



T 2.3 – P 9 Estimation of Source Parameters and Their Uncertainties of Explosion Sources Using Waveform Equalization Technique – Application to the SPE Chemical Explosions at NNSS

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ABSTRACT: We formulated a waveform equalization (WFE) technique to determine source parameters of two nearby low-yield explosions by equalizing seismograms. Let $O_1(t)$ and $O_2(t)$ be the seismograms of the two explosions and let $S_1(t)$ and $S_2(t)$ be the respective time-domain source functions (TDSF). Expressing $O_1(t)$ and $O_2(t)$ as $S_1(t, W_1, h_1) * G_1(t, R_1, h_1)$ and $S_2(t, W_2, h_2) * G_2(t, R_2, h_2)$ respectively (where G_i represent the Green's function of the i^{th} source to a common j^{th} station; W and h 's represent their yields and depths), we convolve $O_1(t)$ with $S_2(t)$ and $O_2(t)$ with $S_1(t)$. The two seismograms resulting from the convolution will be nearly identical provided the Green's functions are similar. This requires that the depth difference between the two events are also small. We validate the technique using waveforms recorded from the chemical explosions conducted during the Source Physics Experiment (SPE) in the Nevada National Security Site (NNSS). The SPE explosions satisfy the necessary constraints. Note that the proposed algorithm does not require an explicit knowledge of the Green's functions (GF). In fact they are included in the observed data. Hence GFs being empirical, they include the lateral variation in structure and geology, and the attenuation along the wave-propagation paths related effects implicitly. The method is useful to determine W and DOB of an explosion provided the W and DOB are known for the other explosion. Currently, we are extending the WFE formulation to include cases when source parameters of both events are unknown. We are also developing a time-domain approach to extract empirical Green's functions (EGF) from waveforms of one explosion. We illustrate that these EGFs can help to extract the TDSFs of the other explosions.

MOTIVATION: Estimating yield and depth of burial (DOB) of a low-yield chemical or nuclear explosion is a challenging task. Often, the P waves are poorly recorded at regional distances. For events with discernible P signal, the often employed method is to average the P spectra from available calibrated stations and model by the far-field spectra predicted by the Mueller and Murphy (1971, MM71) source. Seismologists also use the spectral ratio to estimate the source parameters. In these methods, unless the events have the near similar DOBs, the path effects are not entirely eliminated. This lead to uncertainties in source parameters which may be an issue. The objective of this study is to explore a time-domain technique where the path can be empirically represented, thus reducing its influence in the source parameter measurements.

THEORY: The proposed source equalization method is based on the assumption that seismograms from two or more explosions occurring at the same or different test sites can be equalized for their amplitude and waveform characteristics by convolving the source function of one event with the other including their Green's functions. Mathematically, we express an observed waveform $O_i(t)$ at a regional distance R_i as a convolution of the time-domain source time function (TDSF, $S_i(t)$) with the Green's function $G_i(t)$ of the path, i.e.

$$O_i(t, R_i, W_i, h_i) = S_i(t, W_i, h_i) * G_i(t, R_i, h_i) \quad (1)$$

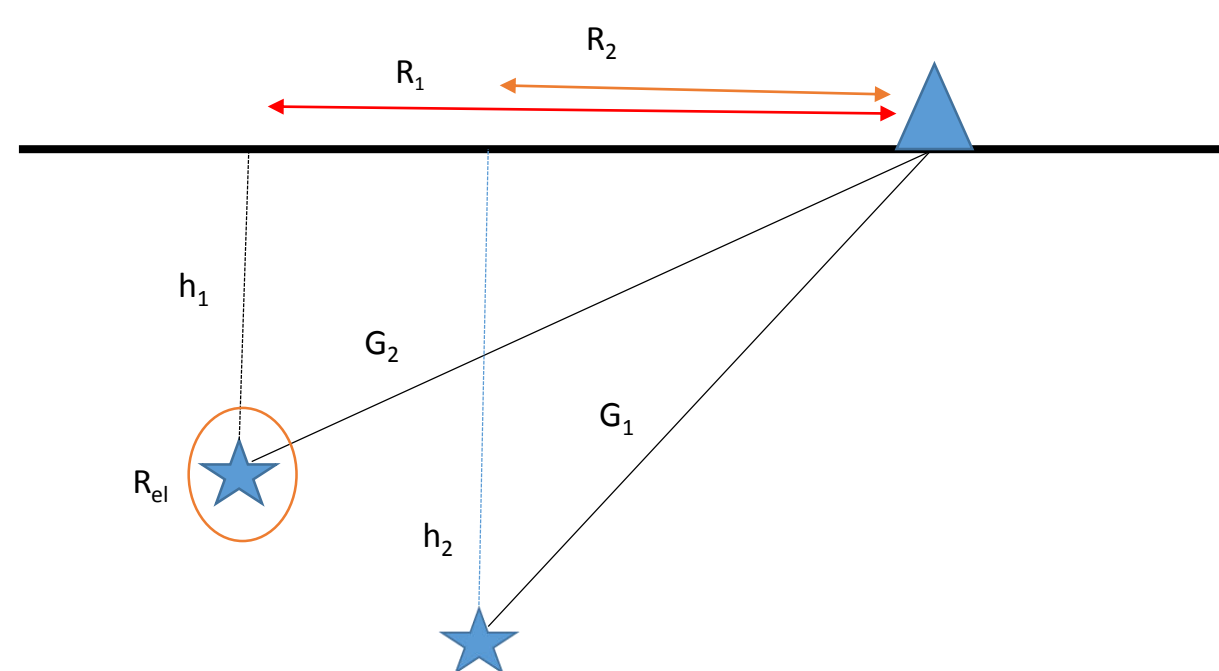
where S_i represents the source time function of the i^{th} explosion for a depth of burial h_i with its corresponding Green's function G_i . Thus for two explosions, we can write

