T2.3-02 Analyzing the Reduced Displacement Potential of DPRK Nuclear Explosions Using Waveform Equalization Technique

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Topics

- Motivation
- Waveform Equalization Method (**WEM**) – Mathematical Formulation
- Reduced Displacement Potential - Formulation for ψ_∞
- **GF** – (Green Function) Similarities - Regional + Far-Regional Distances
- $\mathbf{pP_n+P_n}$ (or **pP+P**) interaction
- **WEM** – Illustration Using Numerical Seismograms
- **WEM** – Application to DPRK Explosions - Regional + Teleseismic
- Conclusions

***Time-domain source function (TDSF) for nuclear and chemical explosions – analysis around Nevada National Security Site (NNSS), Geophys. J. Int (2017) 209, 1048-1063*.**

Motivation

Time domain source function (TDSF): for nuclear explosions as a function of size and overburden

pP+P interaction

- (i) influences the pulse width of P waves – makes source parameter retrieval difficult
- (ii) synthetic seismograms used, but the t* and travel time of pP (depth phase) …

The waveform equalization method (WEM) helps to overcome difficulties involved with pP+P, especially for shallow explosions occurring in the vicinity of one another

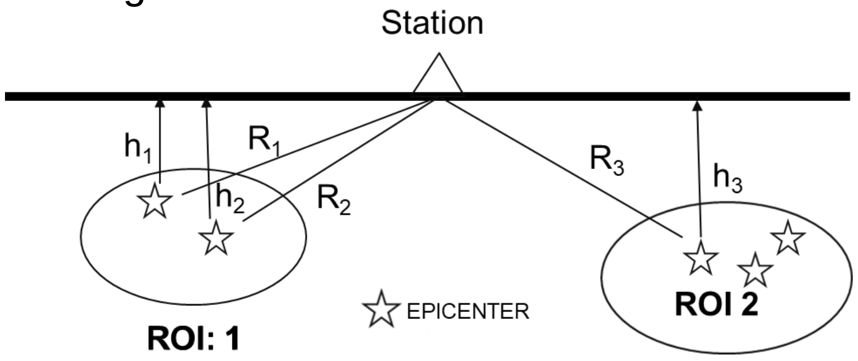
- (i) recorded waveforms: t*, topography, and lateral path are same at a common station
- (ii) simple and easy to apply
- (iii) eliminates the need for synthetics

Waveform Equalization Method (WEM)

A seismogram from an explosion or earthquake is a convolution of **source function** with the **Green's function GF**. For two explosions recorded at a common station, we have the following

$$O_1(t) = S_1(t) * G_1(t, R)$$
$$O_2(t) = S_2(t) * G_2(t, R)$$

O_i(t) represent data vector for the ith event, and **S_i** and **G_i**'s represent the source time function and **GFs**, respectively.



Let $\mathbf{S_1^T}$ (t) and $\mathbf{S_2^T}$ (t) represent source functions with starting size (ψ_∞) and overburden (h) of two explosions.
Convolve O_1(t) with $\mathbf{S_2^T}$ (t) and O_2(t) with $\mathbf{S_1^T}$ (t) and use the two convolved time series to construct a difference seismogram Ξ(t) as follows

$$\Xi(t) = S_2^T(t) * S_1(t) * G_1(t) - S_1^T(t) * S_2(t) * G_2(t)$$

Ξ(t) will be minimum when

$$\begin{cases} S_1^T(t) = S_1(t) \\ S_2^T(t) = S_2(t) \\ G_1(t) \approx G_2(t) \begin{cases} R_1 \approx R_2 \\ \triangle h \longrightarrow 0 \end{cases} \end{cases}$$

MINIMIZATION: VARIANCE REDUCTION, L1 or L2 Norm CRITERIA

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Source Function Used in WEM

Base on the derivation in Saikia (2017), we define displacement wavefield at the elastic radius R_{el} as follows

$$S(R_{el}, t) = \left[\underbrace{\frac{F(t)}{R_{el}^2}}_{\substack{\text{Near Field} \\ \text{(Static)}}} + \underbrace{\frac{\partial_t F(t)}{R_{el} C}}_{\substack{\text{Far Field} \\ \text{(Dynamic)}}} \right] * \underbrace{[e^{-\gamma t} P_o(t) + P_2(t)] H(t)]}_{\substack{\text{Pressure Pulse on the} \\ \text{Cavity surface}}}$$

$$F(t) = \frac{R_{el} C^2}{4 \mu \beta p} H(t) e^{-\alpha t} \sin(pt)$$

C=wave velocity
β = dimensionless
R_{el} = elastic radius
P_o=Hydro-static
P_2=Steady-state
H(t)=Heavy-side Step
γ = Mulle & Murphy (1971)
α, p = parameters (Saikia, 2017)

for the deformation field at R_{el}. Will refer to this deformation field as the time-domain source function (TDSF). Also note that

$$\text{RDP}(t) = F(t) * [e^{-\gamma t} P_o(t) + P_2(t)] H(t)$$

is the **Reduced Displacement Potential (RDP)** – ψ_∞ is the long-period strength. Time-derivative of RDP(t) is used as explosion source function (Chavez *et al*., 2017). ψ_∞ is related to depth and source corner, and used in previous studies to model explosions in Amchitka and Cannikin Islands, Novaya Zemlya, NTS and Semipalatinsk in USSR (Saikia *et al*., 2006; Helmberger and Hadley, 1981; Lay *et al*., 1981; many others)

