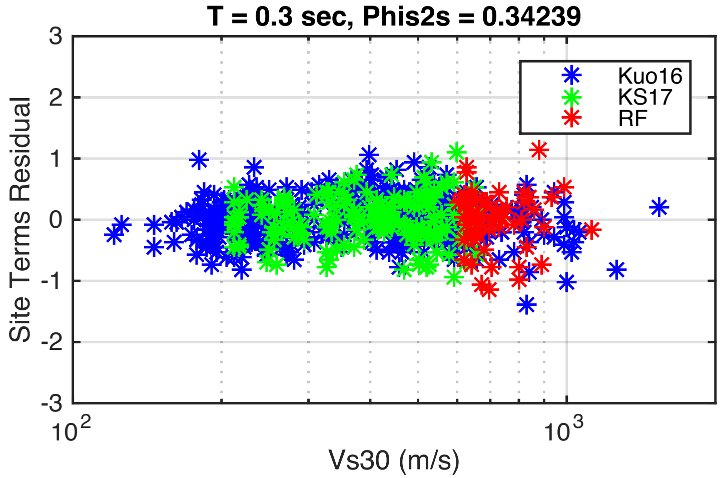


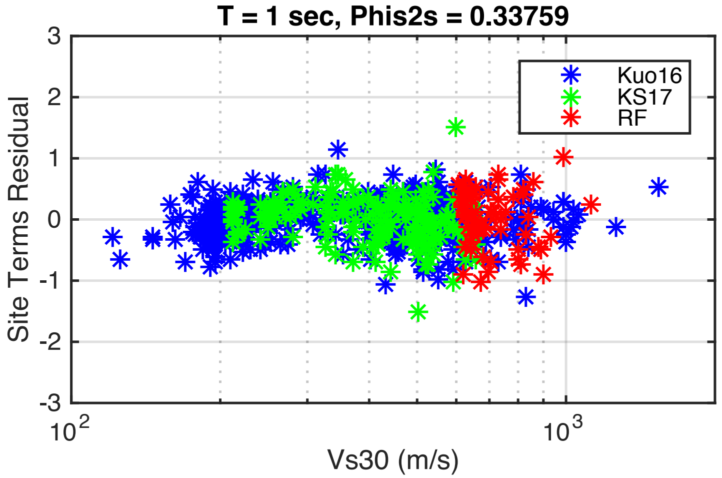
Event-Specific Residual of Subduction Source – II