$$\begin{aligned} O_1(t, R_1) &= S_1(t, W_1, R_{cl}^1, h_1) * G_1(t, R_1 - R_{cl}^1, h_1) \\ O_2(t, R_2) &= S_2(t, W_2, R_{cl}^2, h_2) * G_2(t, R_2 - R_{cl}^2, h_2) \end{aligned} \quad (2)$$

Note that we introduce a new variable R_{cl} which is the elastic radius associated with each explosion. Its value depends on the yield and over burden pressure of the explosion. Convoluting $O_1(t)$ by $S_2(t)$ and $O_2(t)$ by $S_1(t)$, and subtracting one from the other, the difference of the two convolution time series can be expressed as

$$[S_2 * O_1 - S_1 * O_2] = [S_2 * S_1 * G_1 - S_1 * S_2 * G_2] \quad (3)$$

Under the constraints that $R_1 \approx R_2$, $h_1 \approx h_2$, and $G_1 \approx G_2$ (see the schematic figure below), it is clear that the above difference should tend to zero, provided S_1 and S_2 are known.



The above constraints may be satisfied in the case of nuclear explosions which are often limited to a test area and the station is at a large distance. However, there are waveform influencing factors that can impede the WFE. For example, wave-propagation characteristics through a water-saturated medium can be quite different from a dry (or a relatively dry) or wet medium, and depending upon whether an event occurs above and below the water table. Also, an explosion may induce damage in the source region, making waveforms from later explosions complex. There can also be effects in the site and shallow source emplacement conditions.

SOURCE FUNCTIONS: Note that the proposed WFE method requires a source function which provides both the shape and amplitude of the displacement field at the elastic boundary of the HE (high explosive) source as a function of W and DOB . In this study, we used a time-domain source function (TDSF, taken from Saikia, 2017). This TDSF includes both the static (near-field) and dynamic (far-field) contributions at the elastic limit of a spherical cavity created by an explosion. For details of the variables in the formula, we refer to a poster presented in this SnT meeting in Vienna, Austria (Saikia, 2017).

$$S(R_{el}, t) = \left[\begin{matrix} F(t) \\ R_{cl}^2 \end{matrix} \right] + \left[\begin{matrix} \partial_t F(t) \\ R_{cl} C \end{matrix} \right] * [e^{-\gamma t} P_1(t) + P_2(t)] H(t) \quad (12b)$$

Near Field Far Field Pressure Pulse on the Cavity surface

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

$$\alpha = \frac{\alpha_0}{2\beta} \quad p = \sqrt{\frac{\alpha_0^2}{2\beta} \frac{\alpha_0^2}{4\beta^2}}$$

EMPIRICAL SOURCE FUNCTIONS: The proposed WFE technique can also utilize the TDSF replaced by close-in waveform data and will be referred to as the Empirical Source Functions (ESF). ESFs are useful to investigate issues that are involved with the instruments when multiple events waveforms are available. Often, the analysis conducted using data from temporary networks indicates that waveforms are affected by the unwanted malfunctioning of instrument during the operation and structural changes in the site conditions.

WAVEFORM EQUALIZATION – APPLICATION TO THE SPE DATA

SPE is a series of chemical experiment conducted under the auspices of the U.S. Department of Energy to develop a new, more physics based paradigm for nuclear testing monitoring (Snelson et al., 2013, EOS vol 94, no 27). This experiment was instrumented by a large number of geophone stations along five different profiles shown in insets of Figure 2.

