T 2.3 – P15 Time-Domain Source Function (TDSF) for Nuclear and Chemical Explosions – Analysis around Nevada National Security Site (NNSS)

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ABSTRACT: Displacement spectra from accelerograms recorded within a few kilometers (< 3.5 km) of nuclear and chemical explosion shot points indicate that the amplitude spectral level is not flat below the source corner frequency (f_c), but increases gradually towards zero frequency. During an explosion, the volume in the immediate vicinity of the shot point is inelastic. In this paper, we develop a time-domain expression for the deformation at the elastic boundary limit of this volume, which in the frequency domain supports this observation. We refer to this expression as the time-domain source function (TDSF) of an explosion. The proposed TDSF has two terms, the first term representing a ”static" contribution and the second term a "dynamic" contribution to the total deformation field. The static contribution dominates over the dynamic contribution at frequencies below f_c and causes the gradual increase in the spectral level. For the low-yield under/or over-buried explosions (yield < 5 Kt), f_c is relatively high and this increase in spectral amplitude is pronouncedly observed. The correct interpretation of the observed spectral amplitudes below f_c can, therefore, play a crucial role in estimating source parameters of explosions. For $f > f_c$, the dynamic contributions dominate and decay approximately as f^{-2} . For seismic waves propagating from the boundary R_{el} (a transition limit of the non-linear to the elastic zone) to large distances, the static and the dynamic wavefields are affected identically by attenuation and spreading. Hence, the attenuation corrected large distance explosion spectra should exhibit these spectral characteristics. An analysis of the regional P-wave spectra from a few low-yield explosions provides evidence for this finding and also for the yield scaling by a factor of 2 between the nuclear and chemical explosions, especially for similar emplacement conditions. We also illustrate that when convolved with a time function [$\exp(-C/R_{el})$ H(t)], where C is the material velocity at the shot point, the TDSF yields the reduced displacement potential (RDP) at R_{el} of the source. We use this proposed RDP to investigate the influence of yield and depth of burial (DOB) on the spectral overshoot and f_c of explosion sources.

MOTIVATION: In recent years, a concern in the seismological community is that the source corner frequencies (fc) computed for an explosion using the Mueller-Murphy (Mueller & Murphy, 1971; hereafter MM71) and the Denny & Johnson (1991; hereafter DJ91) source functions differ significantly. This discrepancy is caused by possible inaccurate measurements of the long-period amplitude spectra of nuclear and chemical explosions (Ford &Walter, 2013; RMR, 2014, Rougier & Patton, 2015), which may indeed contribute to uncertainty in estimates of the yield and depth of burial (DOB). To address this issue, we examined the near-field velocity spectra plotted for the Non Proliferation Experiment (NPE) and Hunter-Trophy (HT) explosions (Stumps et a., 1994) which showed a flat trend below the source corner frequencies. We collected both regional and close-in stations deployed at less than 3.5 km from both these explosions and analyzed. In contrast to what is predicted by the current empirical models, our analysis shows that the observed displacement spectra are not flat below the source corner frequency fc (Figure 1) . This is pronouncedly observed in the low-yield explosion spectra. The currently used method for estimating yields and depths of burial of nuclear and chemical explosions assumes that the observed displacement spectra remains flat below fc and are approximated by spectra predicted using a far-field spectral formula (Murphy, 1977; Walter & Priestly, 1991).