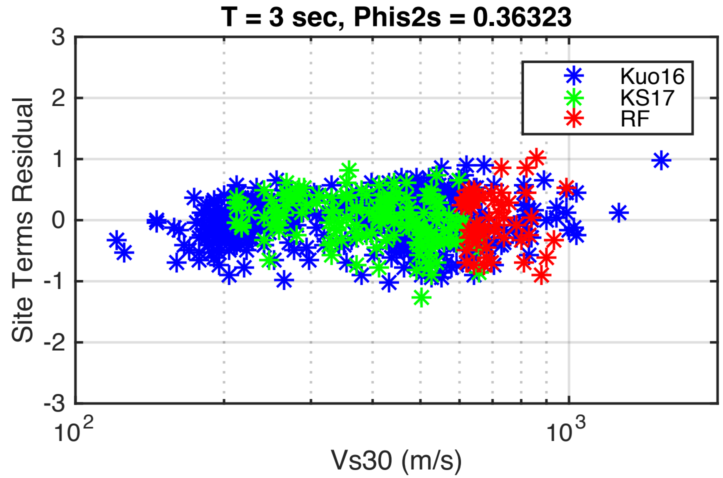


Station-Specific Residual – I

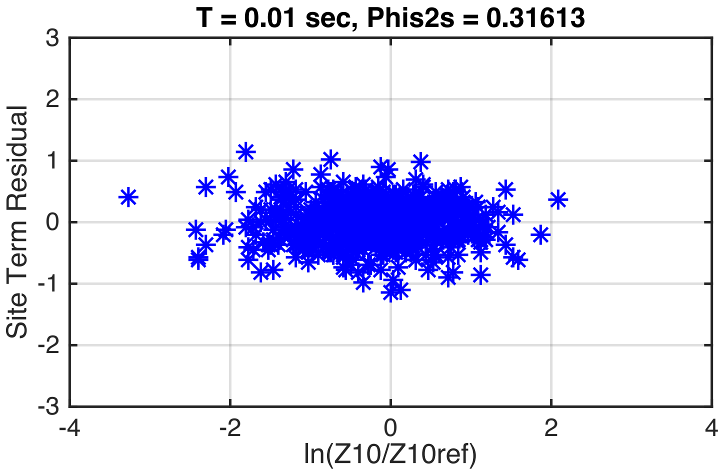


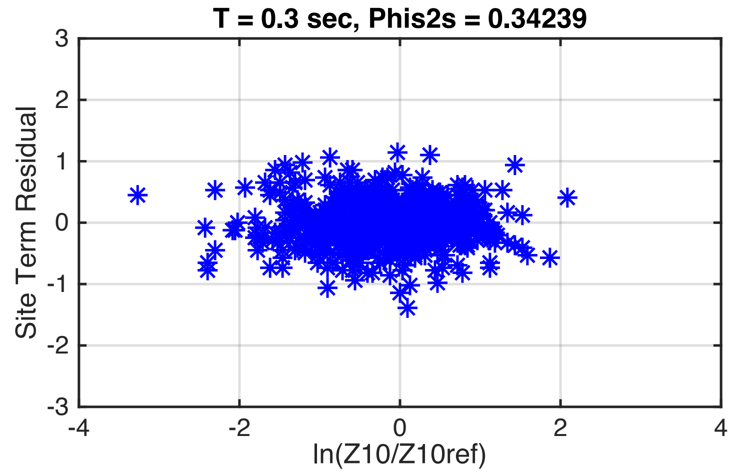


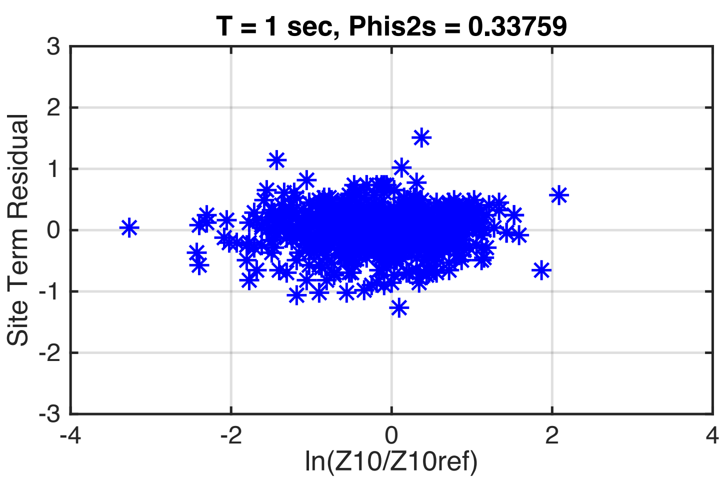


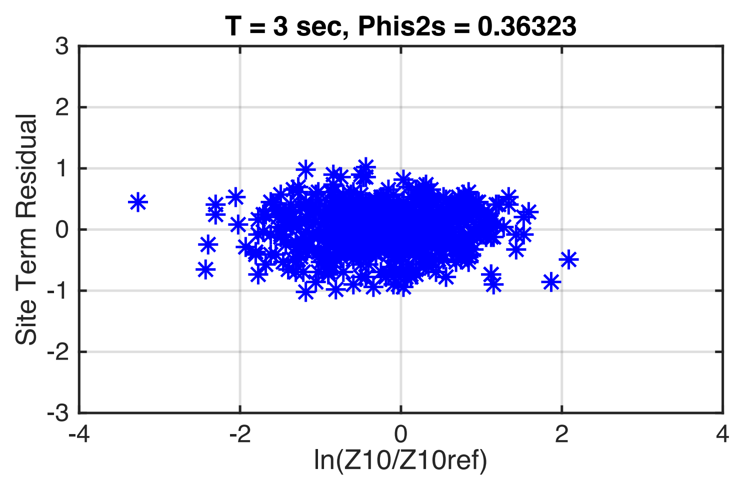


Station-Specific Residual – II

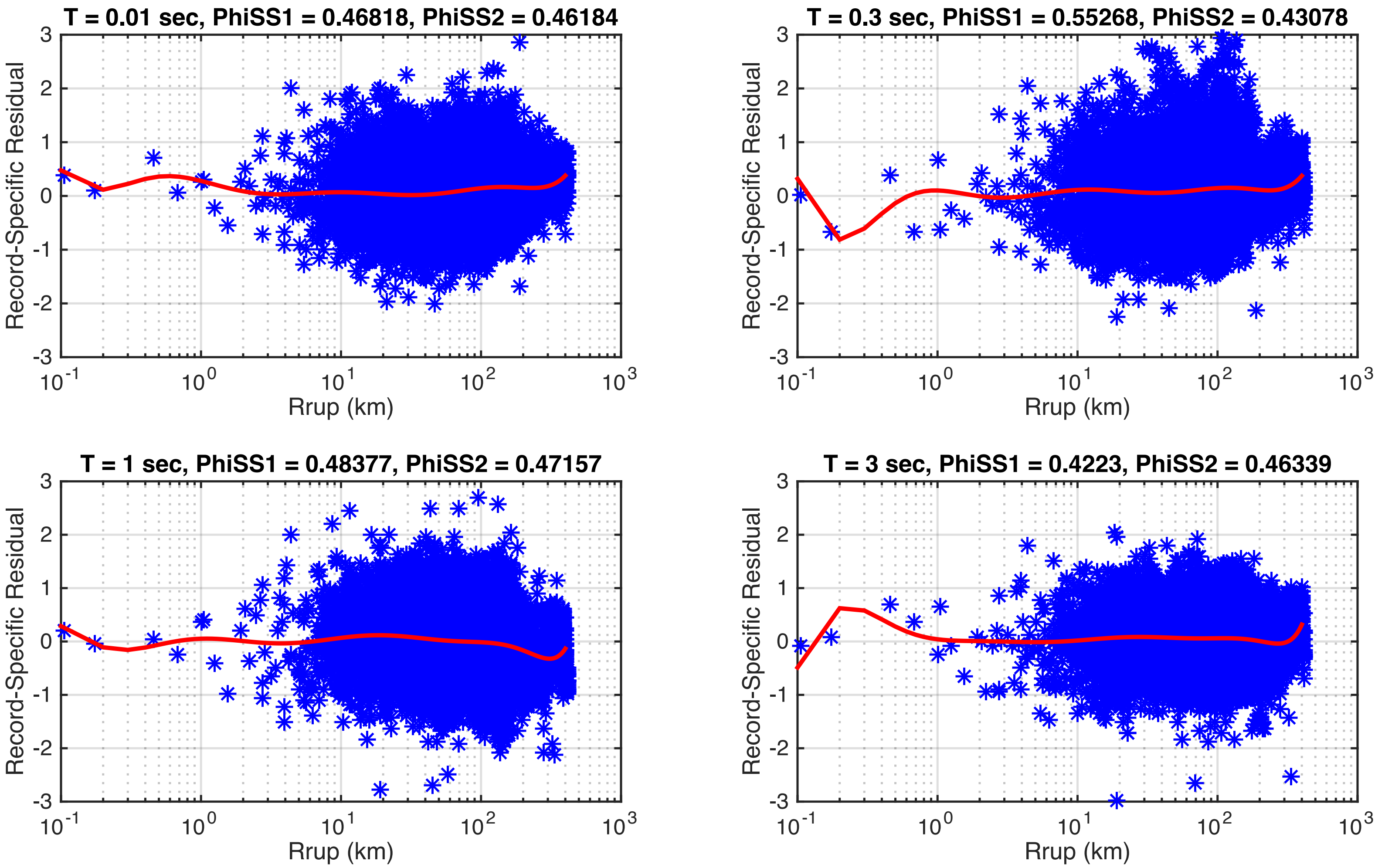




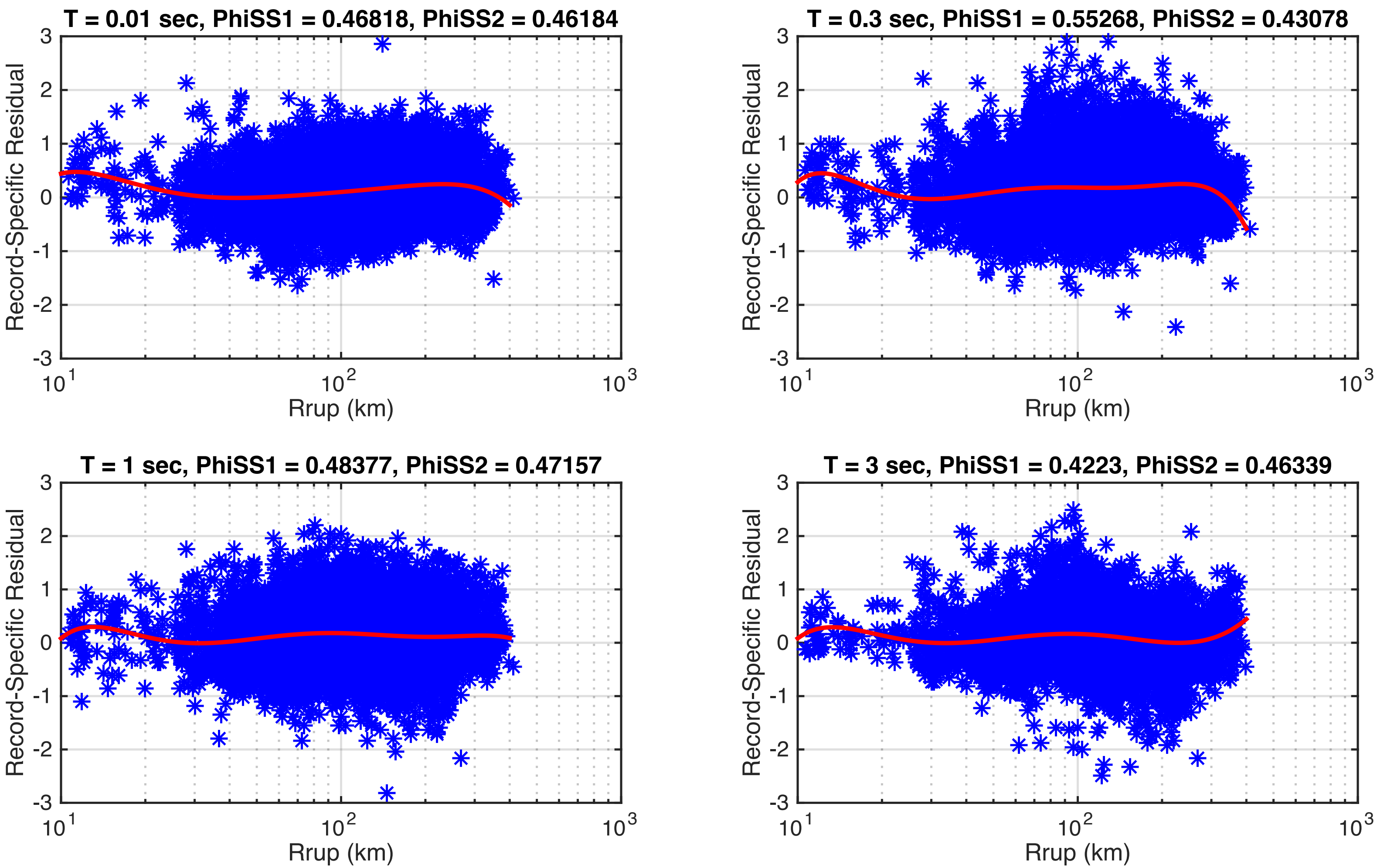




Record-Specific Residual for Crustal Source



Record-Specific Residual for Subduction Source



Thank You for Your Attention !!

Questions ?

Function Form – I

- **Function Form of Median**

$$ln\,S_a = lnS_a^{ref} + S_{source} + S_{path} + S_{site,lin} + S_{site,non}$$

- **Reference Spectrum**

$$lnS_a^{ref} = E^{ref} + S^{ref}$$

$$E^{ref} = c_1F_{cr,ro} + c_2F_{cr,ss} + c_3F_{cr,no} + c_4F_{sb,inter} + c_5F_{sb,intra} + c_6F_{as} + c_7F_{manila}$$

$$S^{ref} = c_{23}F_{kuo17} + c_{24}F_{ks17} + c_{25}F_{rf}$$

- **Source Scaling**

$$S_{source} = S_{mag} + S_{Ztor}$$

$$S_{mag} = S_{mag,cr}F_{cr} + S_{mag,sb}F_{sb}$$

$$S_{mag,cr} = c_8\left(\min\left(M_w, M_{max}\right) - M_w^{ref}\right) + c_{10}\left(\min\left(M_w, M_{max}\right) - M_w^{ref}\right)^2 + c_{11}(5 - M_w)u(5 - M_w)$$

$$S_{mag,sb} = c_9\left(M_w - M_w^{ref}\right) + c_{26}F_{inter}(M_w - M_c)u(M_w - M_c) + c_{27}F_{intra}(M_w - M_c)u(M_w - M_c)$$

$$S_{Ztor} = c_{12}F_{cr}\left(Z_{tor} - Z_{tor,cr}^{ref}\right) + c_{13}F_{sb}\left(Z_{tor} - Z_{tor,sb}^{ref}\right)$$

Function Form – II

- **Distance Scaling**

$$S_{path} = S_{geom} + S_{anel}$$

$$S_{geom} = S_{geom,cr}F_{cr} + S_{geom,sb}F_{sb}$$