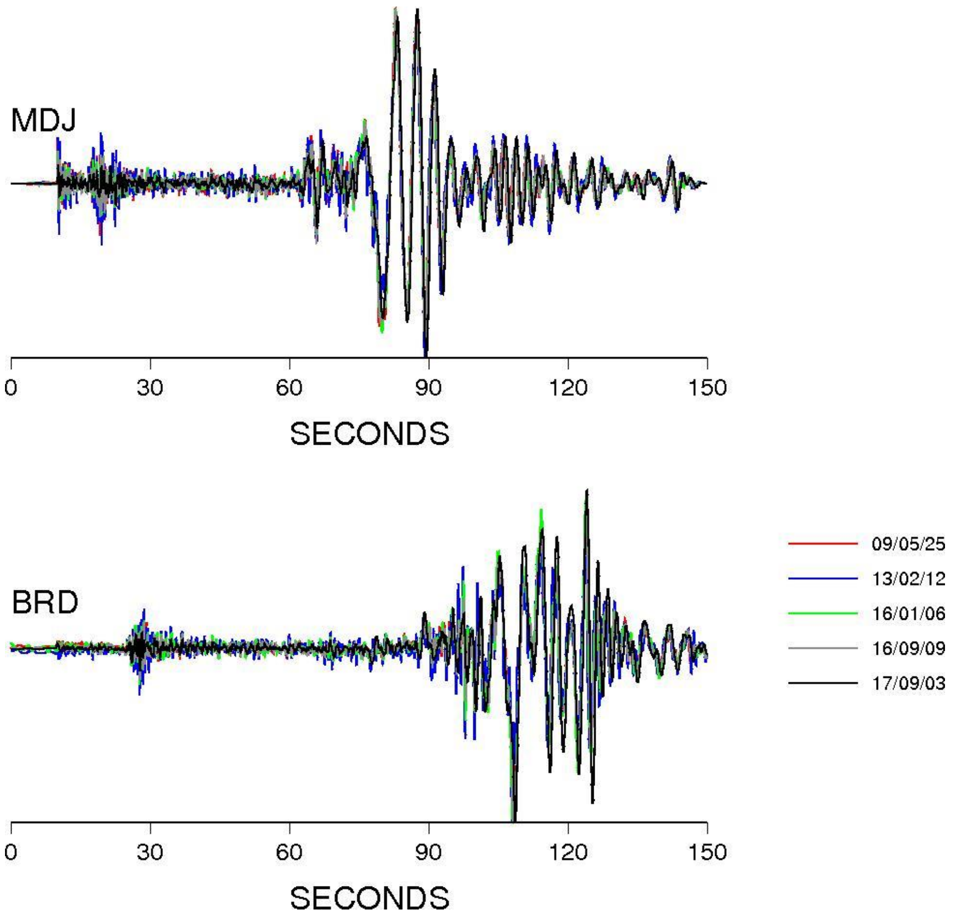
Green Function (GF) Similarity – Surface Waves

Explosions are shallow and are conducted within the top kilometer of a model
- large-scale explosions are exception

Regional Seismograms from DPRK explosions
- amplitude – self normalized
- event-to-event surface waves are similar
- GFS are similar