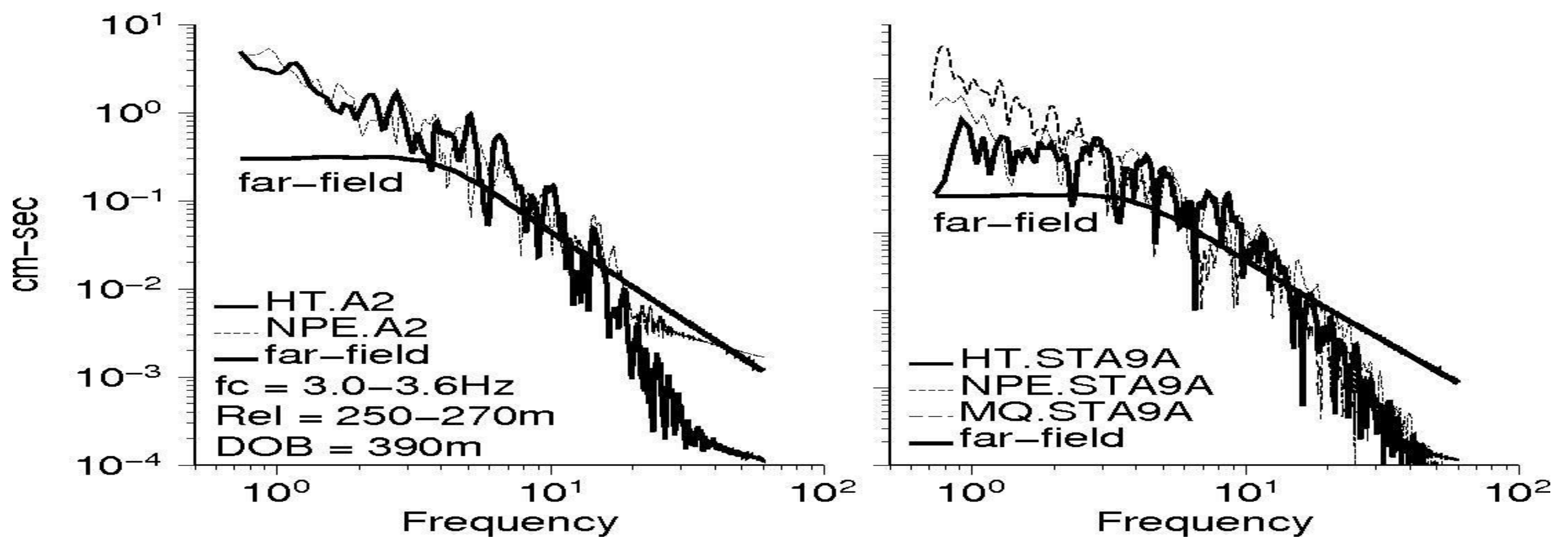


Figure 1

SOURCE FUNCTION MODEL: To understand why the spectra of an explosion below fc rise in the level, I worked through the theory using the equation of motion for an underground explosion in a spherical cavity and using a well known Fourier-transformation pair, developed following expression for the deformation field at R_{el} of the cavity and non-linear zone (Saikia, 2017). In this presentation and the paper, I refer to this deformation field as the time-domain source function (TDSF).

$$S(R_{el},t)=\Bigg[\underbrace{\frac{F(t)}{R_{el}^2}}_{\text{Near Field}}+\underbrace{\frac{\partial_t F(t)}{R_{el}C}}_{\text{Far Field}}\Bigg]*[e^{-\gamma t}P_o(t)+P_2(t)]H(t) \qquad (12b)$$

Pressure Pulse on the Cavity surface

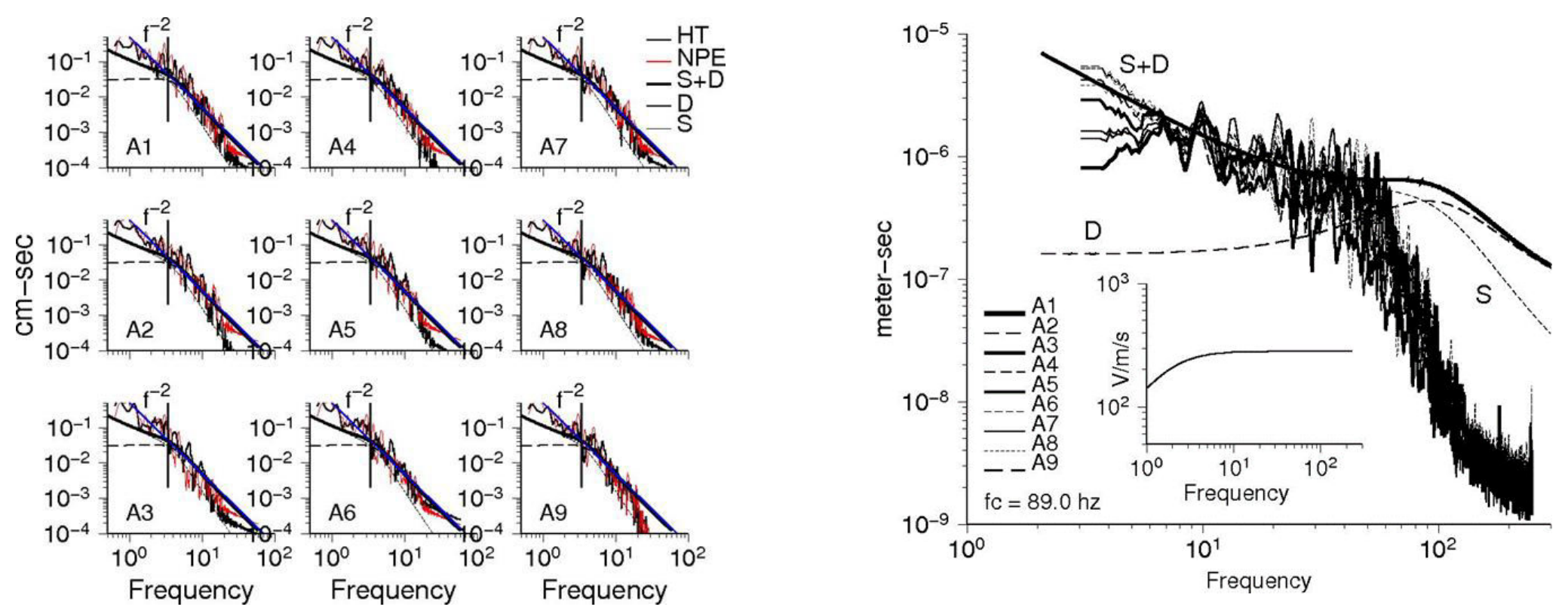
$$F(t)=\frac{R_{el}C^2}{4\mu\beta\, p}\,H(t)\,e^{-\alpha t}\,\sin(pt)$$