SPE SNAPSHOT

Source Physics Experiment is a series of shots in Climax Stock Granite in Area 15 at Nevada National Security Site (NNSS) proposed to study the effects of firing explosives of varying charge strength placed in a variety of geological settings.

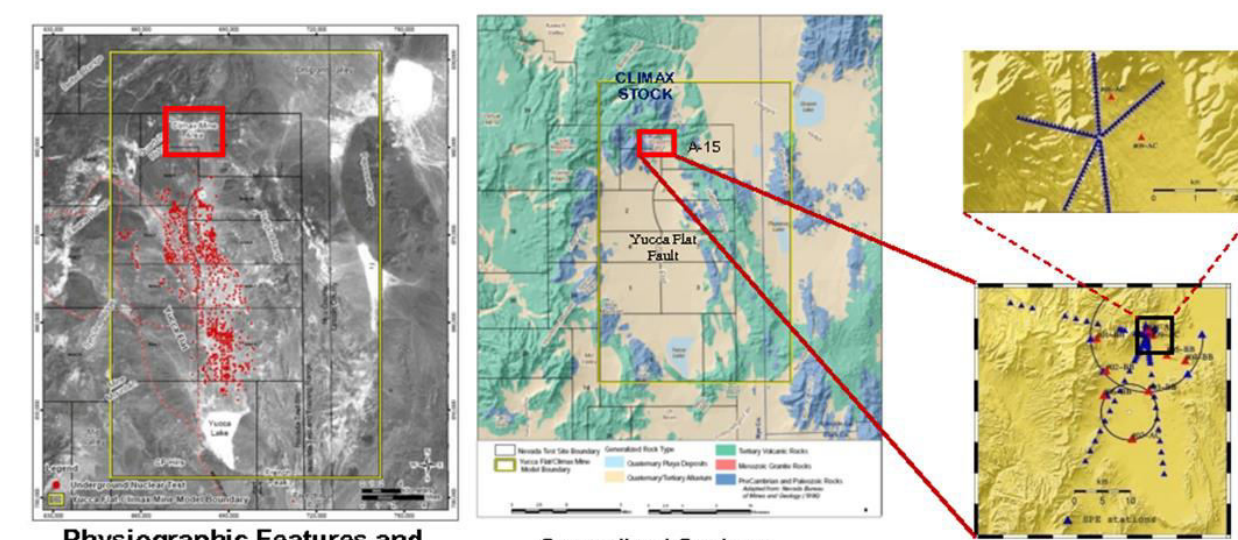


Figure 2. Map showing geology, shot and profiles of station locations.

Table 1. Source Parameters of SPE explosions

Shot Name	DOB (m)	Date	DOB (m)	Yield (kg)	Description and Scientific Basis
SPE 1	54.9	5/31/11	980.0	87.9	GF in a simple geology; simulation capability for non-isotropic effect
SPE 2	45.7	10/25/11	363.0	997.0	Record to large distances (DOB effects relative to SPE-V)
SPE 3	45.8	07/24/12	376.0	905.0	Damage zone effect relative to SPE-V
SPE 4 PRIME	87.2	05/12/15	1549.0	89.14	Minimize spallation, investigate DOB EFFECTS with 0.1-approx GF for SPE-V
SPE 5	76	04/26/06	5000.0		Signal up to 300km
SPE 6	35 (7)		182 (7)	3500.0	

In addition to the geophones, added were more accelerometers at many sites. These six shots were conducted at the same borehole at different depths. Charges of the shots varied and were determined by the science requirements planned for each shot (see Table 1, Snelson et al., 2013; EOS article

SPE DATA ANALYSIS: Using the source function expression (expression 12b, Saikia, 2017) and source parameters provided in Table 1, we predicted displacement wavefields at the elastic limit (R_{el}) for each shot. These predicted TDSFs are convoluted with waveforms recorded at all stations. In the following, we present results of this process for one station (LX-16) located at 1.6 Km from the shot point along the four different azimuths (L1, L2, L4, L5)

