Robust Source-Independent FWI for High-Res Subsurface Imaging in Support of CCS/CCUS Monitoring Systems

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1. Introduction

Full Waveform Inversion

FWI provides high-resolution subsurface models by minimizing the mismatch between observed and modeled seismic waveforms, but its performance strongly depends on data quality and the accuracy of modeling assumptions (Virieux & Operto, 2009).

Sensitivity of L2-Norm to Outlier

The conventional L2-norm objective function is sensitive to large residuals and outliers because residual amplitudes are quadratically penalized, which can degrade the inversion in the presence of non-Gaussian and high-amplitude noise (Aravkin et al., 2011; Jiménez Tejero et al., 2015; Liu et al., 2017; Barbosa et al., 2022).

Source-Wavelet Uncertainty

In addition to noise, source-wavelet uncertainty introduces systematic discrepancies between observed and modeled data, which may be incorrectly mapped into subsurface model updates. (Choi & Alkhalifah, 2011; Wang et al., 2018; Song & Alkhalifah, 2020).

2. Theory

Source Independent Residual by Convolution Approach

To circumvent source uncertainty problem, Choi and Alkhalifah (2011) proposed a time-domain convolution method. In this approach, the observed data is convolved with a synthetic reference trace, and the synthetic data is convolved with an observed reference trace:

$$r = u * d_{ref} - d * u_{ref}$$

With u and d is regarded to synthetic and observed seismogram and u_ref and d_ref is regarded to one reference trace as convolution kernel from synthetic and observed seismogram

Robust FWI using Student's t-Distribution

The Student's t-penalty, derived from the heavy-tailed Student's t-distribution, is formulated as:

$$p(r) = \frac{v+1}{2} \; log\left(1 + \frac{r^2}{v\sigma^2}\right)$$

where $v\sigma$^2 is a scaling parameter related to the degrees of freedom. The derivative of this penalty, which acts as the weighting factor in the adjoint source (gradient calculation), is:

$$\Psi(r) = \frac{\partial p}{\partial r} = \frac{(v+1)\, r}{v\sigma^2 + r^2}$$

The Combined Framework

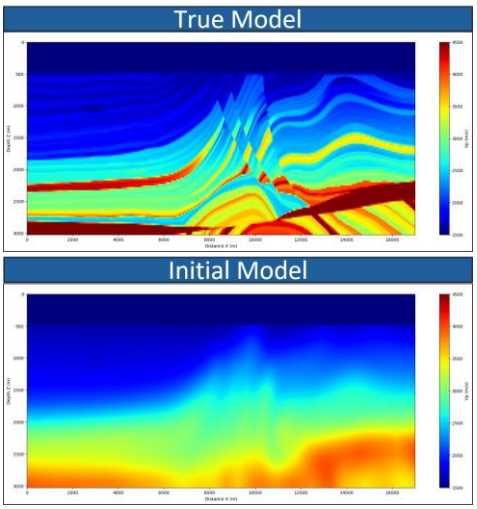
By synthesizing the convolution-based SI-FWI with the Student's t-distribution penalty, we construct a unified objective function:

$$J(m) = \frac{v+1}{2} \sum log(1 + \frac{(u * d_{ref} - d * u_{ref})^2}{v\sigma^2})$$

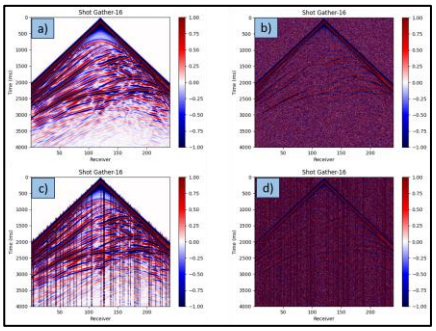
4. Conclusion

The combined SI-FWI + Student-t objective benefits from two complementary mechanisms: SI-FWI reduces sensitivity to source-wavelet uncertainty, while Student-t suppresses the influence of high-amplitude residual outliers. This explains why the combined formulation provides the strongest overall reconstruction under combined noise and remains stable after source-wavelet error is introduced.