$$\alpha=\frac{\omega_o}{2\beta} \qquad p=\sqrt{\frac{\omega_o^2}{2\beta}-\frac{\omega_o^2}{4\beta^2}}$$

For details of the parameters in above expression, I refer readers to expression (12b) in Saikia (2017). Note that the above expression does not have any assumption except for the source, which has a spherical symmetry and waves propagate from the source radially outward. Since the displacement is evaluated at Rel (often a small number), the contribution from the first term of first [] on the left hand side is significant and large compared to the contributions from the second term below f_c. Above f_c, it is the contribution of the second term which is dominantly larger.

VALIDATION OF SOURCE FUNCTION: We used the above formula in frequency domain and processed the spectral displacements using the close-in data from both NPE and Hunter Trophy explosions, including the high-frequency waveforms from the recent chemical explosions conducted as a part of the Source Physics Experiment (SPE) in Nevada National Security Site (NNSS).

In Figure 2, displacement spectra are plotted for accelerograms recorded at about 3.5 Km from the NPE and HT explosions. Also plotted are the predictions made using the formula below. The dotted line contains only the far-field (dynamic) and solid line contains the contributions from both near-field (static) and far-field (dynamic) terms. I also plot the f^{-2} line to illustrate these spectra above the source corner follow a f^{-2} model.



$$\underbrace{S(R_{el},\omega)}_{\text{Displ at Rel}}=\underbrace{\left[\frac{1}{R_{el}^2}+\frac{j\omega}{R_{el}C}\right]}_{\text{Conversion Factor}}\underbrace{\left[\frac{P_o}{\gamma+j\omega}+\frac{P_2}{j\omega}\right]\left[\frac{R_{el}}{4\mu}\,\frac{C^2}{[\omega_o^2+j\omega_o\omega-\beta\omega^2]}\right]}_{\text{Reduced Displacement Potential}}$$

Figure 2. Display of displacement spectra computed using the data at the same stations. This is small event and highly over buried and its expected corner is at about 90Hz. However, the spectra start to decay at about 50Hz and the probable cause for this is the site effect (say KAPPA). The main point here is that the spectra below f_c increase gradually as also predicted by the theory.