$$S_{geom,cr} = \left[c_{14} + c_{16}\left(min\,\{M_w, M_{max}\} - M_w^{ref}\right)\right] ln\left(\frac{\sqrt{R_{rup}^2 + h^2}}{\sqrt{(R_{rup}^{ref})^2 + h^2}}\right)$$

$$S_{geom,sb} = \left[c_{15} + c_{17}\left(min\,\{M_w, M_c\} - M_w^{ref}\right)\right] ln\left(\frac{\sqrt{R_{rup}^2 + h^2}}{\sqrt{(R_{rup}^{ref})^2 + h^2}}\right)$$

$$S_{anel} = c_{18}F_{cr}\left(R_{rup} - R_{rup}^{ref}\right) + c_{19}F_{sb}\left(R_{rup} - R_{rup}^{ref}\right)$$

Function Form – III

- **Site Scaling**

$$S_{site,non} = c_{20} u(V_{s30}^{ref} - V_{s30})\{-1.5 ln\left(\frac{V_{s30}}{V_{s30}^{ref}}\right) - ln(\hat{S}_{a1100} + 2.4) + ln\left(\hat{S}_{a1100} + 2.4(\frac{V_{s30}}{V_{s30}^{ref}})^{1.5}\right)\}$$

$$S_{site,lin} = c_{21}\, ln\left(\frac{V_{s30}}{V_{s30}^{ref}}\right) + c_{22}\, ln\left(\frac{Z_{1.0}}{Z_{1.0}^{ref}}\right)$$

$$Z_{1.0}^{ref} = \exp\,(\frac{-4.08}{2} ln\left(\frac{V_{S30}^{2} + 355.4^{2}}{1750^{2} + 355.4^{2}}\right))$$

Function Form – IV

- **Function Form of Sigma**
  - Event-Specific Residual Term

$$\delta_e = N(0, \tau)$$

$$\tau = \tau_{cr} F_{cr} + \tau_{sb} F_{sb}$$

$$\tau_{cr} = \tau_{1,cr} + \left(\tau_{2,cr} - \tau_{1,cr}\right) f(M)$$

$$\tau_{sb} = \tau_{1,sb} + \left(\tau_{2,sb} - \tau_{1,sb}\right) f(M)$$

$$f(M) = 0.5\{\min\{6.5, \max\{4.5, M_w\}\} - 4.5\}$$

  - Station-Specific Residual Term

$$\delta_s = N(0, \phi_{s2s})$$

Function Form – V

– Record-Specific Residual

$$\delta_r = 0.5N(0, \phi_{ss}^1) + 0.5N(0, \phi_{ss}^2)$$

$$\phi_{ss}^1 = (1 + \alpha)\left(\phi_{ss,cr}F_{cr} + \phi_{ss,sb}F_{sb}\right)$$

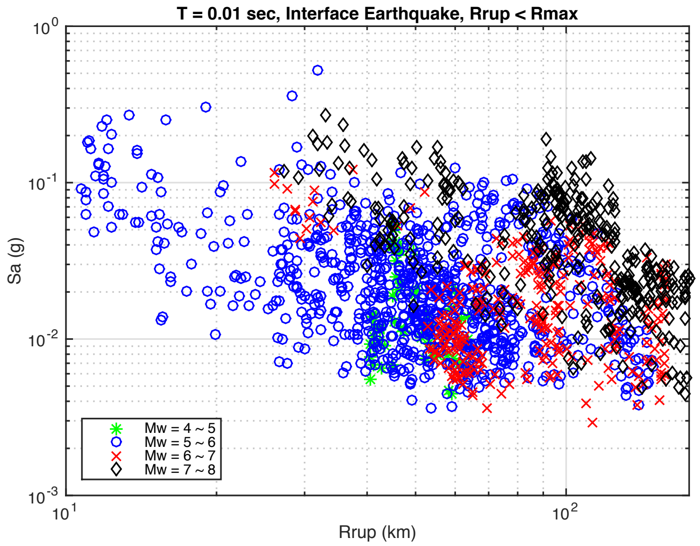
$$\phi_{ss}^2 = (1 - \alpha)\left(\phi_{ss,cr}F_{cr} + \phi_{ss,sb}F_{sb}\right)$$