At low frequency, they become well suited **to** WEM**.**

P waves can exhibit topography effect
- at a common station remarkably similar



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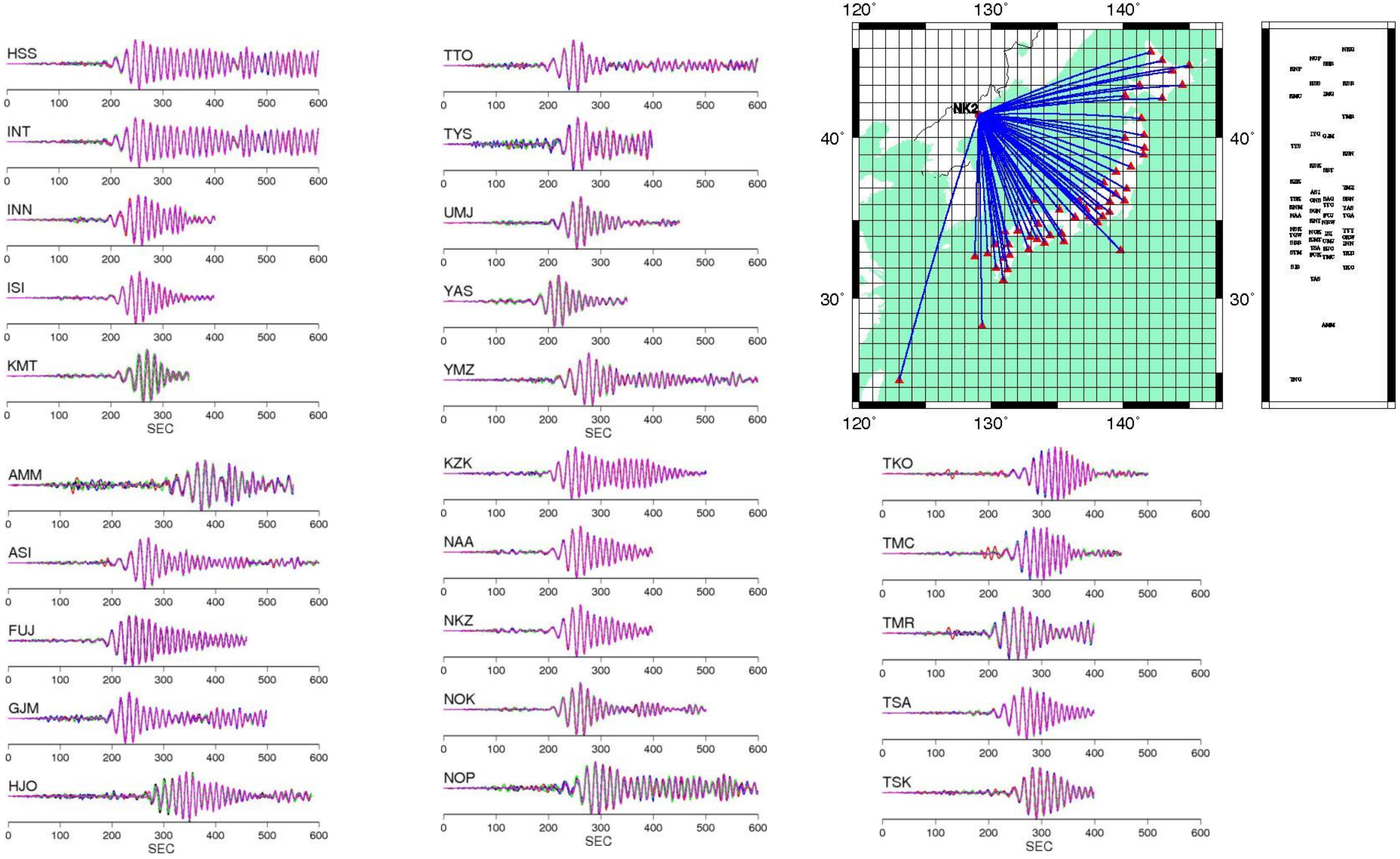
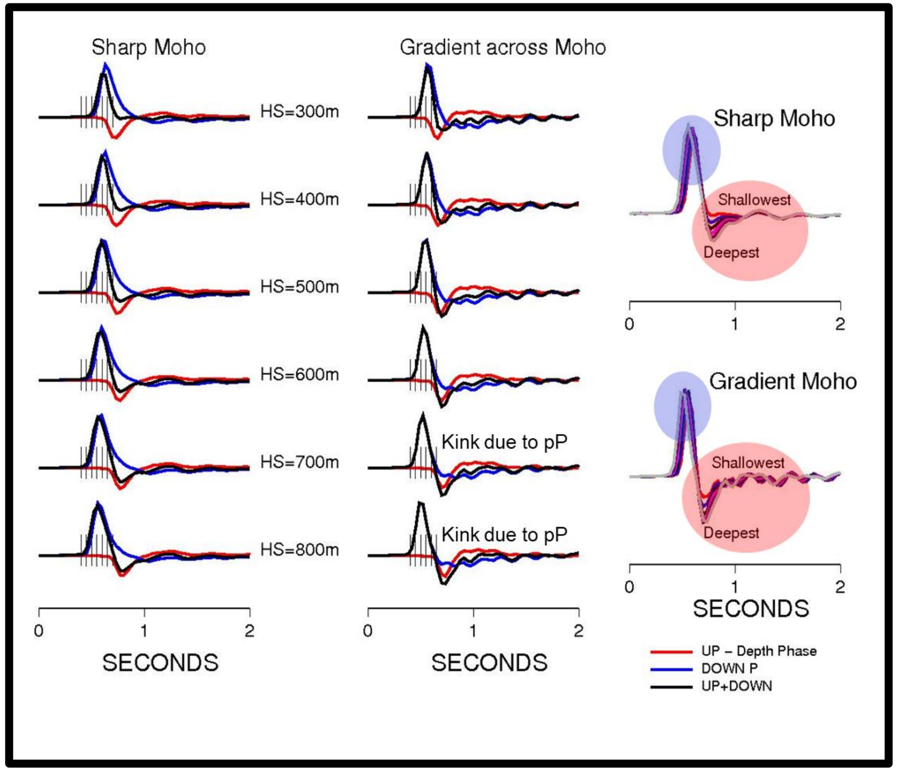
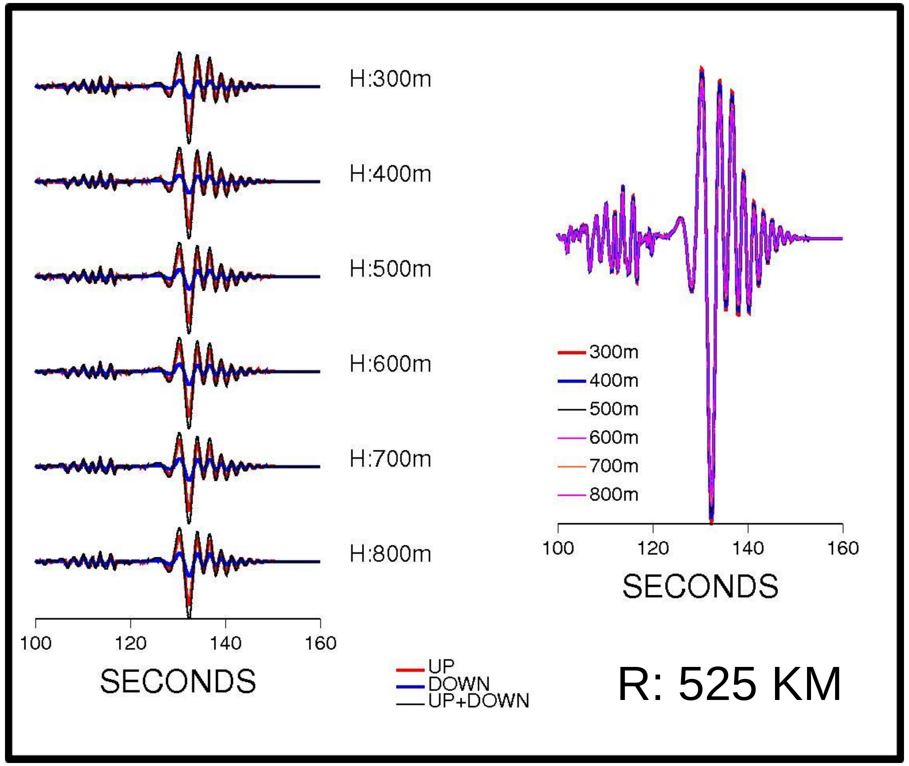
Similarity of DPRK Explosion Waveforms Recorded at the Japanese Network Stations