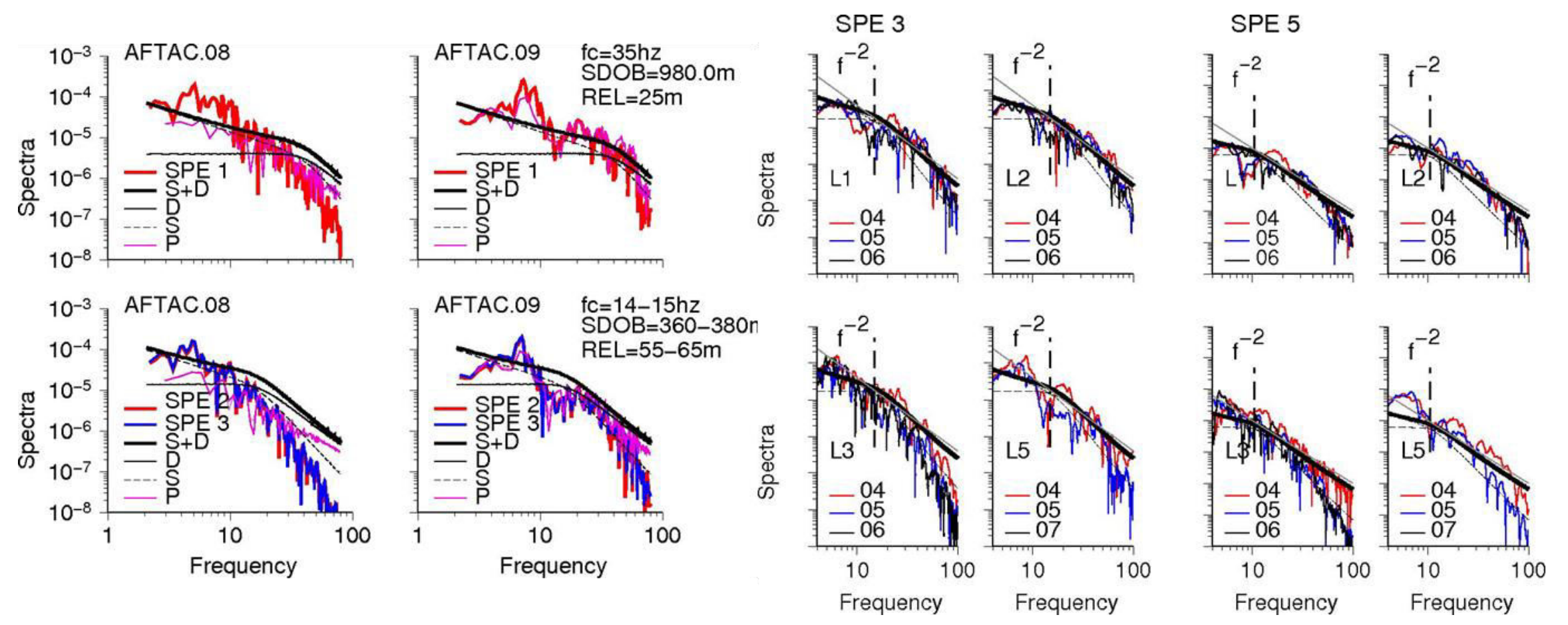
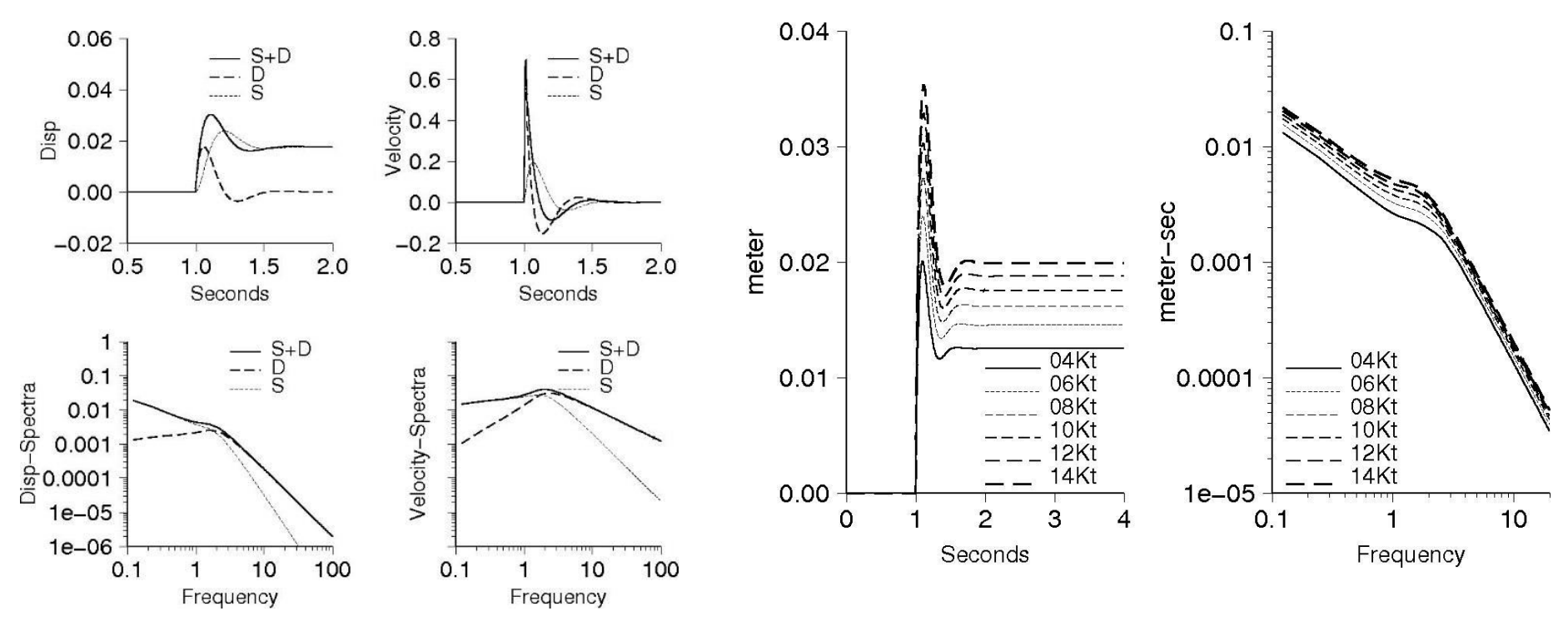


Figure 3 shows additional example of displacement spectra processed using waveforms recorded by geophones deployed during the PHASE I of the Source Physics Experiment. The observation that close-in displacement spectra from explosion sources increase in spectral level below the source corner frequency is borne out by this new dataset.

