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Yield and Depth of Explosions Inverted from Regional Seismograms with Source Complexity – Effectiveness Using Synthetic Seismograms

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INTRODUCTION

A method to estimate yield and depth of explosions (EX) in the presence of DC and a strong CLVD contributions. CLVD contribution is computed usings single couple contribution for the ZDD/RDD seismograms which have amplitude by a factor of 2 less compared to the double-couple DC source. Source functions for the explosions are from TDSF expression of Saikia (2017).

METHODS/DATA

Current moment tensor estimation method uses Herrmann and Hutcheson (1993) equivalent to adding the CLVD and EX contributions to the DC waves treating both the same but representing each source type by own GFs and with the same moment elements for three sources. This method estimates scalar moments of three sources separate and uses EX scalar moment for yield and depth estimates.

START

RESULTS

Our e-poster provides the mathematical background for the forward grid search algorithm to determine the scalar moment and the dip, slip and strike of the DC source and scalar moments of the CLVD and EX sources. We use L1 & L2 norms and variance reductions as measures of the fit, of which the L1 & L2 constraints perform significantly better.

CONCLUSION

The proposed method solves directly for the M_{DC}, M_{CLVD}, and $M_{EX..}$ Using these results, we correct the observe waveforms for the DC and CLVD contributions and model the corrected explosion seismograms in time domain to extract its yield and depth. The synthetic experiment illustrates the high effectiveness of the proposed method.

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Introduction

- Yield and depth of explosions are often estimated by matching the long-period level of the observed P-wave spectra to the long-period level predicted using the far-field Mueller-Murphy source spectra for the specified values of the source parameters.
- Waveform modeling is used to identify source type by plotting the inverted moment-tensor elements on the lune plot (Tape and Tape, 2012) where the isotropic seismic moment is estimated as $\frac{(M_{xx}+M_{yy}+M_{zz})}{3}$ which can be related to yield of the explosion (Ford *et al*., 2023).
- The proposed method eliminates the need for the inversion of the moment-tensor elements, and it seeks directly to estimate the contributions of the DC, CLVD and EXP sources to the total seismic moment of an event. This algorithm uses contributions from the DC source in terms of dip, slip and strike of the fault and the contributions from both CLVD and explosion sources.
- Validated the proposed method is validated using synthetic waveforms and need additional work to include cases when an event (i) is only be recorded at large-distance stations, (ii) is small in magnitude, and (iii) is recorded only by a few stations and including the dominance of noise in waveforms.

Theory

THEORY

Seismograms from an explosion can be expressed as linear sum of contributions from explosion (EX), double couple (DC) and CLVD sources with seismic moments of $\boldsymbol{M_{EX}}, \boldsymbol{M_{DC}}$ and $\boldsymbol{M_{CLVD}}$ respectively as follows

$$M_{EX}[S_{EX}(t,W,h) * GF_{EX}(t,r,h)] + M_{DC}[S_{DC}(t) * GF_{DC}(t,r,h)] + M_{CLVD}[S_{CL}(t,h) * GF_{SC}(t,r,h)] \quad (1)$$

- *GF*s with indices are wave-propagation effects of three source types (SC=Single Couple)
- *GFs* for CLVD sources are from vertically symmetric single couples. Both single and double couples involve zeroth order Bessel's function(kr) contribution, and for single couple its amplitude is half of the double-couple radiation (Saikia, 2025 manuscript in preparation).
- $S_{DC}(t)$ and $S_{CLVD}(t)$ are δ functions – used for long-period seismograms modeling
- $S_{EX}(t,W,h)$ (Saikia (2017) where yield W in Kt and depth h in meter). For long-period analysis all published work used δ function
- $XMOM =$ scalar explosion moment – explosion is large enough to have DC and CLVD contributions.
- In presence of source complexity, one can express as

$$XMOM = M_{EX}.XMOM + M_{DC}.XMOM + M_{CLVD}XMOM \text{ i.e., } M_{EX} + XM_{DC} + XM_{CLVD} = 1 \quad (2)$$