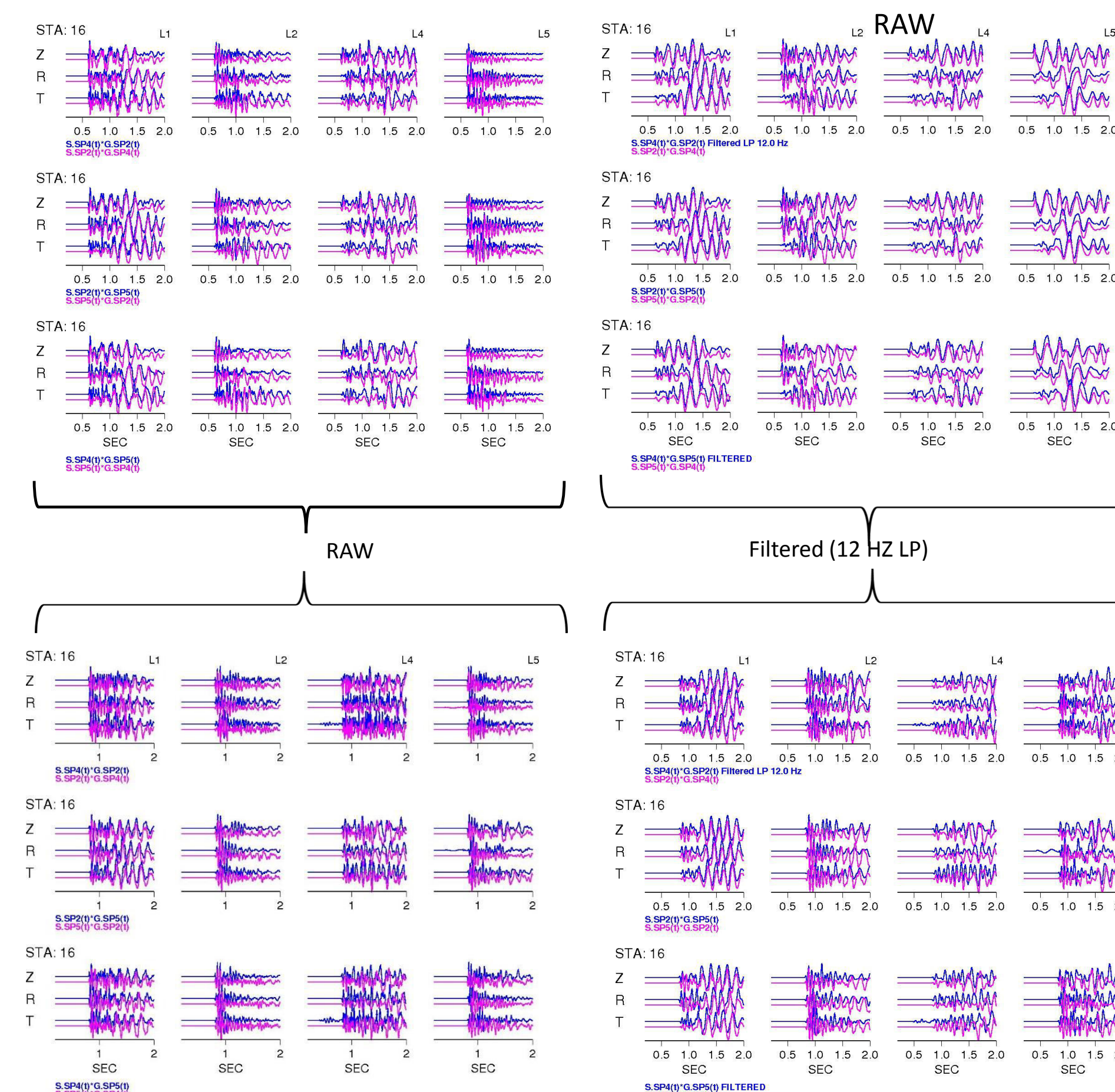


Figure 3. WFE applied to three-component waveforms from the SPE 2, SPE 4 and SPE 5 chemical explosions.