STATIC AND DYNAMIC TIME HISTORIES & SPECTRA AS PRECIDTED BY TDSF



: Figure 4 shows displacement and velocity time histories for the static (S), dynamic (D) and static+dynamic (S+D) terms contributions as predicted by the TDSF formula (2b) On the right panel, I show TDSF and its spectra as a function of yield (W) for an explosion buried at its scale depth..

REDUCED DISPLACEMENT POTENTIAL (RDP): Reduced displacement potential is an important function that is often related to the yield and depth of burial (DOB) of an explosion. In this presentation, I discuss the analytical method presented in Saikia (2017) that can be used to predict the RDP given the yield and DOB of an explosion and to invert a recorded waveform the very close to an explosion. Referring to Saikia (2017), we can rewrite expression (10) as

$$S(R_{el},\omega)=\left[\frac{1}{R_{el}^2}+\frac{j\omega}{R_{el}C}\right]\varphi(R_{el},\omega)=\frac{1}{R_{el}C}[\eta+j\omega]\varphi(R_{el},\omega) \qquad \eta=\frac{C}{R_{el}}$$

Above expression can now be used to invert for the time-domain RDP function to a form given by

$$\varphi(R_{el},t)=R_{el}C[S(R_{el},t)*e^{-\eta t}H(t)]$$

Expression (12b) can also be modified to express the RDP function in the following form