Grid Search : Formulation for the Moment Partition

Let express the three component wavefield as a linear combination of contributions from three source types as follows

$$\begin{aligned} U_z &= M_{DC}.XMOM.[a_1ZSS + a_2ZDS + a_3ZDD] + M_{CLVD}.XMOM.[\overline{ZDD}] + M_{EX}.[S(W,h) * ZEX] \\ U_R &= M_{DC}.XMOM.[a_1RSS + a_2RDS + a_3RDD] + M_{CLVD}.XMOM.[\overline{RDD}] + M_{EX}.[S(W,h) * REX] \\ U_T &= M_{DC}.XMOM.[a_4TSS + a_5TDS] \end{aligned} \quad (3)$$

where

$$\begin{aligned} a_1 &= (f_1n_1 - f_2n_2)\cos(2Az) + (f_1n_2 + f_2n_1)\sin(2Az) \\ a_2 &= (f_1n_3 + f_3n_1)\cos(Az) + (f_2n_3 + f_3n_2)\sin(Az) \\ a_3 &= f_3n_3 \\ a_4 &= (f_1n_1 - f_2n_2)\sin(2Az) - f_1n_2 + f_2n_1)\cos(2Az) \\ a_5 &= (f_1n_3 + f_3n_1)\sin(Az) - (f_2n_3 + f_3n_2)\cos(Az) \end{aligned}$$

$$\begin{aligned} f_1 &= \cos(\lambda)\cos(\varphi) + \sin(\lambda)\cos(\delta)\sin(\varphi) \\ f_2 &= \cos(\lambda)\sin(\varphi) - \sin(\lambda)\cos(\delta) \\ f_3 &= -\sin(\lambda)\sin(\varphi) \end{aligned}$$

δ, λ, φ correspond tp dip, slip and strike

$$\begin{aligned} n_1 &= -\sin(\delta)\sin(\varphi) \\ n_2 &= \sin(\delta)\cos(\varphi) \\ n_3 &= -\cos(\delta) \end{aligned} \quad (4)$$

Two formulae below show how the $a_i's$ are transformed to the moment formulation for a DC sourceType equation here. (adopted from Saikia, 1985 and Langston, 1980). We are showing only for U_z^{DC} and U_T^{DC} (U_R^{DC} is same as U_Z^{DC} $-$ just replace Z by R)

$$U_Z^{DC} = \left[\frac{ZSS}{2}.\cos(2AZ) - \frac{ZDD}{2}\right]M_{xx} + \left[-\frac{ZSS}{2}.\cos(2Az) - \frac{ZDD}{2}\right]M_{yy} + [ZSS.\sin(2Az)]M_{xy} + [ZDS.\cos(Az)]M_{xz} + [-ZDS.\sin(Az)]M_{yz}$$

$$U_T^{DC} = \left[\frac{TSS}{2}.\sin(2Az)\right]M_{xx} - \left[\frac{TSS}{2}.\cos(2Az)\right]M_{yy} - [TSS.\sin(2Az)]M_{xy} + [TDS.\sin(Az)]M_{xz} - [TDS.\sin(Az)]M_{yz} \quad (5)$$

By adding $[\frac{ZDD}{3}M_{xx}, \frac{ZDD}{3}M_{yy}, \frac{ZDD}{3}M_{zz}]$ for the CLVD and $\left[\frac{ZEX}{3}M_{xx}, \frac{ZEX}{3}M_{yy}, \frac{ZEX}{3}M_{zz}\right]$ for the EX to U_z^{DC} and likewise to U_R^{DC}, one can arrive at the expressions in Dreger and Minson (2008), which were taken from Herrmann and Hutcheson (1993).