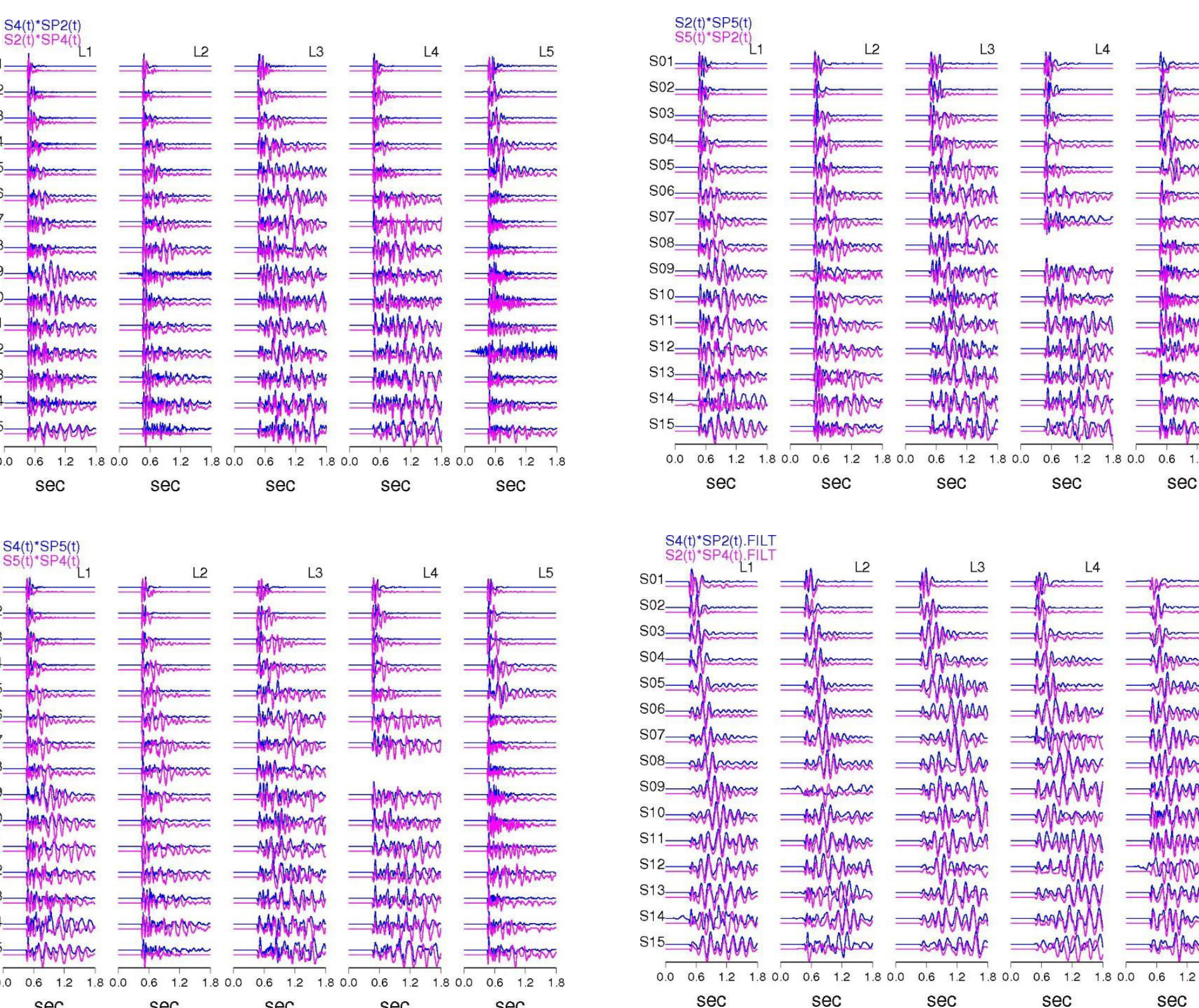


Figure 4. WFE using vertical component data recorded by geophones along the 5 profiles for SPE 2 vs SPE 4 (top) and SPE 4 vs SPE 5 (bottom) using the TDSF of each shot using published source parameters. Left panel shows for the raw and the right panel shows for the filtered data.

Normalized each seismogram by its maximum amplitude. The normalization was done for each pair separately as the ratios were not the same amongst the stations even along the same profile. We noted this using the empirical source functions also (Figure 5). This suggests that there may have been changes in the site condition or in the coupling of the instrument to the ground between the events which also varied from station to station. The depth variations may also be the effect caused by the interaction of seismic waves with the local geological model. We plan a synthetic calculation of waveforms using the geological framework model of the region + stochastic velocity variation to investigate this problem.