$$\varphi(R_{el},t)=F(t)*[e^{-\gamma t}P_o(t)+P_2(t)]H(t)$$

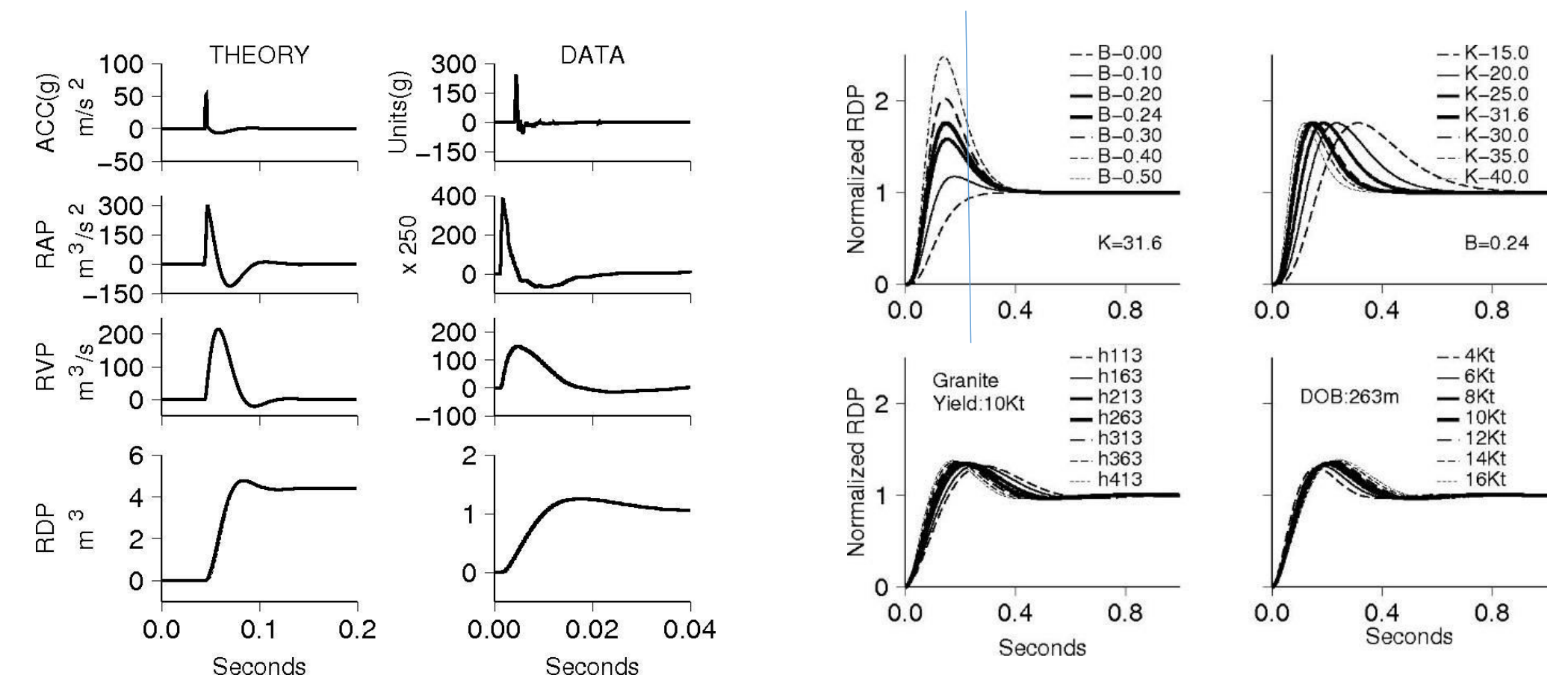


Figure 5 (a) (b)

Figure 5a is display which validates the new formulation on RDP’s. Top trace in the left column is an acceleration time series predicted for a known yield and DOB of an explosion. It is inverted using the first RDP formula to create RAP, which is integrated to construct RVP and RDP, respectively. Also plotted on the inverted RDP is a dotted line which is the predicted RDP for the same yield and DOB using the other RDP formula. The two curves overlap on top of each other. The right column is an illustration using close-in acceleration data recorded very close to an SPE explosion. In Figure 5b and in the left column are shown the RDPs as a function yield and DOB using the proposed TDSF. Those predicted using the HASKELL (1967) for various B and K values are shown in the right.

YIELD SCALING: CHEMICAL VERSUS NUCLEAR EXPLOSIONS: It is often assumed that a chemical to the nuclear explosion has a yield scaling by a factor of 2. Goldstein & Jarpe (1994), Glen & Goldstein (1994), and Walter et al. (1994) used a limited data set from the Lawrence Livermore National Laboratory (LLNL) network for the same explosions to illustrate this equivalence. In this section, we analyzed additional waveforms to further justify this yield equivalence for these two explosions having the same material properties. We examined vertical and radial component regional P-wave seismograms and displacement spectra from the Hunter Trophy (HT, red) nuclear and the NPE (blue) chemical explosions recorded at CMB station from the Berkeley Seismic Network (BKS) California and at nine other regional stations at distances between 280 to 500 Km (Fig 6). Waveforms in Fig 6a are remarkably similar, which suggests that the Green's functions and source characteristics of the two explosions are similar. The array stations had different instruments and their waveforms were equalized to a common instrument response. Regional P-wave spectra computed for the HT and NPE explosions using these equalized waveforms are shown in Fig 6b. Based on the spectral agreement between the two explosions, it can be concluded that the HT nuclear and NPE chemical explosions have the same yield at the source, which validates that the yield scaling is indeed a factor of 2.