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Grid Search : Estimate Moment Partition and Extract Explosion Seismograms

We reformulate expression (3) into a matrix formula Given below

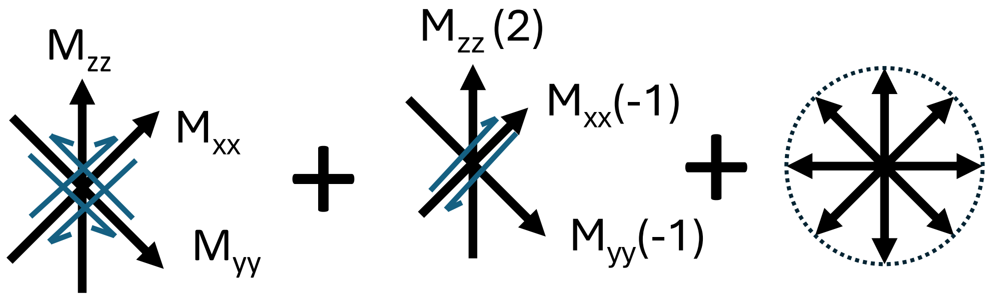
$$\underbrace{\begin{bmatrix} U_z(t_1) \\ U_R(t_1) \\ U_T(t_1) \\ U_z(t_2) \\ U_R(t_2) \\ U_T(t_3) \\ \vdots \\ U_z(t_m) \\ U_R(t_m) \\ U_T(t_m) \end{bmatrix}}_{[D]} = \underbrace{\begin{bmatrix} U_z^{DC}(t_1) & ZEX(t_1) & \overline{ZDD}(t_1) \\ U_R^{DC}(t_1) & REX(t_1) & \overline{RDD}\,(t_1) \\ U_T^{DC}(t_1) & 0 & 0 \\ U_z^{DC}(t_2) & ZEX(t_2) & \overline{ZDD}\,(t_2) \\ U_R^{DC}(t_2) & REX(t_2) & \overline{RDD}(t_2) \\ U_T^{DC}(t_3) & 0 & 0 \\ \vdots & \vdots & \vdots \\ U_z^{DC}(t_m) & ZEX(t_m) & \overline{ZDD}(t_m) \\ U_R^{DC}(t_m) & REX(t_m) & \overline{RDD}\,(t_m) \\ U_T^{DC}(t_m) & 0 & 0 \end{bmatrix}}_{[A]} \underbrace{\begin{bmatrix} XM_{DC} \\ XM_{ex} \\ XM_{clvd} \end{bmatrix}}_{[X]} \qquad (6)$$

$$[\mathrm{X}] = \left[\mathrm{A}^{\mathrm{T}}\mathrm{A}\right]^{-1} [\mathrm{A}]^{\mathrm{T}}\mathrm{D} \qquad (7)$$

Note that [A] is mx3 matrix leading $[A^TA]$ to be a 3x3 Matrix and use a simple matrix inversion code.

- ZDD is same as $\overline{ZDD}$ when the factor of 2 is omitted where ZDD is from a DC and $\overline{ZDD}$ is from a single couple source
- δ function is assumed as source functions for all sources
- Moment-tensor elements are composite for all sources
- Sources are at the same depth but not necessary

Schematic Representation



- Computed synthetic seismograms for CLVD and explosion sources and all combinations of the dip, slip and strike of the fault separately.
- For each combination of the fault parameters, employed the waveform inversion using the formulation in the left and estimated the scalar moment partitions.
- Next subtracted the CLVD and DC wavefields from the observed wavefield leading to the extraction of the explosion seismograms.

Grid Search for Yield and Depth of Explosions

$$S(w,h,t) = \underbrace{\left[\frac{R}{4\mu}\right]\left[\frac{C^2}{\beta p}\right]\left[\left[\partial_t[H(t)e^{-\alpha t}\sin(pt)]\right]\right]}_{A(t,hW)} * \underbrace{[e^{-\gamma t}P_1 + P_2]}_{B(t,h,W)} \quad (8)$$