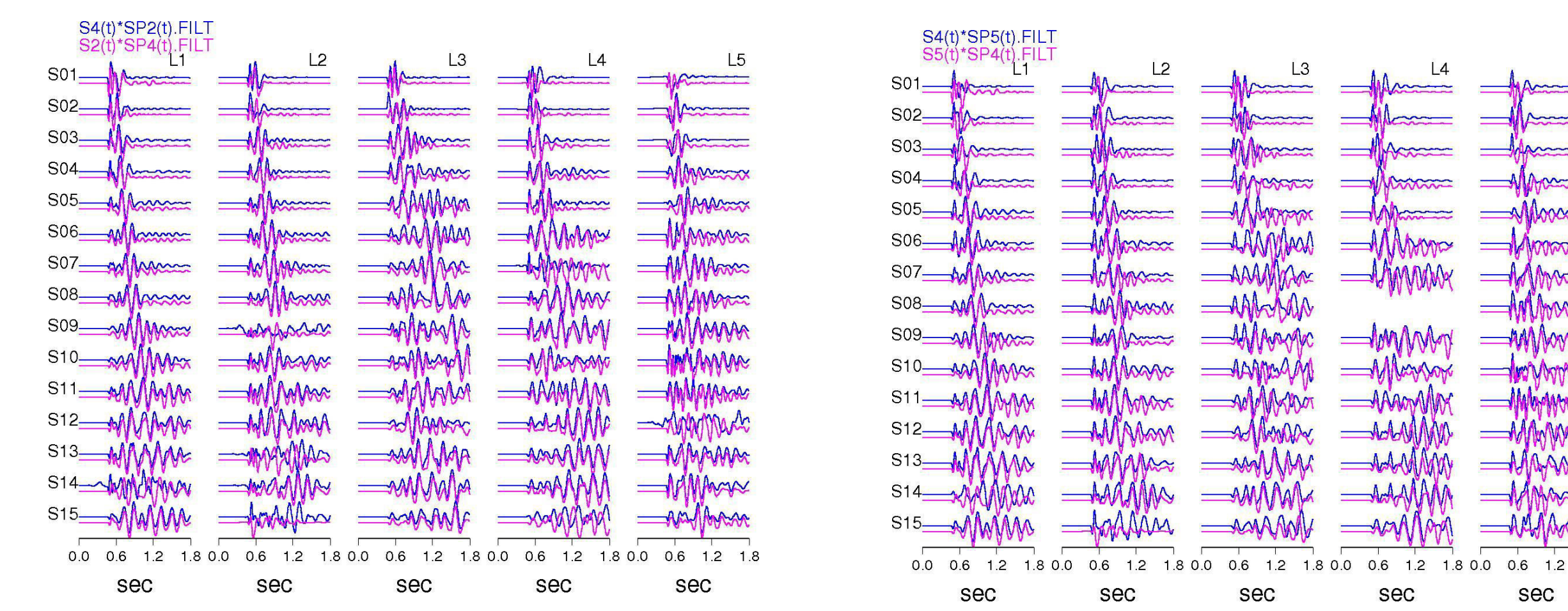


Figure 5. Displays results using empirical source function. Waveform recorded at 400m away (STA-04) from each shot along each profile is used as the ESF.

WFE: SOURCE & GREEN'S FUNCTION UNKNOWN – THEORETICAL EXTENSION

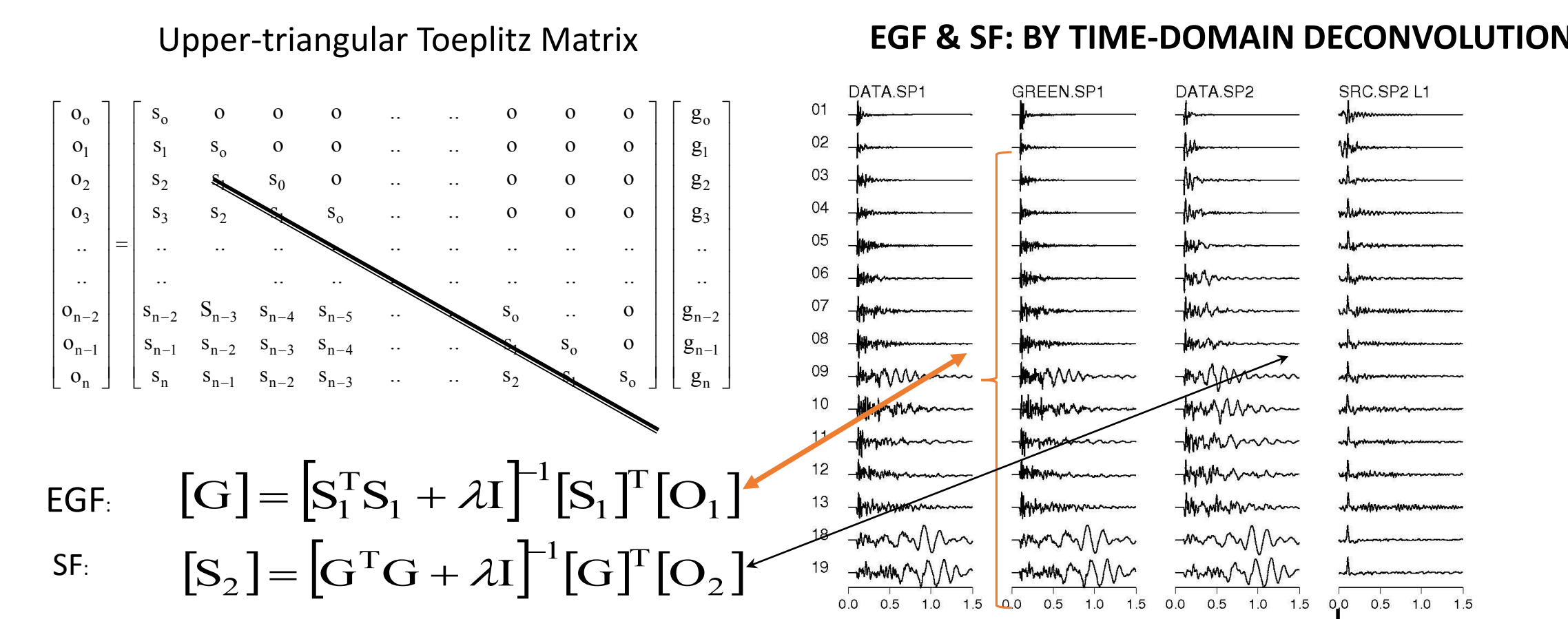
Let us convolve the first expression of (2) by $G_2(t)$ and second expression by $G_1(t)$, by doing so we can write