Similarity of these waveforms suggests that the amplitude difference must have been caused by both explosion size and depth of burial (DOB). *Special thanks to NIED National Research Institute for the Earth Science and Disaster Resilience, Japan for making digital data available to be used in this research study*.

Stability of P+pP and Surface Waves in Synthetic Seismograms of the Shallow Explosion Sources

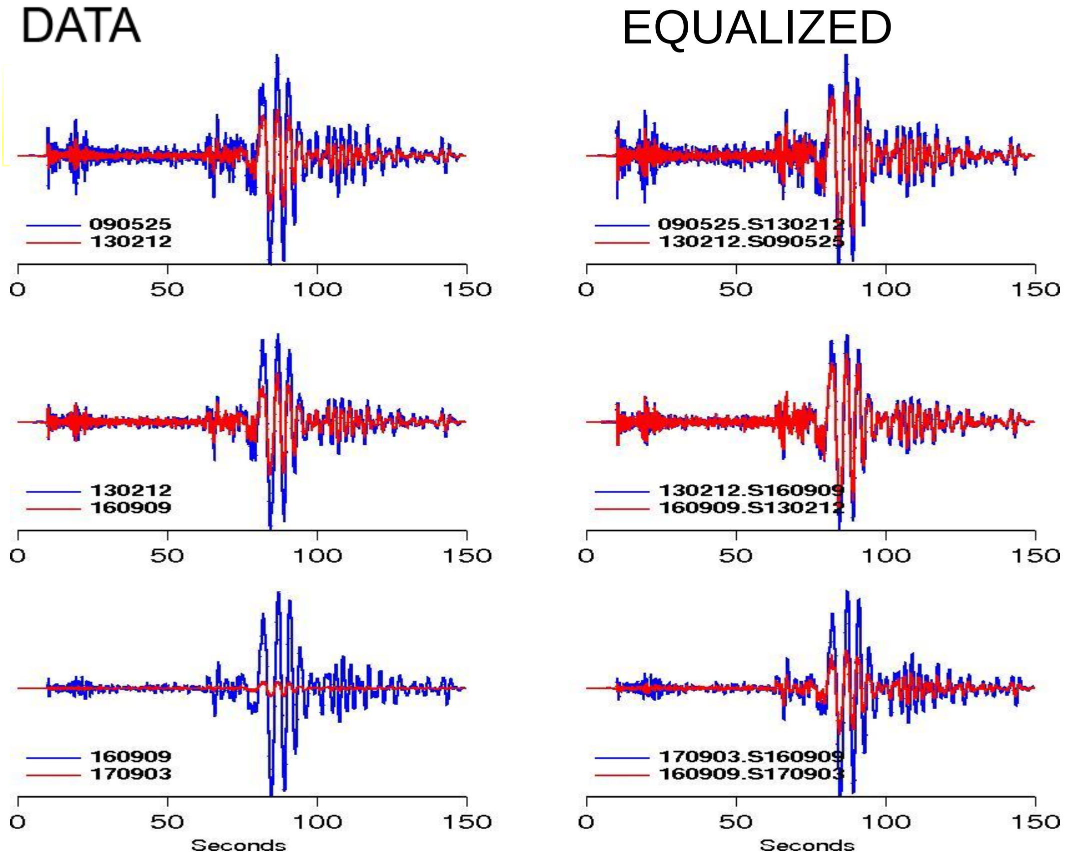




LEFT PANEL - sharp and gradient-like velocities across the Moho discontinuity.
P WAVES amplitude in the down-swing P waves (caused by the late pP wave arrival).

RIGHT PANEL - plotted in absolute amplitude – and they are marginally different;
SURFACE WAVES amplitude difference in recorded data may be due to the yield, not due to the depth variation

Application of WEM
On Multiple-Event Waveform Scheme



(a) TWO-EVENT APPROACH

EV1
EV2
Cycle through RDPs of both events for fixed or free depths and **minimize objective function $\boldsymbol{\Xi(t)}$.**

EV2
EV3
Fix EV2; cycle for RDP of EV3, and **minimize $\boldsymbol{\Xi(t)}$**

EV3
EV4
Fix EV3, cycle for RDP of EV4, and **minimze $\boldsymbol{\Xi(t)}$**

$$\boldsymbol{\Xi(t) = S_i^T(t) * O_j(t) - S_j^T(t) * O_i(t)}$$

(b) MULTIPLE-EVENT APPROACH

$$\Xi(t) = \left[S_j^T * O_i - S_i^T * O_j\right] + \left[S_k^T * O_j - S_j^T * O_k\right] + \left[S_l^T * O_m - S_m^T * O_l\right] + \cdots..$$

Multiple-event scheme yielded convergence to actual source parameters when applied to synthetics.