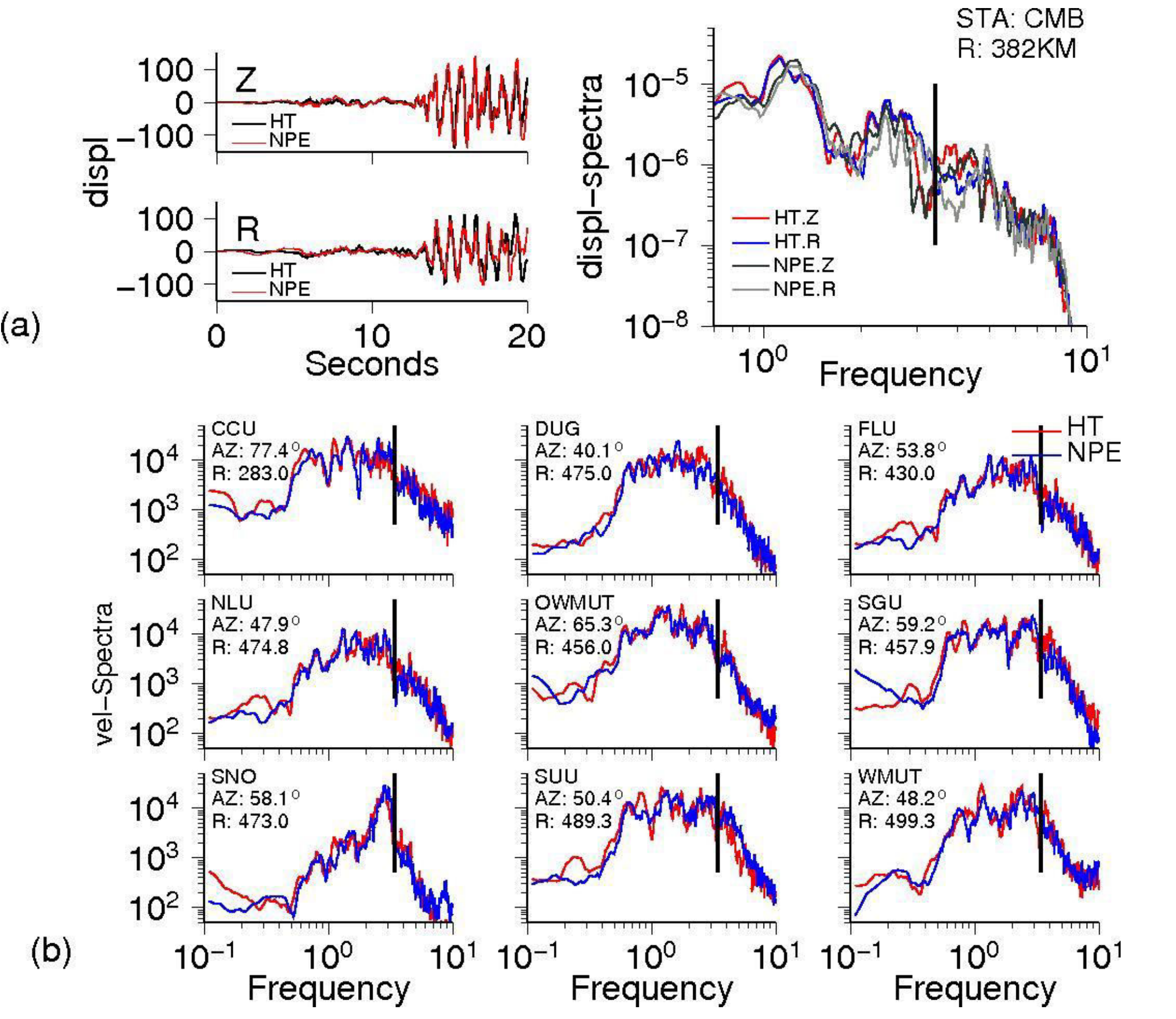


Figure 6. (a) Recorded vertical and radial component P-wave displacement seismograms at station CMB from the HT (red) nuclear and NPE (blue) chemical explosions (left). The vertical line in the spectral display corresponds to the fc of the two explosions. The agreement observed in these displacement spectra confirms the yield equivalence between the nuclear and chemical explosions established in Goldstein & Jarpe, 1994; Glen & Goldstein, 1994; and Walter et al., 1994). (b) Examples of additional regional P-wave velocity spectra using the waveforms recorded by the Utah Seismic Digital Network (USDN) stations. Note that below fc (shown by the vertical line), spectra is almost flat which is consistent with the spectral characteristics of the proposed TDSF.

DISCUSSION: This investigation was motivated by the current focus of the seismological community on topics related to developing the capabilities for estimating reliable yields of shallow low-yield nuclear and chemical explosions Depth of burial and yield are the two key source parameters, which are often derived from the observed corner frequency (f_c) and the long-period level of the amplitude spectra.

In a majority of high-yield explosions, the DC and CLVD mechanisms make the explosion source process highly complex. The source function of a DC mechanism is often consistent with the f^{-2} model with a flat spectra below f_c . Also, we do not yet have a definite knowledge how the source function should look like for a CLVD mechanism whose sources are mostly at the explosion depth or shallow. The seismic moment partition to the DC, CLVD and explosion sources when each source type is involved can be crucial. In the presence of a strong DC or the CLVD source, the individual source type may dominate the explosion source such that it can influence the static-term characteristic of the explosion component, rendering its contribution below f_c hardly observable. In this study, we suggest this as a possible reason why the contribution from the static term in the spectra of the high-yield explosions was not noted and why these spectra could be modeled using only the far-field term

We also processed RDPs using SPE data from two shots recorded at the shot depth (Fig 7). The RDPs for the two shots have different inter-station estimates of the long-period level. The theoretical RDPs shown by the solid lines fit the processed RDPs and were processed using our proposed RDP formula.