$$[O] = [S][G] = [G][S] \quad (3)$$

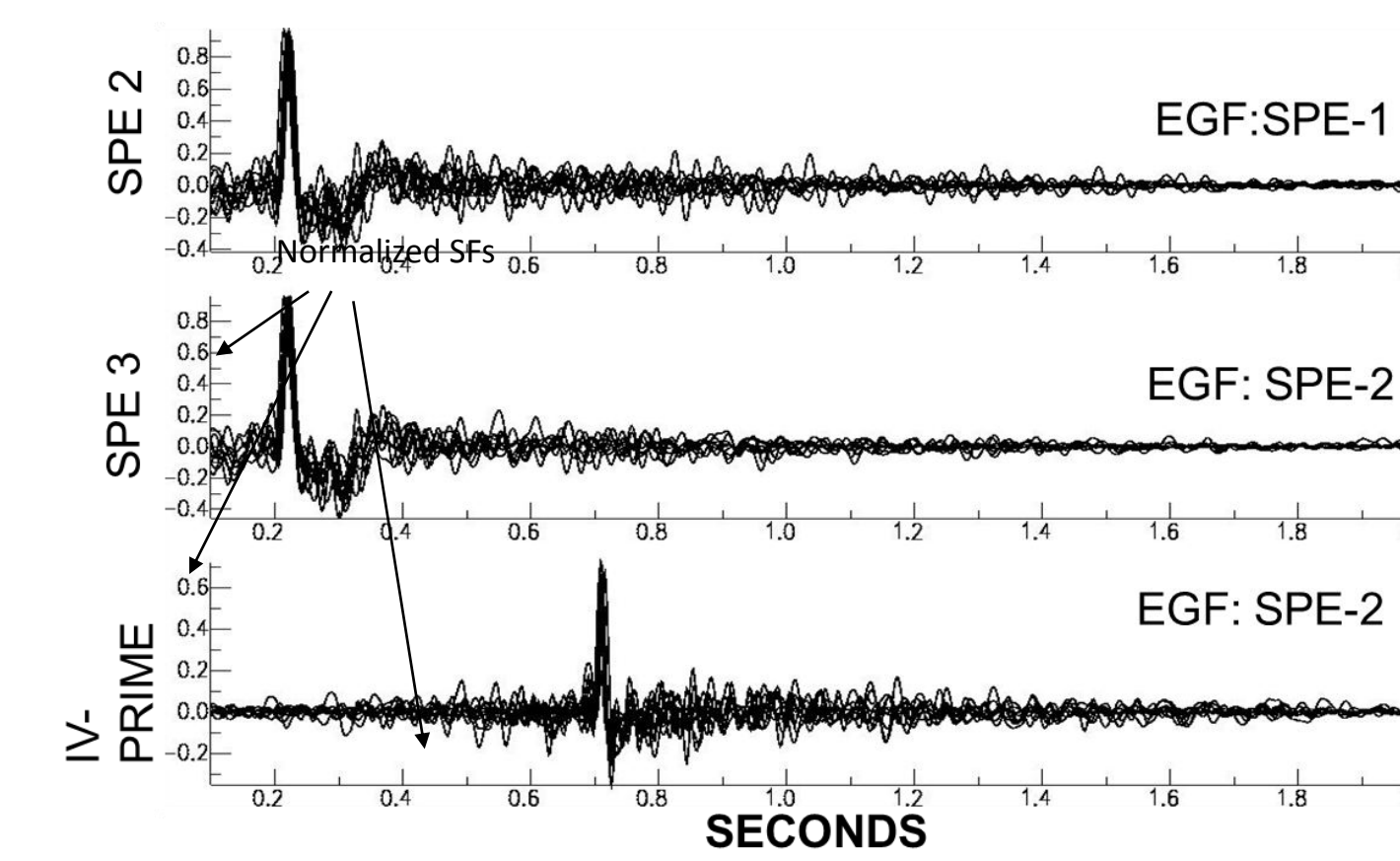
The right side of expression (4) suggests the difference between the two equations should generate a “null” trace provided S_i 's and G_i 's are accurately known; however they can often be unknown. In (4) let assume that G_i 's can be represented empirically (EGF). Let express eqn (1) convolution in a matrix format as follows