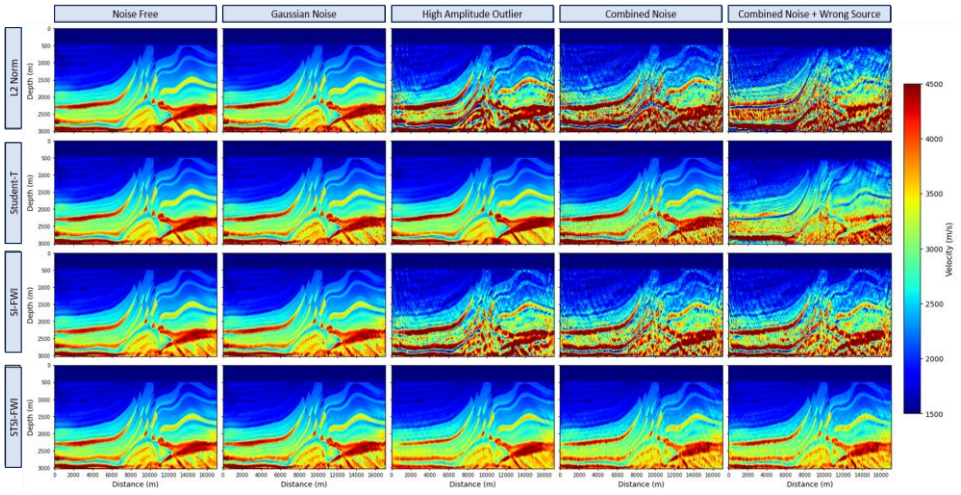
3. Implementation



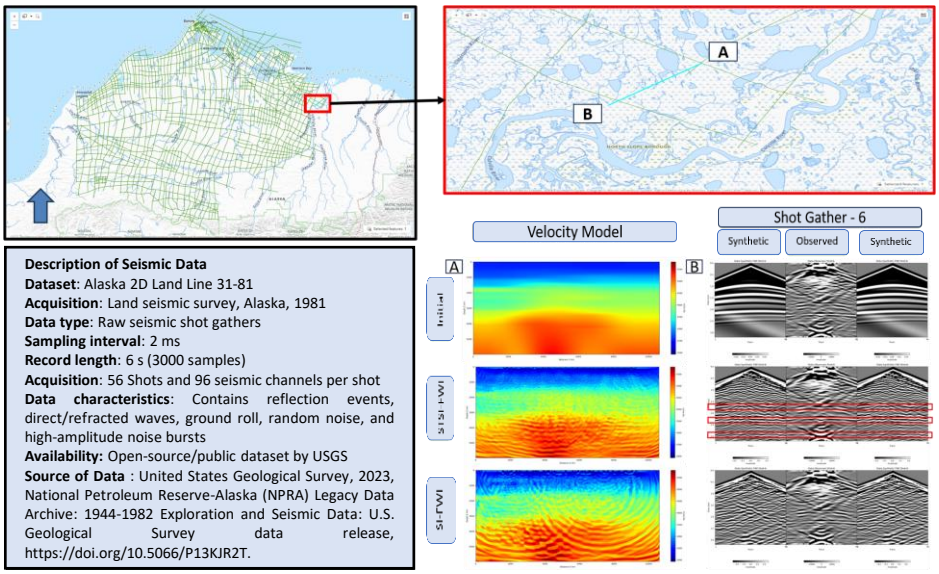
Picture 1. *True marmousi II synthetic model (top) and initial model from gaussian smoothing of true marmousi II model (bottom).*



Picture 2. *Seismic gather of (a) noise-free data, (b) random Gaussian noise, with a noise amplitude of 50% of the RMS amplitude of each shot gather, (c) high-amplitude outliers, where 20% of the traces are corrupted with amplitudes 20 times larger than their original amplitudes, and (d) a combination of random noise and high-amplitude outliers.*



Picture 3. *Result of Full Waveform Inversion from each type case data with different objective approach including proposed of Student-T Source Independent methods (STSI).*



Description of Seismic Data
Dataset: Alaska 2D Land Line 31-81
Acquisition: Land seismic survey, Alaska, 1981
Data type: Raw seismic shot gathers
Sampling interval: 2 ms
Record length: 6 s (3000 samples)
Acquisition: 56 Shots and 96 seismic channels per shot
Data characteristics: Contains reflection events, direct/refracted waves, ground roll, random noise, and high-amplitude noise bursts
Availability: Open-source/public dataset by USGS
Source of Data : United States Geological Survey, 2023, National Petroleum Reserve-Alaska (NPRA) Legacy Data Archive: 1944-1982 Exploration and Seismic Data: U.S. Geological Survey data release, https://doi.org/10.5066/P13KJR2T.

Picture 4. *Methods testing on real seismic data from Alaska 2D Land Line 31-81 from open source USGS dataset. Result showing comparation of velocity model from FWI with Source Independent (SI-) and Student-T Source Independent (STSI-) with related shotgather from real and synthetic created by initial and FWI result from both methods.*