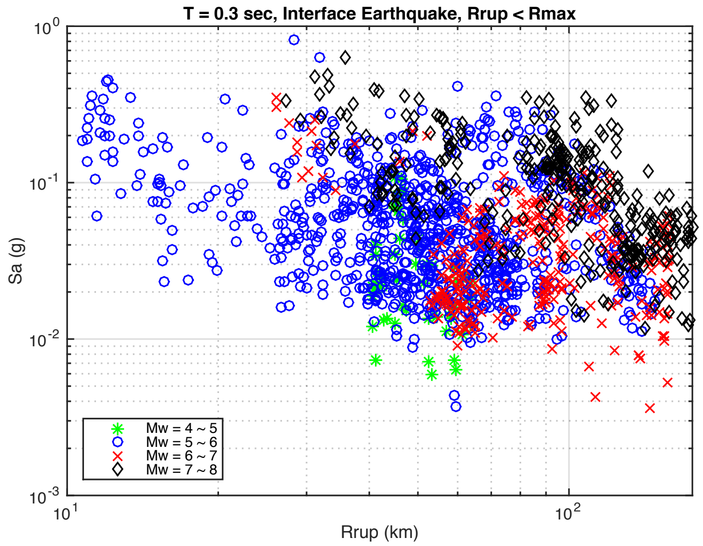
$$\phi_{ss,cr} = \phi_{ss1,cr} + \left(\phi_{ss2,cr} - \phi_{ss1,cr}\right)f(M)$$

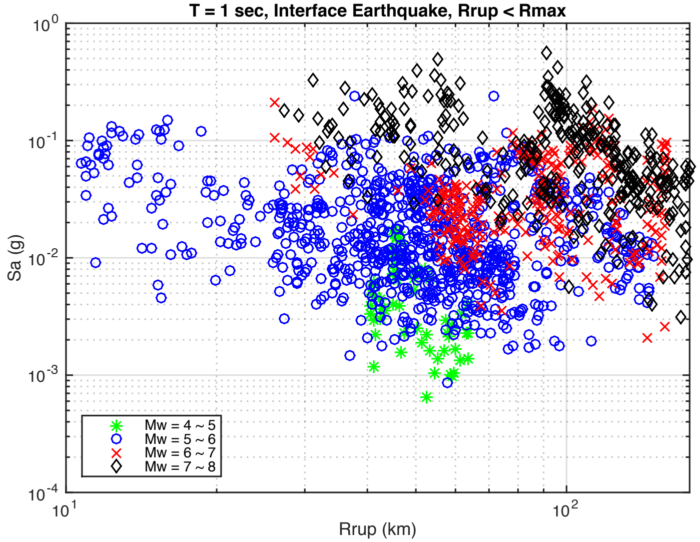
$$\phi_{ss,sb} = \phi_{ss1,sb} + \left(\phi_{ss2,sb} - \phi_{ss1,sb}\right)f(M)$$

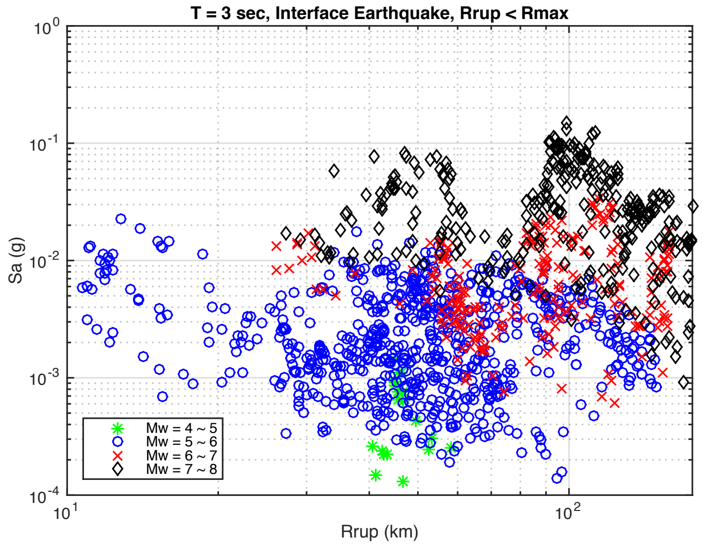
$$f(M) = 0.5\{\min\{6.5, \max\{4.5, M_w\}\} - 4.5\}$$

