Least-Squares Migration: Status and Opportunities

Least-Squares Migration (LSM) treats seismic imaging as an inverse problem, and can be implemented in a diverse range of ways. The common elements are that the output aims to provide an improved Pre-Stack Depth Migration (PSDM), and the velocity model is not updated during the process. When implemented using finite difference operators in an iterative workflow, LSM can be extended to imaging the full seismic wavefield. In addition to improving the amplitude and spatial wavenumber content of seismic images, LSM is now being explored as a solution to compensate for different acquisition geometries and/or shooting directions in 4D projects, or as a possible solution to deliberately reduce the acquisition cost and effort.

Why Consider Least-Squares Migration?

Figure 1 compares a traditional one-pass pre-stack depth migration (PSDM) of a multisensor towed streamer seismic dataset with a 'Least-Squares' migration (LSM) of the same data. Details will follow later, but in essence the LSM corrected many of the deficiencies inherent in the PSDM. From an interpretation perspective, the following benefits can be observed:

- The balance of event amplitudes is far more uniform throughout the vertical section and depth slices being displayed.
- Resolution of dipping features—notably fault planes—is improved because the high wavenumber content has correspondingly improved. This benefit is also observed in the frequency-wavenumber (FK) plots (lower right corner) derived from windows of the seismic data.
- Shadow zones and areas of 'poor illumination' are reduced. Note that the term 'illumination' can be used in different context by different seismic practitioners: for interpreters, poor illumination may simply refer to zones of washed out event amplitude and character; or for acquisition and processing geophysicists, poor illumination may refer to a fundamental inability or failure to propagate sufficient acoustic energy from all the survey source locations to the target geology in the subsurface and then record the reflected wavefields in a coherent manner at all the relevant receiver locations for each shot point.
- Vertical or temporal resolution may be improved if the LSM implementation includes some form of spectral recovery or balancing. This may not always be properly acknowledged.
- Various imaging artifacts observable in the PSDM result are suppressed in the LSM result. As discussed later, pernicious migration artifacts referred to as 'crosstalk' are particularly relevant, but other artifacts related to suboptimal destructive interference during traditional migration may also be mitigated.

Note that in all commercial implementations of LSM today, of which there are many flavors, the velocity model is not adjusted. LSM alters the way that seismic energy is reconstructed on the final seismic images.

How Does Least-Squares Migration Work?

Migration produces a representation of the earth's reflectivity. The image resolution is controlled by a number of factors including: the acquisition parameters (source and acquisition geometry); the earth properties (velocity, illumination and attenuation), and the migration algorithm. The influence of these factors can be reduced during acquisition and processing using: multisensor data; rich-azimuth acquisition geometries; accurate velocity models, and compensation for attenuation. Where the geological overburden is complex and the acquisition geometry leads to poor source and receiver surface coverage, both the illumination and wavenumber content of the migrated images can be suboptimal. This leads to uncertainty in interpretation and a lack of confidence in reservoir characterization. It can be shown that migration can be formulated as an inverse problem that attempts to find the best reflectivity model by minimizing the difference between observed and modeled data. The mathematics involved requires the knowledge of the inverse of the 'Hessian matrix', a vast array of numbers that describe the curvature information within the objective function being minimized. Mathematically, the Hessian matrix contains first-order information about the subsurface illumination for a given acquisition geometry and earth model, as well as second-order scattering information. The most relevant information in the full Hessian matrix occurs close to the main diagonal of the matrix, and indeed, this can be used as a proxy for illumination, as shown in Figure 2.