WEM – Evaluation of the Method Using Numerical Seismograms

EVENT	W(kt)	DOB(m)
EV1	5	500
EV2	15	600
EV3	30	400
EV4	230	700

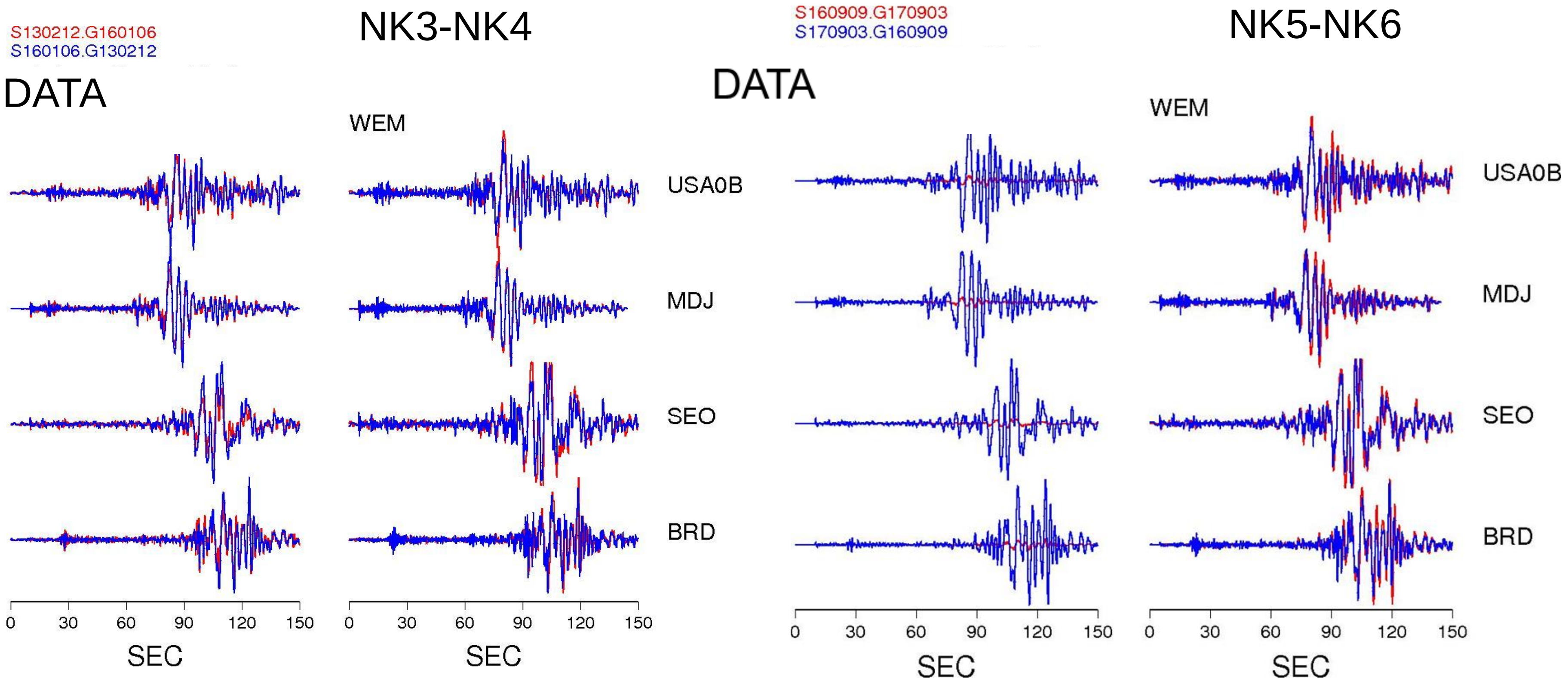
Seismograms for this numerical analysis were generated by convolving of the RDP (or RVP) of individual explosion with the corresponding explosion Green function (F-K) computed at 525 km from the source.

Yield Solutions with 95% variance reduction for various combinations of explosions

EVENT	Range (kT)	Increment In W (kt)	W(123) Kt	W(124) Kt	W(234) kt	W(431) kt	W(1234) kt
EV1	1 to 10	1	5-10	5-7		4-6	3-5
EV2	5 to 30	5	15-30	15-20	10-20		10-20
EV3	15 to 60	5	30-60	-	20-40	25-35	20-40
EV4	110 to 460	10	-	220-300	150-290	180-250	150-290

The best solution for the case W(1234) converged to actual values in the upper table (we did not allow DOBs to vary).

Equalized Waveforms Constructed Using RDP and DOB Obtained by minimizing $\Xi(t)$

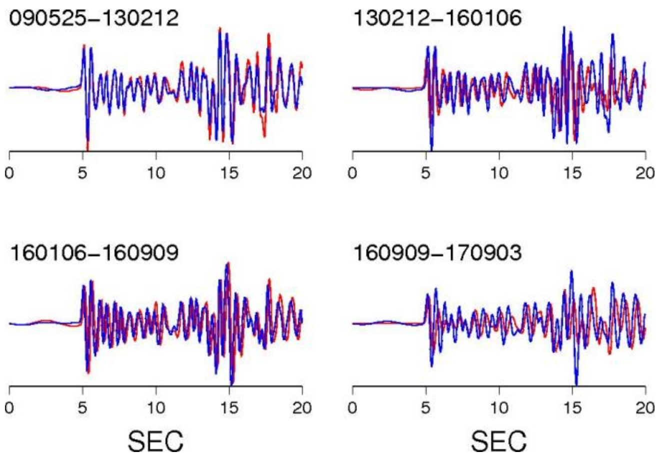


Initial equalization started with NK2 and NK3 waveforms. As discussed, we allowed the RDP to vary for both events (i.e., essentially varying the size). We permitted depth of burials to vary or be fixed. For the pair NK3-NK4, we fixed the RDP of the NK3, allowed the RDP of NK4 to vary, and minimized our objective function. Likewise for the KN5-NK6, the RDP of NK5 was fixed and the RDP of NK6 was allowed to vary.