Ground Motion Data of Interface Source

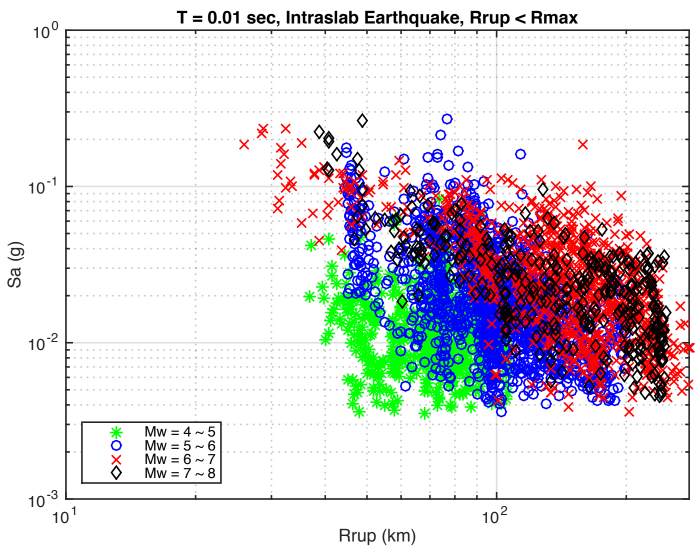


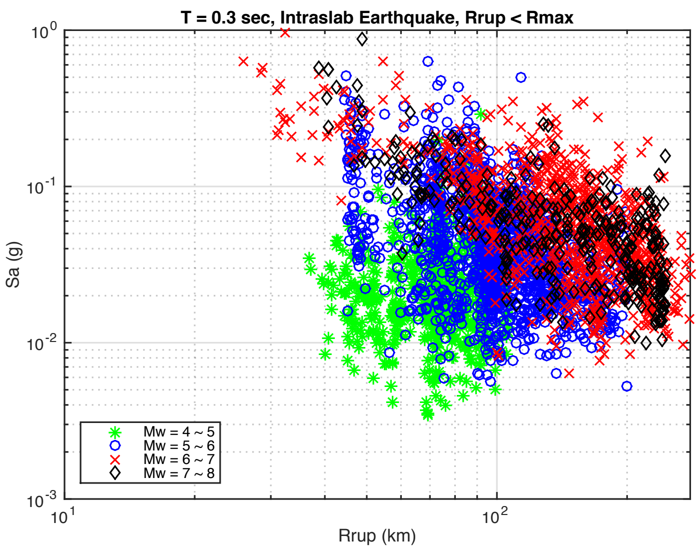


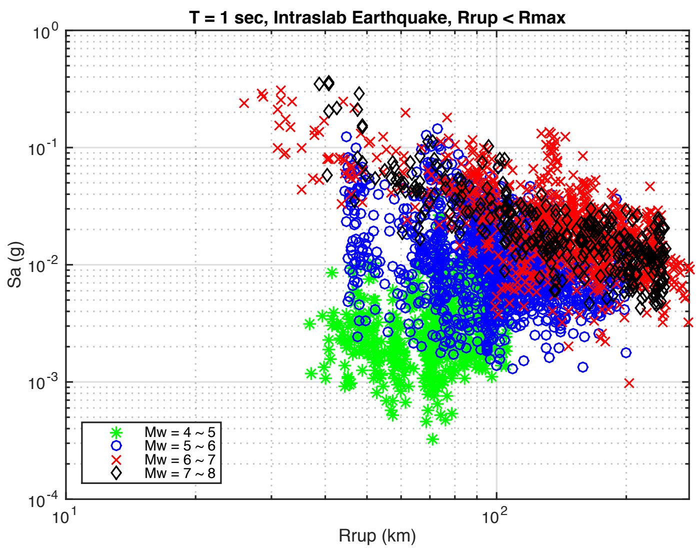


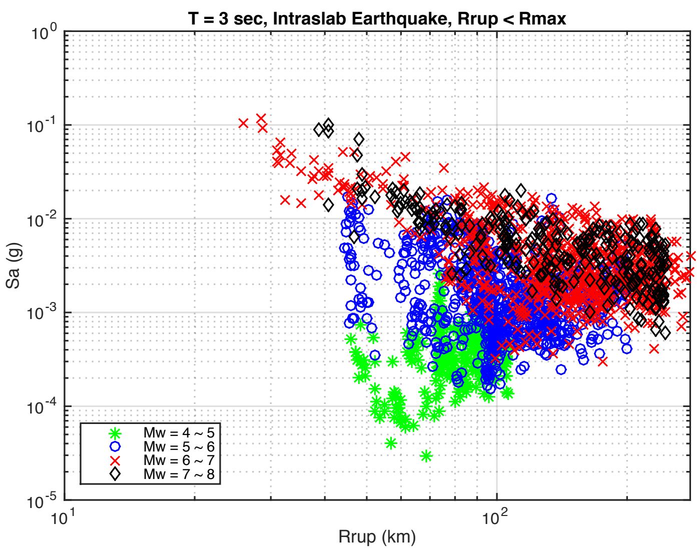