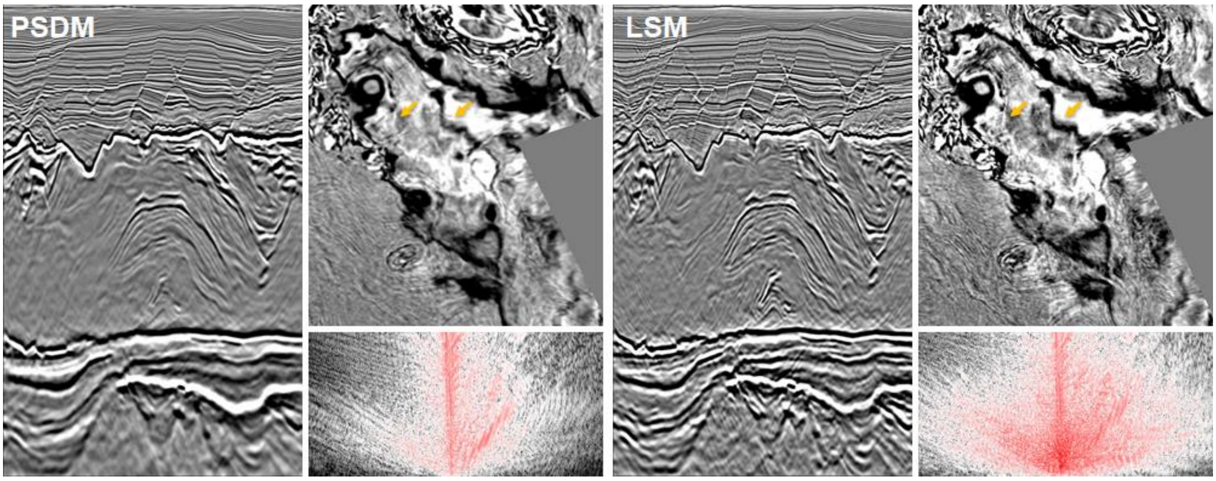

Figure 1. (left) Conventional PSDM of a complex salt province. Note the variable illumination and variable spatial resolution; (right) LSM of the same data.

An approximation to the Hessian matrix can be explicitly computed in the image (migrated) space as 'Point Spread Functions' (PSFs), and a multidimensional deconvolution can be used to recover the unknown (desired) reflectivity from the migrated image and the PSFs. Each PSF describes the response of the imaging system to a point source. Various flavors of this are the most common approach used today. Figure 3 shows slices through a conventional pre-stack depth migration (PSDM) on the left, and the construction of a coarse 3D grid of PSFs on the right. Figure 4 shows a conventional PSDM vs. LSM of the well-known Sigsbee synthetic model using the image space implementation of LSM. Note the improved wavenumber content after LSM, and the correspondingly improved spatial resolution of dipping features and local stratigraphy.

LSM may alternatively be implemented in the data (unmigrated) domain. The Hessian matrix is implicitly computed when the data are migrated with a finite difference-based PSDM, the migrated image is then used to model synthetic data, and the difference between the observed and modeled data is iteratively minimized. Each iteration updates the migrated image. This approach can be robustly adapted to Full Wavefield Migration (FWM) of both primary reflections and multiples in the input data.

Industry Trends

Over the past few years, the EAGE (European Association of Geoscientists & Engineers) and SEG (Society of exploration Geophysicists) have arranged an increasing variety of dedicated annual conference technical sessions and dedicated international workshops on LSM. Some implementations use Kirchhoff migration; and may be based upon PSFs or forms of match filtering. In this context, the primary benefit is the balancing of amplitudes throughout the migrated image. Some Kirchhoff-based implementations also include attenuation compensation in the workflow to improve vertical resolution. One-way (Wave Equation Migration: WEM) and two-way (Reverse Time Migration: RTM) implementations of LSM are far less common due to the complexity of developing the algorithms and the higher computational cost. Results shown from all implementations at industry workshops vary considerably from the mundane (almost no benefit) to spectacular—particularly when the full wavefield is used. PGS delivered one of the largest-ever applications of LSM in 2018 when over 30 000 square kilometers of offshore Brazil data from the Santos Basin were imaged with an RTM implementation.

Improvements in angular illumination from LSM can also be exploited for producing LSM prestack offset or angle gathers for a better Quantitative Interpretation (QI) in areas of complex geology. Figure 5 illustrates the difference in PSFs for two incidence angles that differ by only 10°. With time, the sophistication of LSM solutions will also increase to accommodate elastic wave propagation.