$$\begin{aligned} S_2(t) * O_1(t) * G_2(t) &= S_2(t) * S_1(t) * G_1(t) * G_2(t) \\ S_1(t) * O_2(t) * G_1(t) &= S_1(t) * S_2(t) * G_2(t) * G_1(t) \end{aligned} \quad (4)$$

where $[G]_{n \times 1}$ can be obtained if $[S]_{m \times n}$ is known and vice versa. Explicitly, the “ $m \times n$ ” matrix $[S]$ is a banded-Toeplitz matrix. The solution matrix being “ $n \times 1$ ”, the $[S]$ matrix is indeed an upper-triangular Toeplitz matrix. We used Marquardt-Levinson inversion [MLI] scheme to invert the $[O]$ to estimate $[G]$. However, the Toeplitz-matrix is ill-conditioned as both $[S]$ and $[G]$ start with low values (sometimes null values) prior to the signal. If included in the construction $[S]$ or $[G]$ “ $m \times n$ ” dimensional matrices, MLI solutions may suffer from large oscillations, especially in the amplitude. SFs obtained for the individual explosions are shown below.



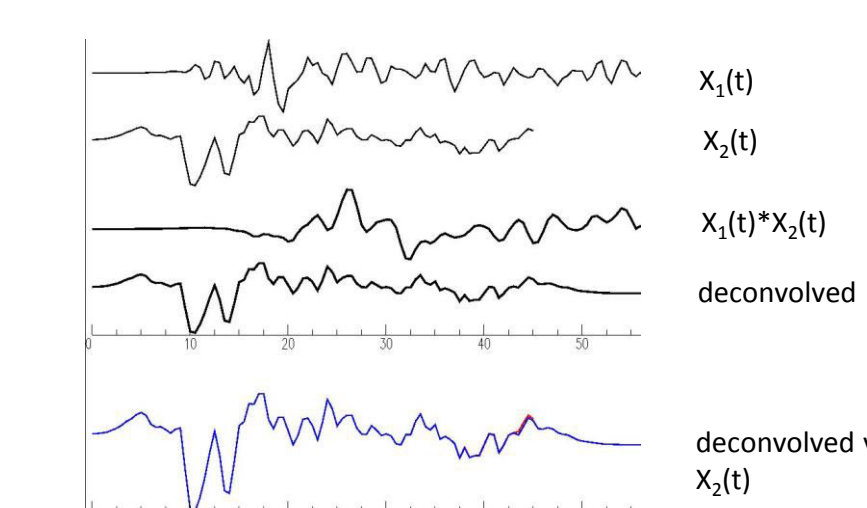
EGF: Empirical Green's Functions SF: Empirical Source Functions



To invert the ill-conditioned upper-triangular Toeplitz matrix, we developed a new code based on the Elden's algorithm. This algorithm is efficient and it uses the Tikhonov-Phillips regularization to minimize the Euclidean norm $\|O - Sg\|$ subjecting to a condition such as $\|Cg\| \leq \rho$, where ρ is factor that control the problem. From the theory of Lagrange multipliers, for each ρ there is a λ such that the solution to problem

$$\text{minimize} \quad \left\| \begin{matrix} O \\ \lambda Cg \end{matrix} \right\|$$

is also to the problem in hand. C is a “ $m \times n$ ” matrix and can be constructed using a first- or second-order difference matrix. We used the first-order difference. The mathematical detail of the time-domain deconvolution is not presented because of the limited space. Following is an example of the application of our code in which we present the time series obtained by the deconvolution of $X_1(t)$ from the time series $X_1(t) * X_2(t)$. Both target and deconvolved time series are remarkably similar.



CONCLUSIONS:

- Waveform equalization (WFE) algorithm produced fairly well matched waveforms for the SPE explosions.
- Empirical SFs/TDSFs can be used to extract GFs of the path, which in turn can be employed to extract TDSFs.
- Empirical SF can be exploited to determine the state of the station (without any ambiguity).
- For WFE to be successful, a time-domain stable deconvolution scheme is needed to invert an ill-conditioned Upper-Triangular Toeplitz matrix. Elden's algorithm provides the necessary mathematical background to develop such an essential computational code.

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