Ground Motion Data of Intraslab Source

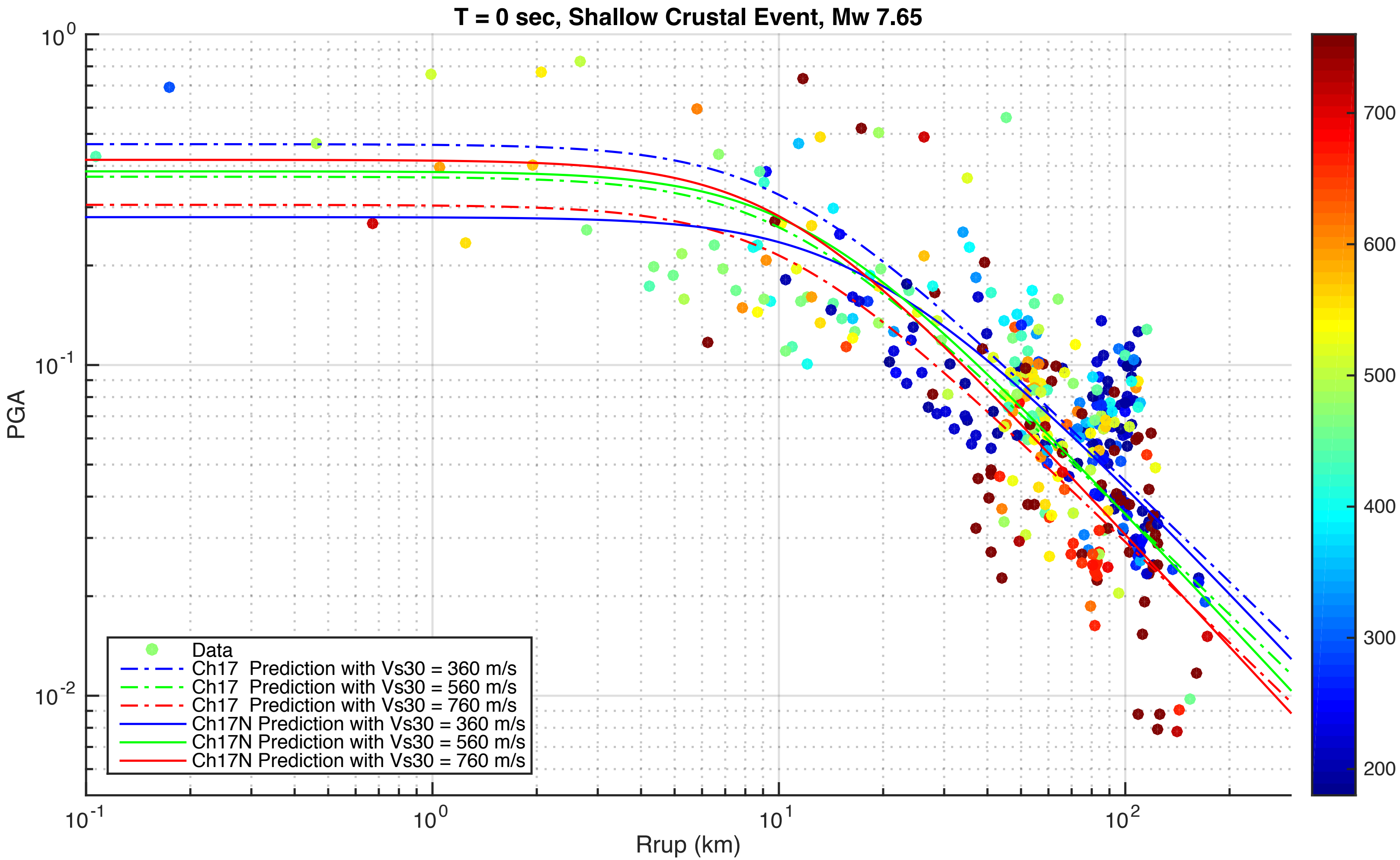




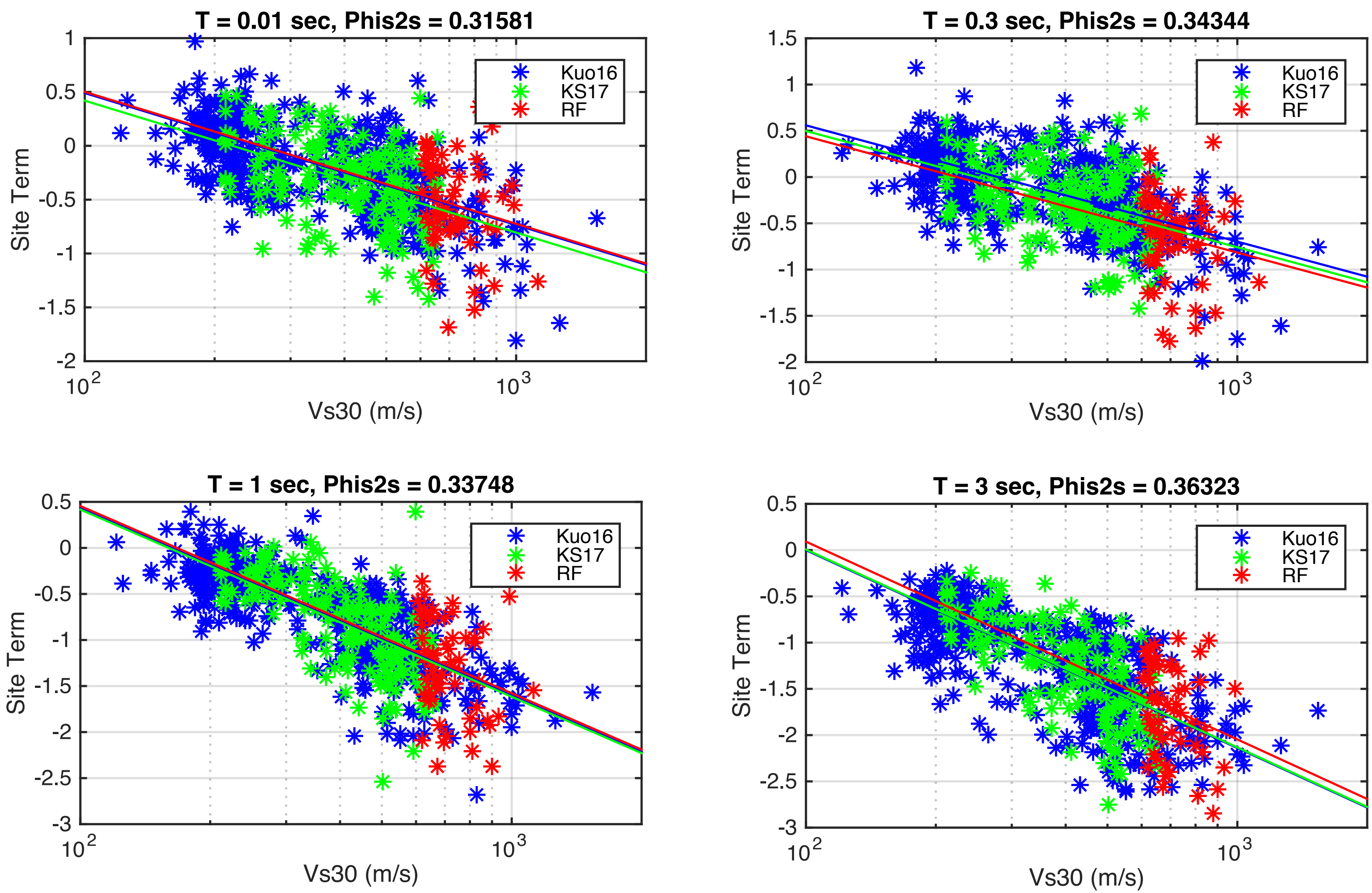




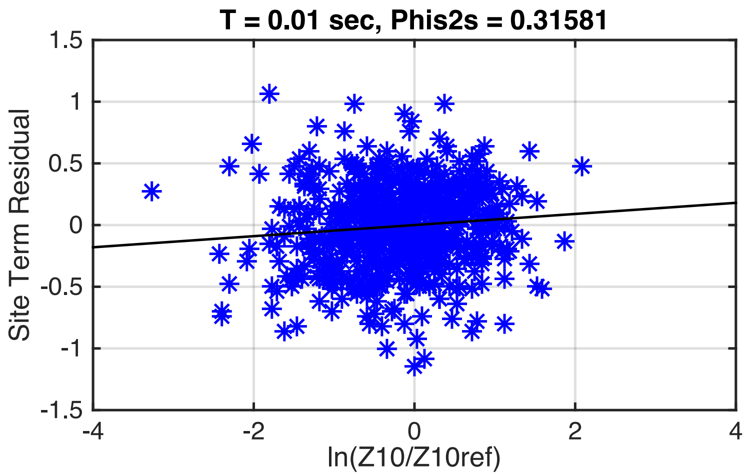
Ch17 Model Prediction for Chi-Chi Earthquake with/without Nonlinear Site Effect