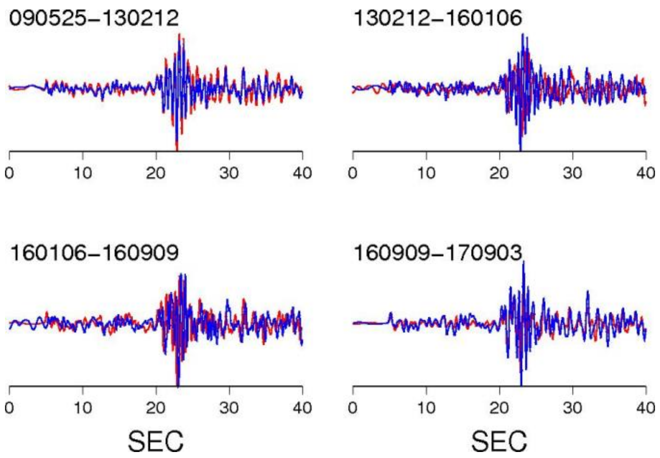
Note that only the two-event approach was applied to analyze the DPRK explosions.

Equalized P Waves Constructed Using RDP and DOBs Obtained by minimizing $\Xi(t)$

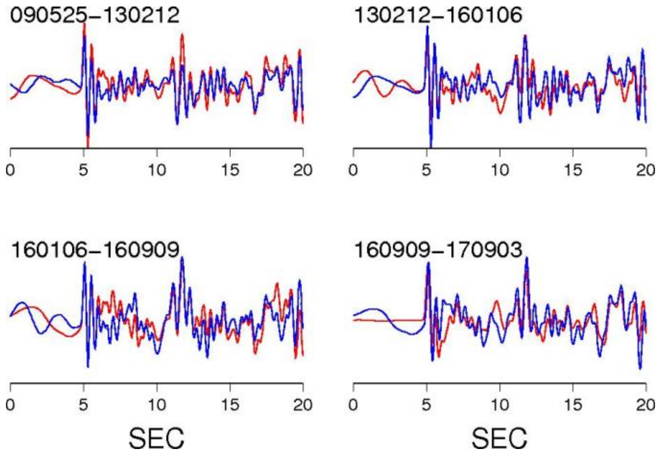
MDJ



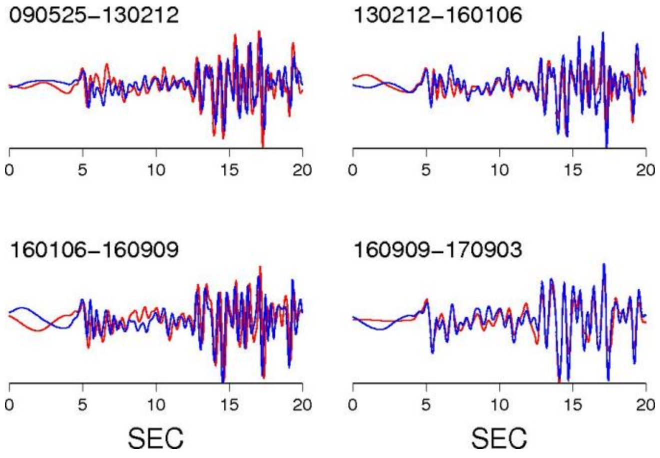
BRD



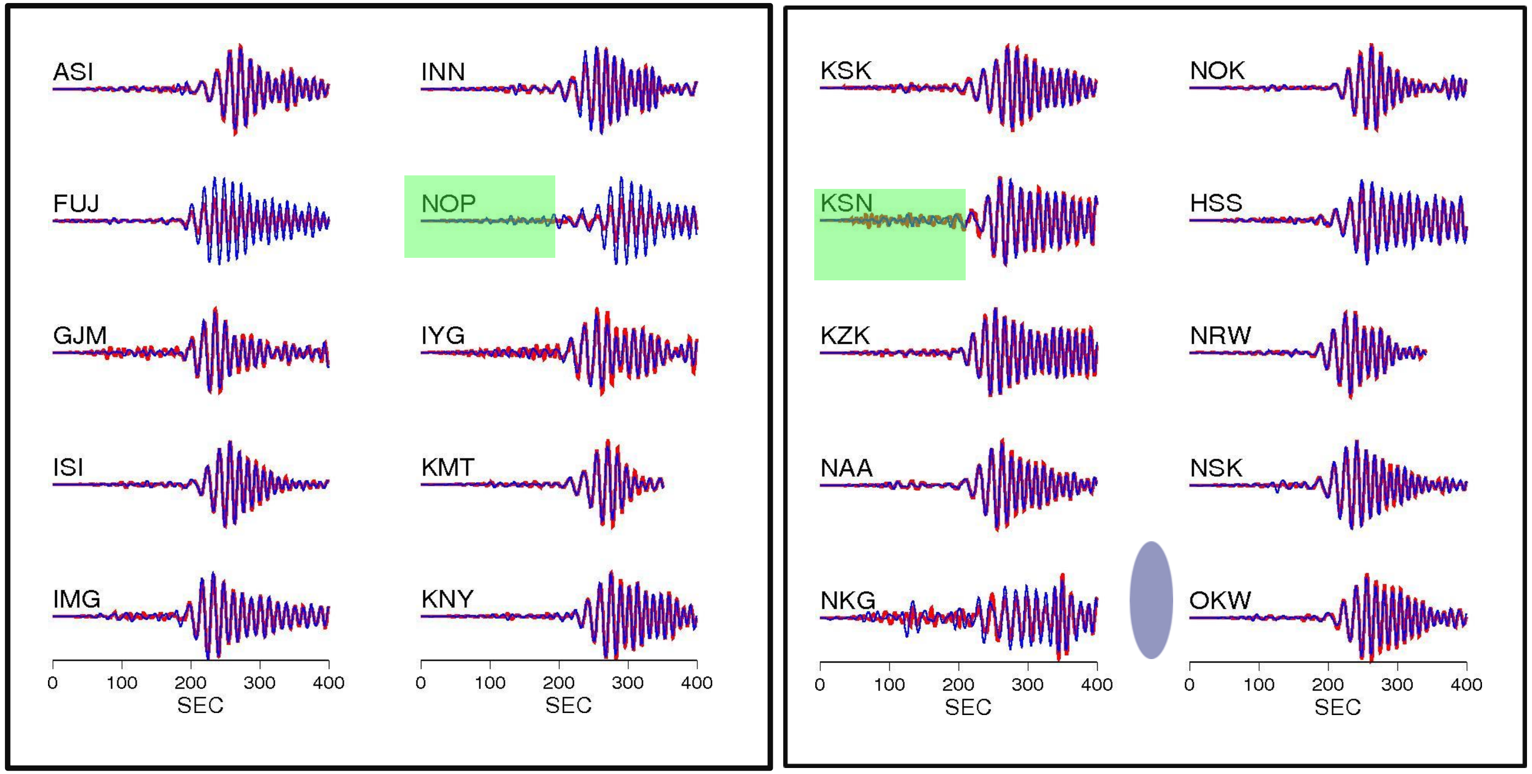
SEO

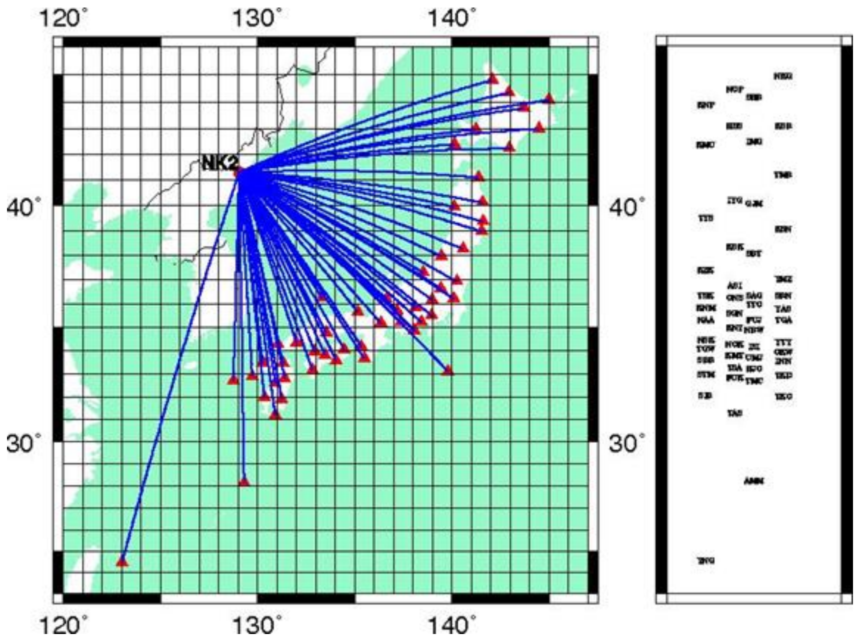


USA0B



Equalized Waveforms Predicted for the NK2 & NK3 Explosions at Japanese Stations