Refer to Saikia (2017) for the variable description. C is the compressional velocity and $\beta = \sqrt{(\lambda + 2\mu)/4\mu}$. The following variables have been recently derived

$$P_1 = P_{10}\left[\frac{h}{h_o}\right] \qquad P_2 = P_{20}\left[\frac{h_o}{h}\right]^{\frac{n-9}{3n}} W^{-0.13} \qquad \gamma = \gamma_o\left[\frac{h}{h_o}\right]^{\frac{1}{n}} W^{-\frac{1}{3}} \qquad \propto = \frac{\omega_o}{2\beta} \qquad p = \omega_o\sqrt{\frac{1}{\beta} - \frac{1}{4\beta^2}} \qquad \omega_o = \frac{C}{R_o}\left[\frac{h}{h_o}\right]^{\frac{1}{n}} W^{-\frac{1}{3}}$$

$$U_{EX}(t) = A(t,h,W) * B(t,h,W) * GF_{EX}(t,h) \quad (9)$$

Computation of long-period $GF_{EX}(t,h)$ using many flat layered earth model suggests GFs are not sensitive to the depth variation within the upper kilometer of the crust.

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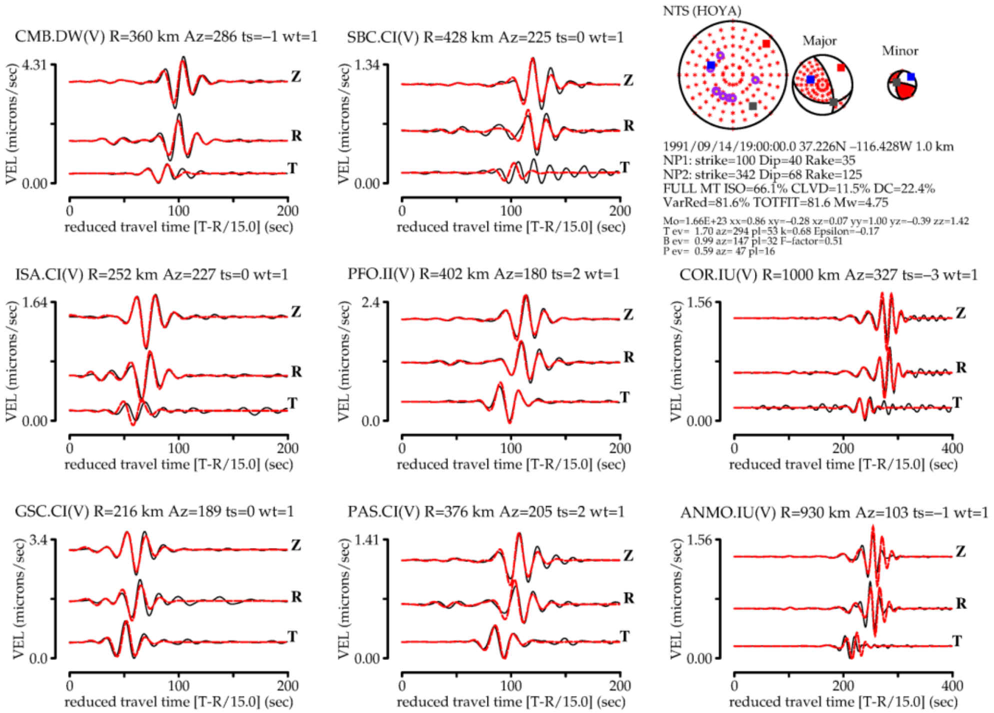
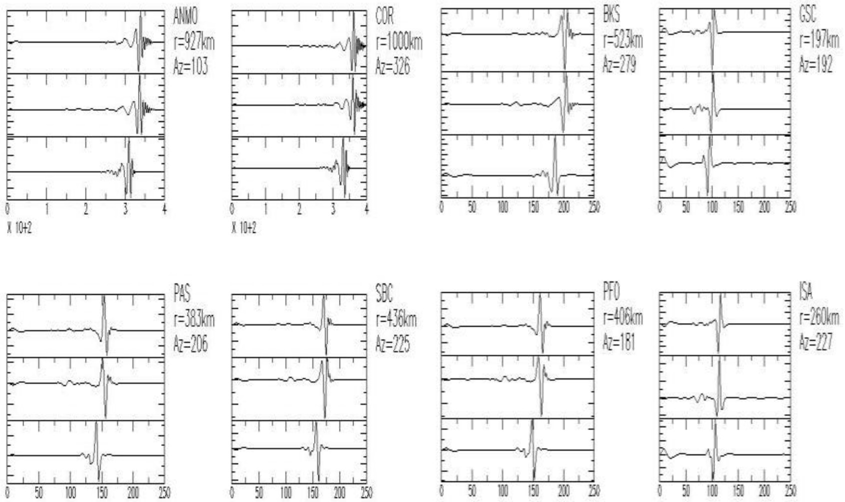
Waveforms for Inversion – Surrogate Synthetics