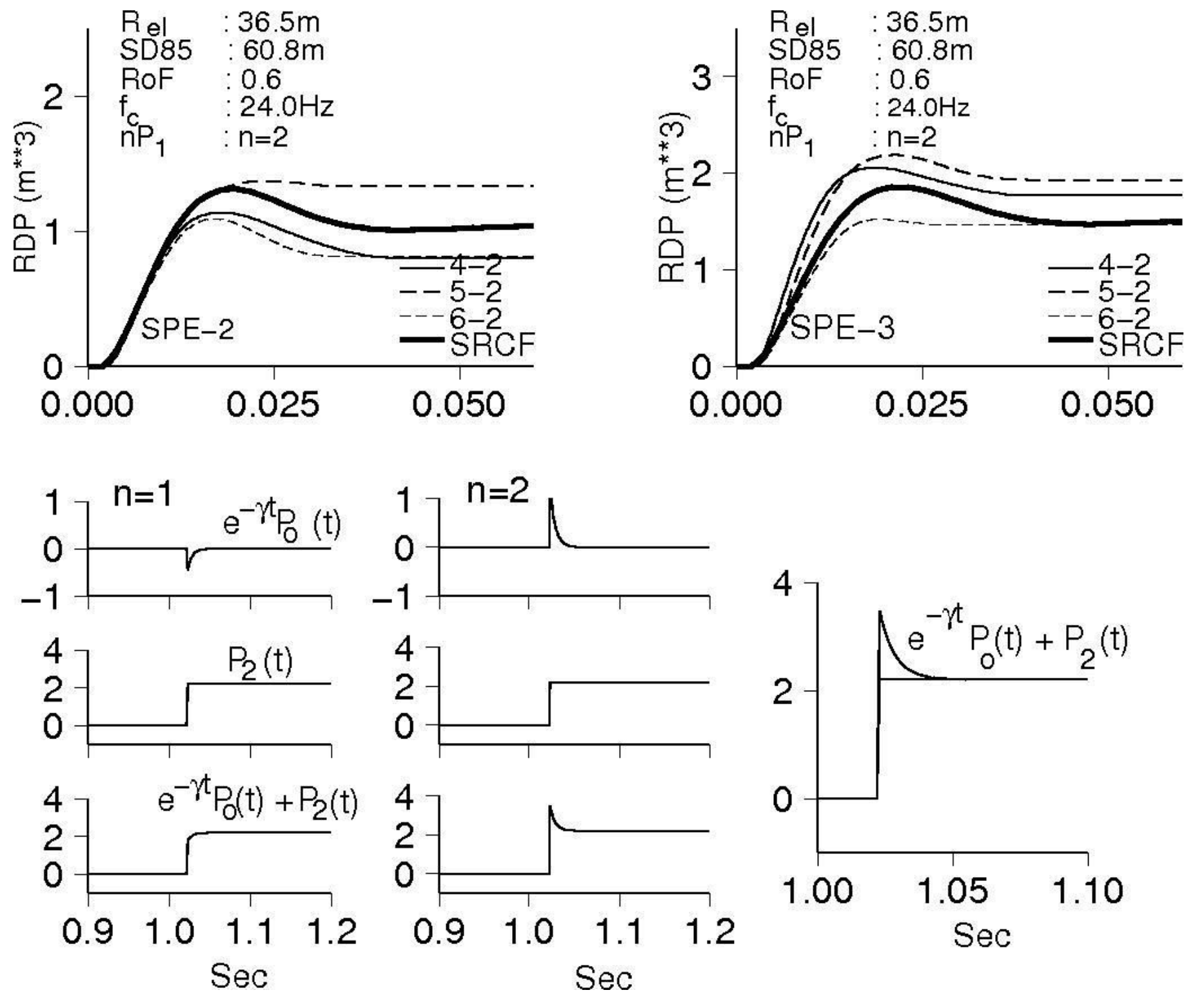


Figure 7 : RDP for the SPE-2 and SPE-3 chemical explosions using their shot depth radial accelerograms recorded by the DTRA accelerometers (deployed at boreholes #4, 5, and 6). These RDP were computed using the algorithm discussed in Fig 5a. SRCFs (solid traces) were computed using the source parameters published in Snelson et al. (2013) and formula (20b). Also shown in the bottom are the shock-wave pulse [$e^{-\gamma t}P_o$] and the pressure pulse [$e^{-\gamma t}P_o + P_2$] for two cases n=1 and n=2. The case n=1 is often used, which in this case has a negative polarity in the upper trace for the yield and DOB used. A negative polarity is unphysical for an explosion. It clearly reduces the strength of the overshoot. For the case n=2, the polarity is positive and it increases the strength of the overshoot.

CONCLUSIONS:

- The static term in the TDSF function contributes significantly to the spectral shape of nuclear and chemical explosions, which is pronouncedly observed below fc .
- Our empirical waveform analysis and others suggest a yield scaling factor of 2 between the chemical and nuclear explosions for similar emplacement conditions.
- Planned field studies may provide understanding on the transportability of the scaling factor amongst various emplacement conditions.
- Two expressions, given by (19) and (20b) in Saikia (2017), can be used to construct the RDP functions for explosions.

REFERENCES:

Saikia (2017) Time-domain source function (TDSF) for nuclear and chemical explosions – analysis around Nevada National Securrity Site (NNSS), DOI: 10.1093/ji/ggx072, 209, 1048-1063.

FOR OTHER RELEVANT REFERENCES SEE SAIKIA (2017)