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ψ_∞ and source related parameters of the DPRK explosions (Chaves *et al*. 2018)

EV	Yield (kt)	DOB (m)	Stand Depth(m)	SDOB (m)	R_{el} (m)	f_c (hz)	Ψ_∞ WEM	Ψ_∞ WAVEFORM
NK2	2.6	600	153	444	214	4.1	8.5e+4	4.3e+4
NK3	6.8	420	190	262	303	2.9	1.0e+5	7.1e+5
NK4	11.9	750	211	421	264	3.3	1.8e+5	1.1e+5
NK5	18.8	750	253	360	313	2.8	2.3e+5	1.6e+5
NK6	230.0	750	602	150	747	1.2	2.7e+6	1.6e+6

*T*aken from Chavez, Lay and others (2018, GRL)

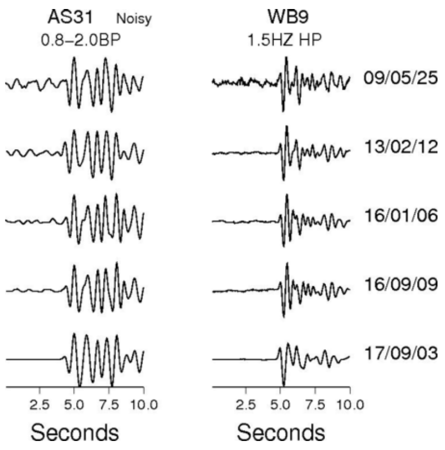
Computed Using TDSF for the determined ψ_∞ derived from the RDP source