Regional Seismogram Inversion of HOYA waveforms, which is NTS explosion (Ref: Saikia et al., 2014); Jorge Roman-Nieves performed the analysis using Dr. Ichinose's code which implemented Dreger and Minson (2008).



- Used WUS velocity model to computed GFs of fundamental fault and explosion sources
- Explosion waveforms were convolved with a time domain source function generated for 100 Kt yield at 100m depth.
- Equivalent seismic moment was partitioned at 0.3:0.2:0.5 for the DC:CLVD:EX and was used to construct the surrogate synthetics using expression (3).



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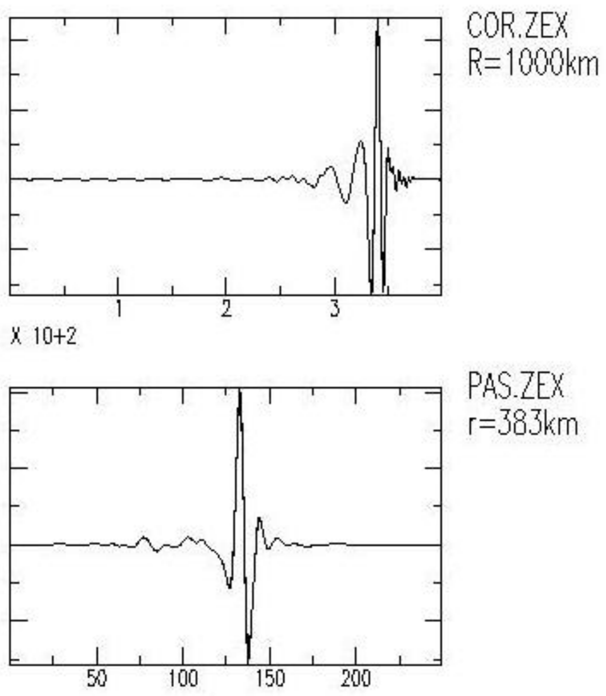
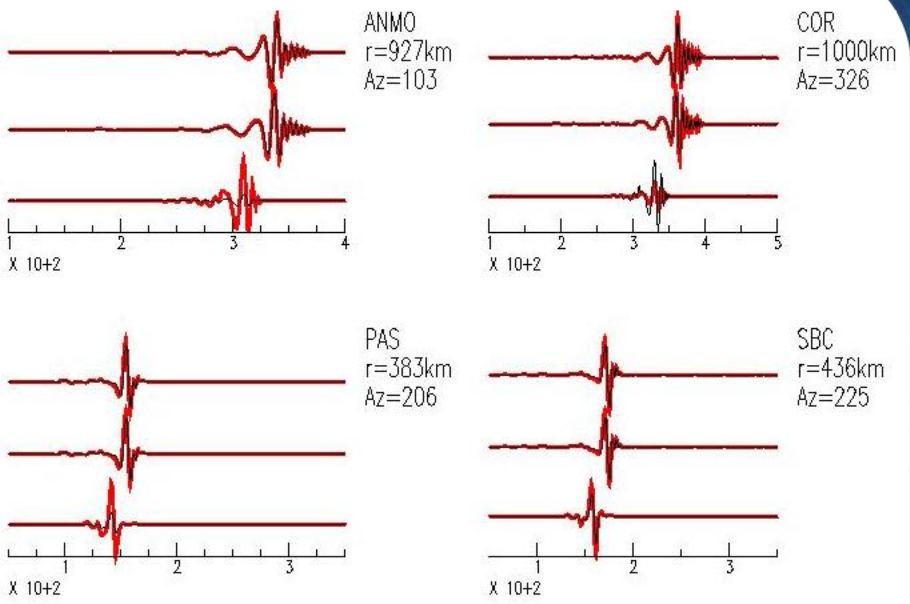
Depth Seinsitivity of Long-Period GFs – Example of Variance Reduction Insensitivity