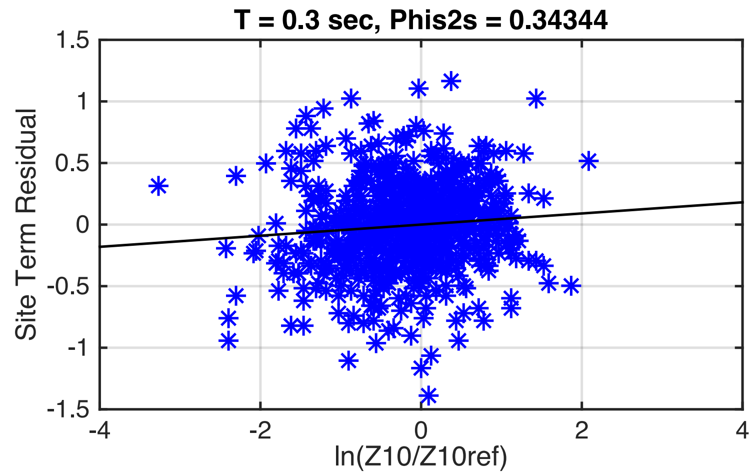


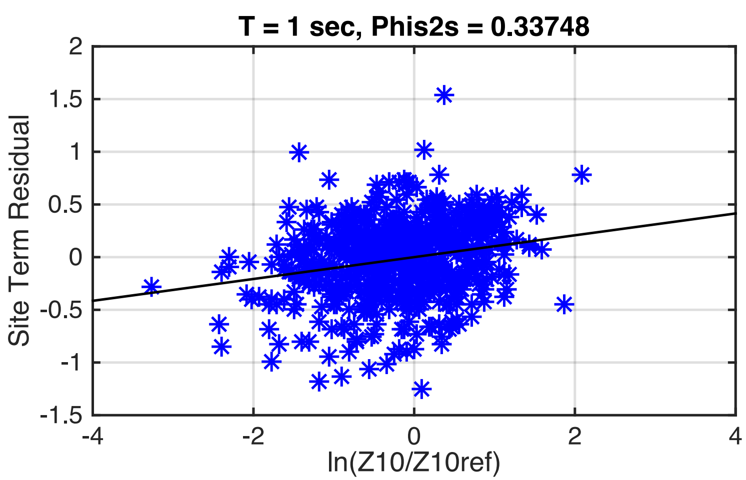
Estimated Station Term and Vs30 Scaling

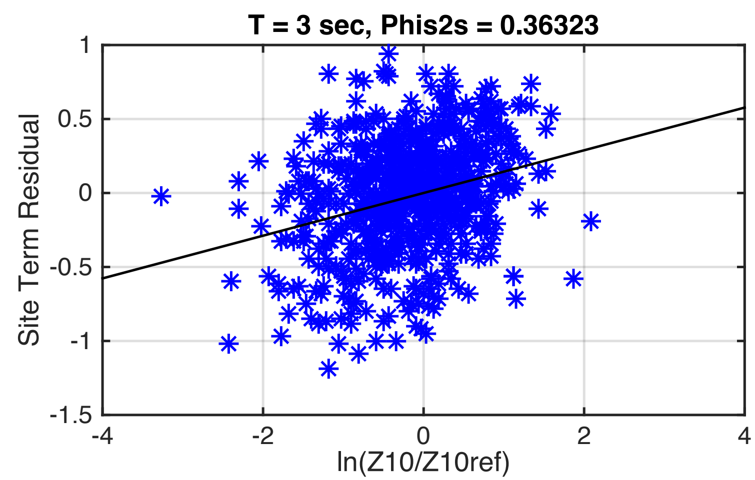


Estimated Station Term and Z1.0 Scaling

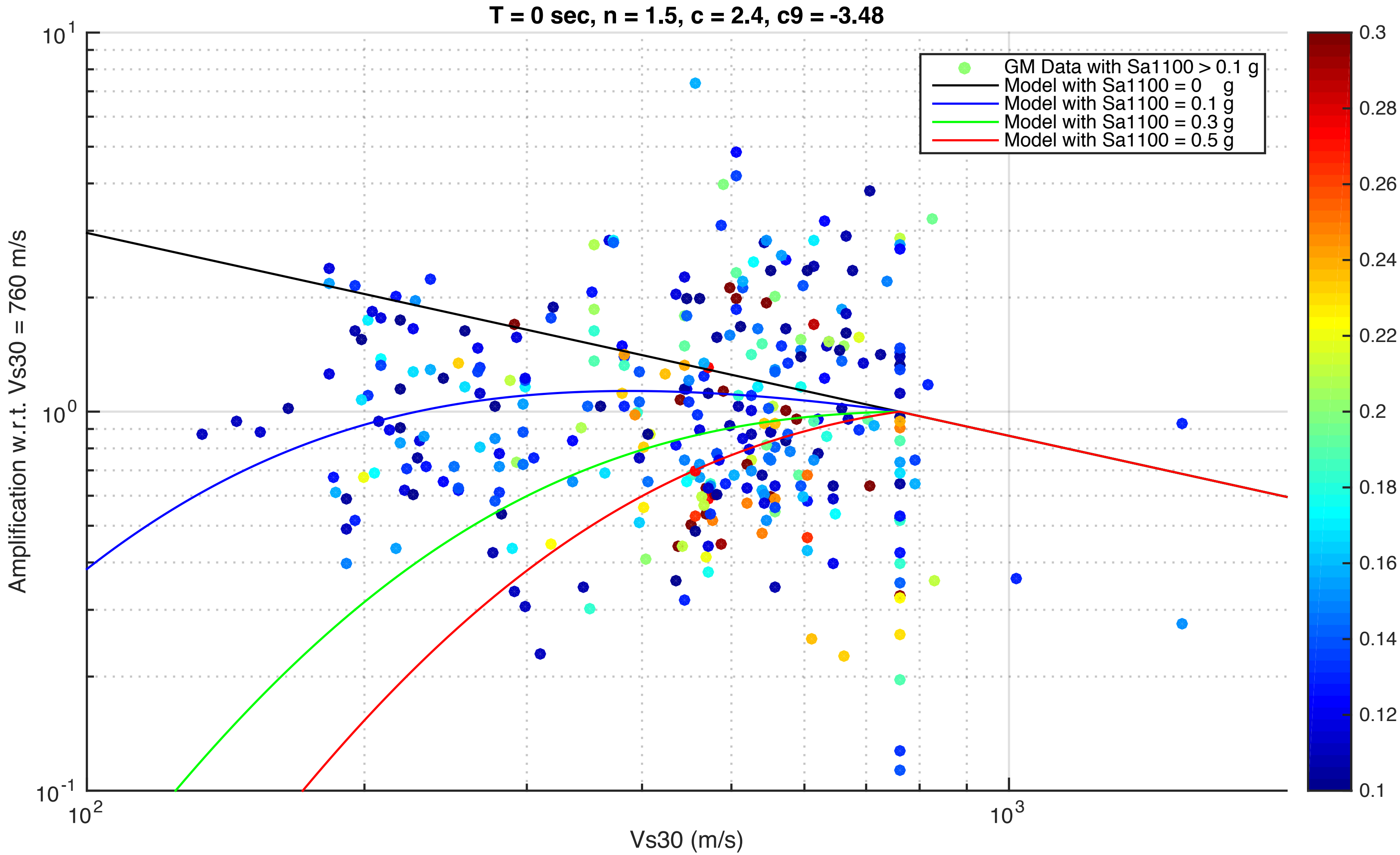




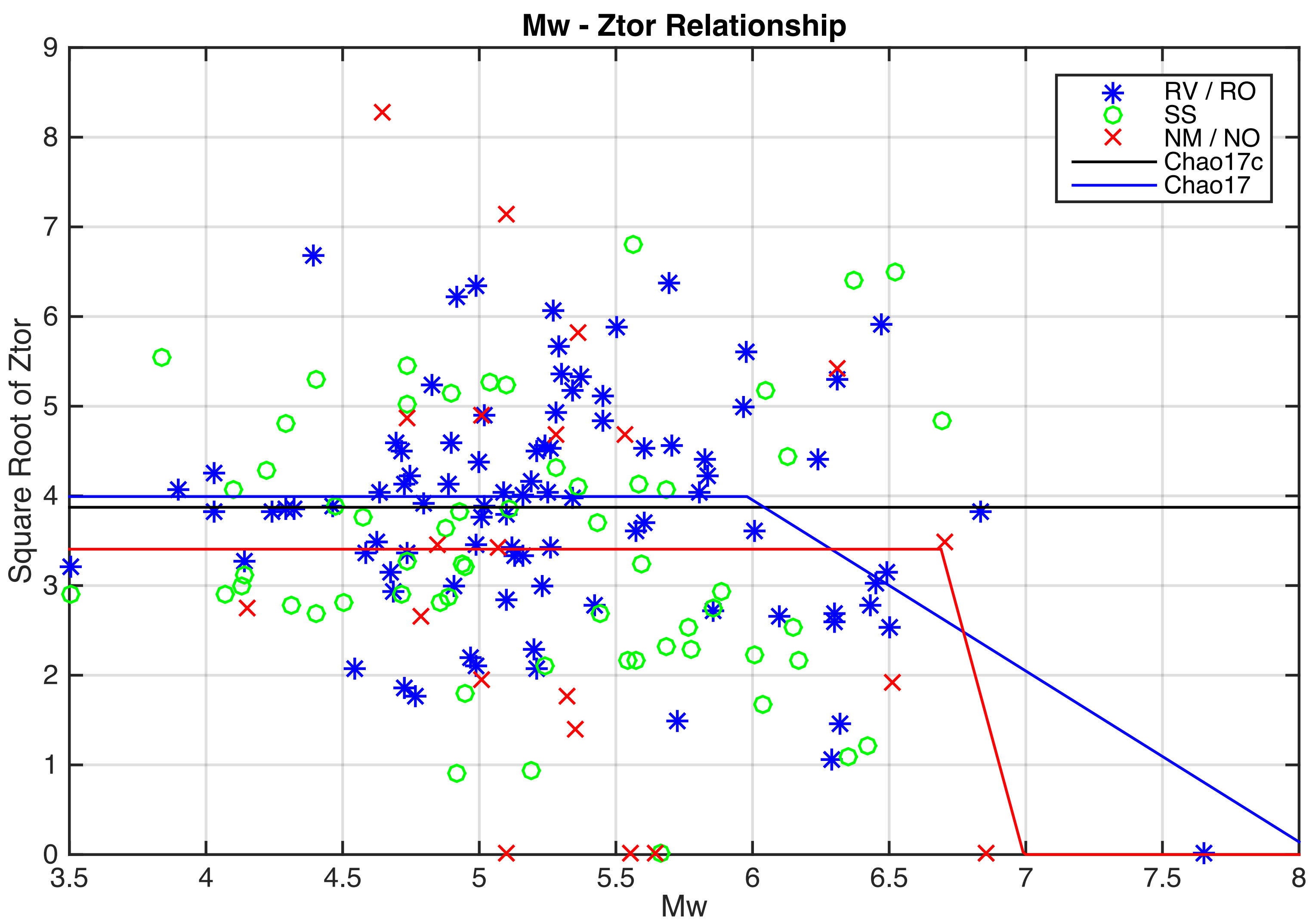