ψ_∞ = RDP (m^3)
M_{ISO} = $4\pi\rho C^2\psi_\infty$
C = P wave velocity (m/sec)
P = density (kg/m^3)

M_{ISO} – derived from regional waveform inversion for full moment-tensor matrix and its partition to DC, CLVD and isotropic sources

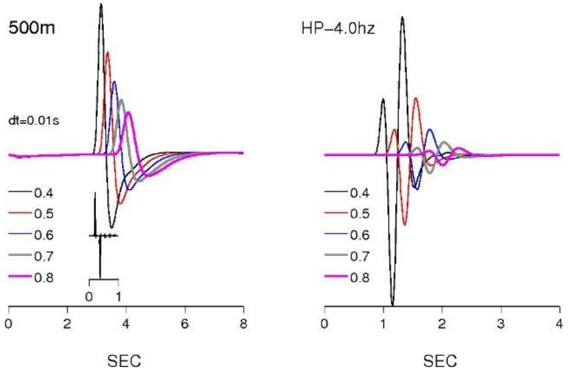
Teleseismic P Waves : Influence of t* and Explosion Size

Teleseismic P in Australia



(a)

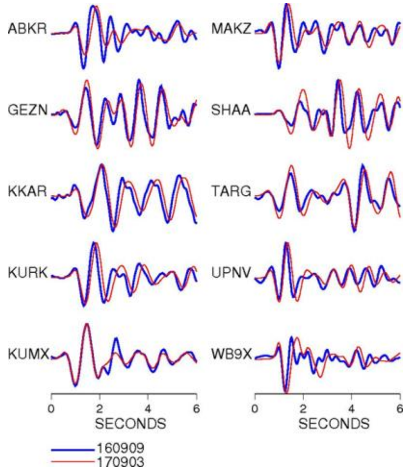
t* - Used band-limited attenuation operator of Carpenter (1966) developed based on Futterman (1962) for the causal attenuation.



Causality for t* Broadband Vs. 4Hz (HP)

(c)

09/09/2016 vs 09/03/2017



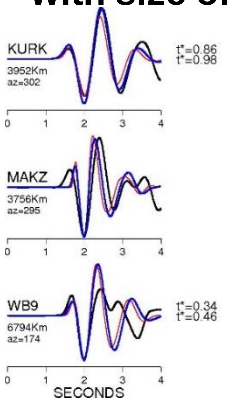
1-5Hz
t* same
ψ_∞ Varies
Self normalized

Note: Same Pulse Width

DATA

(b)

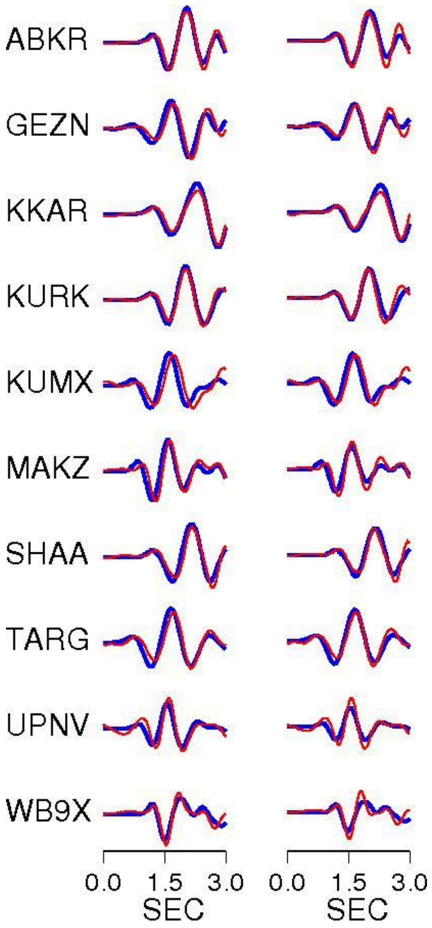
Effect of t* and its trade-off with size of nuclear explosions



Blue – Data
Red – Synthetics computed for two ψ_∞: RDP of this study and ψ_∞ of Chaves *et al*. (2018)

(d)

Teleseismic P Wave Equalization



Left: RDP using ψ_∞ of Chaves *et. al*. (2018)

Right: RDP using ψ_∞ estimated in this study.

Agreements are similar – note that the yield of **NK5** is based on their inter-correlation of teleseismic P waveforms using the RDP of **NK6**.

Our solutions are constrained by the size estimated for **NK2** and **NK3**.

Chaves et al. (2018). Yield estimate (230 Kt) for a Mueller-Murphy model of the 3 September 2017, North Korean nuclear test (mbNEIC=6.3) from teleseismic broadband P waves assuming extensive near-source damage, Geophy. Res. Lett, 45, 10,314-10,322,hhttp://doi.org/10,10029/2018GL079343.

Conclusions

- WEM does not need path calibration. When applied to shallow explosions occurring in one target region, t* and lateral paths remain same. The method is well suited for surface waves.

- When waveforms from only two explosions are used, WEM can produce the reliable solution provided source parameters of one explosion are known.

- By applying WEM to the synthetic waveforms from multiple explosions occurring at shallow depths (less than 800m), solutions determined by the minimization of the objective function converged to the correct solutions.

- WEM is also applicable to P waves.   Interferences of pP on the initial P wave may not impede the analysis, as was observed in the agreement in the waveforms constructed for the equalized P waves.