In each panel above, bandpass filtered GFs between 0.03 to 0.1Hz for 10 depths ranging between 300m to 1200m at an interval of 100m are shown on top of each other. The WUS model has a 5.5 km top thick layer. Unless the near-surface and wave-propagation paths are complex, this observation suggests no significant differences in the waveforms (may see a feeble effect in the amplitude !!!).



Example of simulated seismograms (dark traces) which were computed using an arbitrary solution from many that had a 98% variance reduction. Actually we encountred many solutions in the neighborhood of 98-99% variance reductions.

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Results of the proposed Grid-Search Algorithm

Dip deg	Slp deg	Str deg	W Kt	h meter	M_w	M_o-10^{24} dyne-cm	L1 Norm	L2 Norm	VR	Partition DC:CLVD:EX
0	60	180	150	1100	4.93	0.280	-0.114e-10	0.352e-06	99	03:-05:26
30	30	30	50	900	4.67	0.115	-0.482e-07	0.244e-06	99-	-55:-50:159
20	120	150	100	1000	4.84	0.203	-0.450e-13	0.105e-10	100	30:20:50
80	120	270	100	1100	4.83	0.196	0.104e-10	0.140e-06	99	27:02:51
50	90	60	100	900	4.85	0.214	-0.158e-10	0.207e-06	100-	29:21:46
50	**90**	**60**	**100**	**1000**	**4.84**	**0.203**	**-0.450e-13**	**0.105e-10**	**100**	**30:20:50**
50	90	60	100	1100	4.83	0.196	-0.507e-10	0.196e-07	100-	31:19:54
80	120	270	100	1100	4.83	0.196	0.104e-10	0.140e-06	99-	27:02:51
50	60	240	200	1000	5.01	0.372	-0.255e-09	0.210e-06	99+	12:05:15
10	150	360	50	900	4.95	0.210	0.272e-10	0.336e-06	98	-19:-04:44
70	60	90	50	1000	4.66	0.111	0.201e-10	0.318e-06	98+	-25:-20:163
60	90	30	200	1000	5.01	0.372	0.320e-11	0.303e-06	98+	11:03:15
90	90	270	100	900	4.85	2.10	0.876e-10	0.3459e-06	97+	-02:-03:46
90	180	360	200	1100	5.0	3.72	-0.452e-10	0.151e-06	99+	-08:-09:15

A sample of random solutions picked from a pool of 10,920: dip varied from 0 to 90^o with a 10^o interval, slip from 0 to 180^o and strike from 0 to 360^o both with a 30^o interval, including W, and h. Many of the solutions violated the scalar moment conservation. Evaluation of the effect of erroneous GFs and noise contamination is still on-going.

- VR is high for all cases
- L1 and L2 norms were small.

L1 and L2 norms are small by several orders than the values of the neighboring or near equal ground truth solution.

CONCLUSIONS

- Formulated the mathematical background for an algorithm to estimate yield and depth of an explosion when accompanied by the DC and CLVD source types.
- The algorithm uses GFs for fundamental faults and explosions from a velocity model and directly search for the source mechanism of the DC source, and then the source parameters the explosion.
- Our study indicates that variance reduction is not a suitable constraint to correctly establish the depth of the explosion in the shallowest part of the crust. Need to work at high frequency to evaluate the performance this constraint.
- These are only preliminary results and investigation in presence of noise is on-going and with GFs from varying velocity models are in process.
- Comments are welcome.