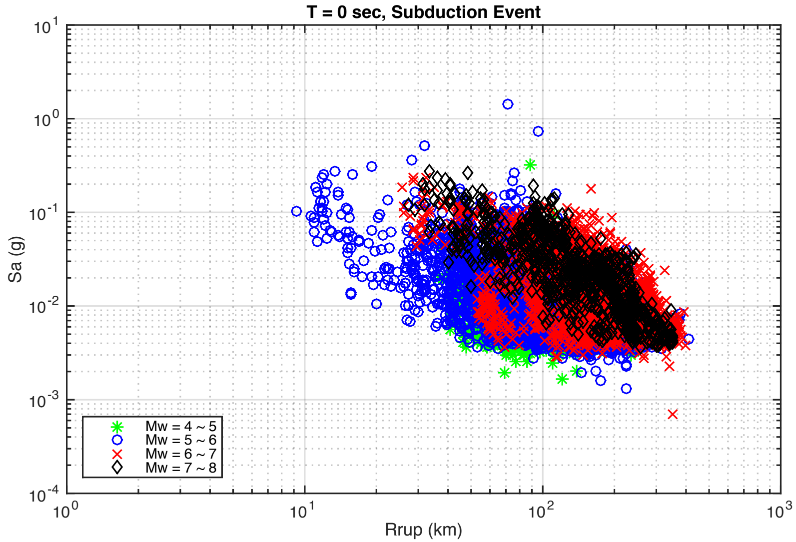
Nonlinear Site Effect Model for PGA

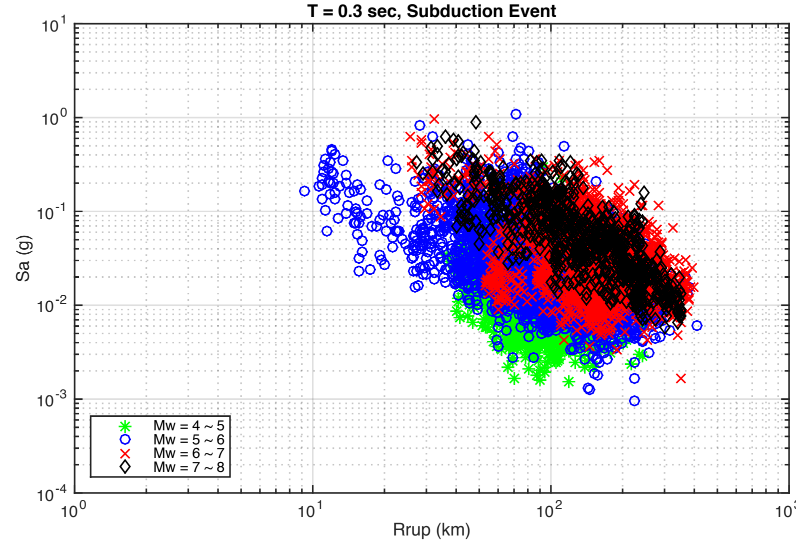


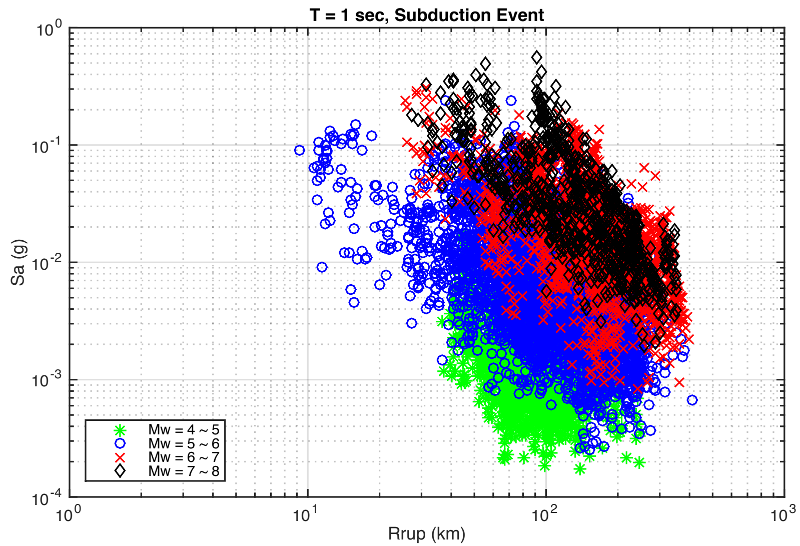
Mag. Dependent Depth vs. Constant Depth

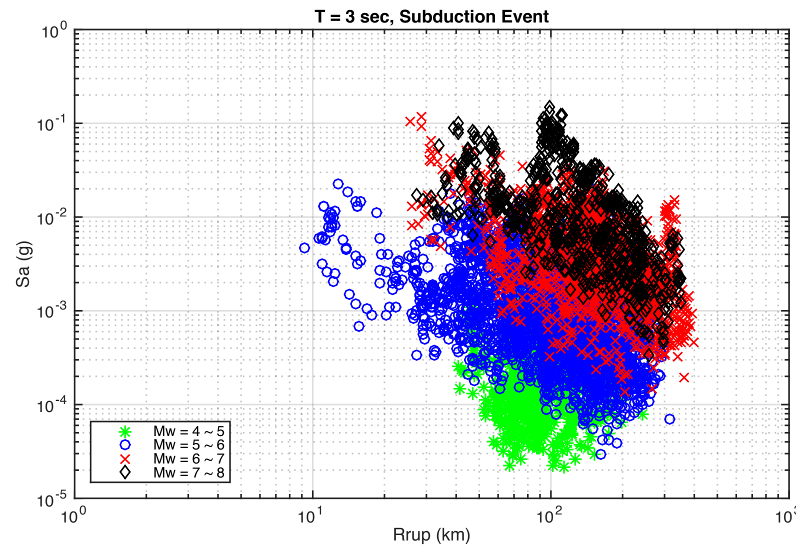


GM Data of Subduction Event









GM Data of Crustal Event