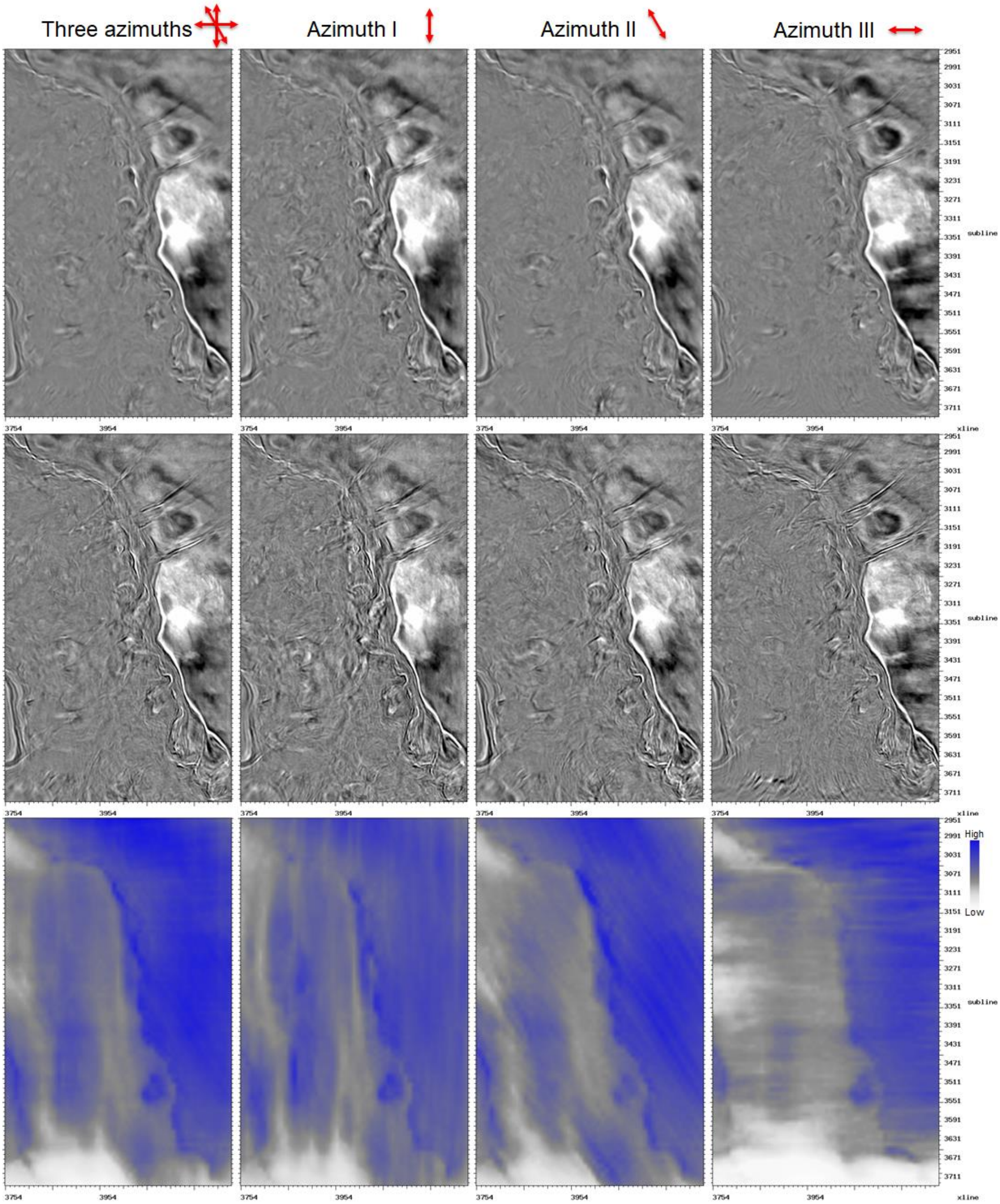

Figure 2. (top row) Depth slices from a multi-azimuth (MAZ) survey, where the conventional PSDM image of the combined volume and the constituent azimuths is shown, respectively; (middle row) Equivalent depth slices from LSM processing; and (lower row) The relevant illumination information from the main diagonal of the Hessian matrix, where blue represents the strongest illumination.

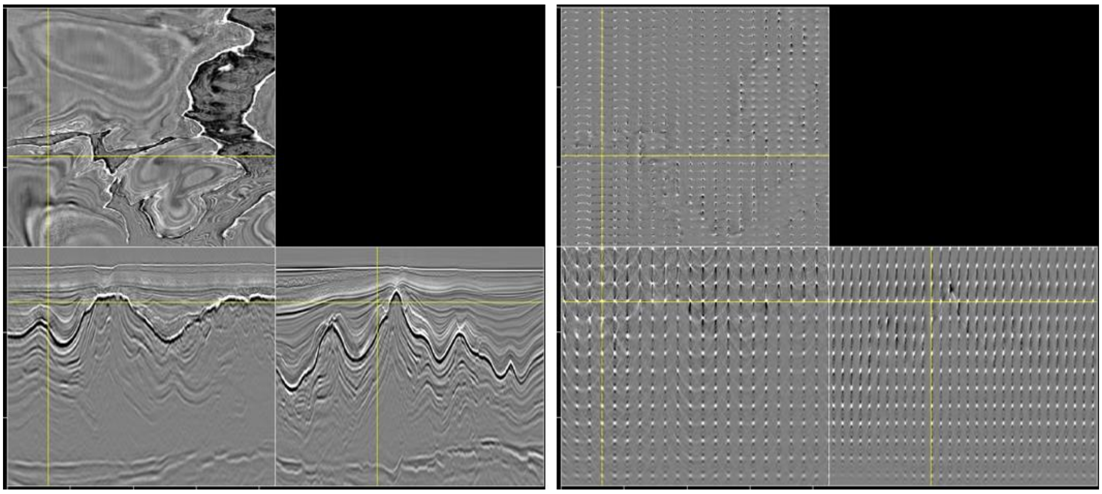

Figure 3. (left) Horizontal and vertical image slices through a PSDM volume; (right) A 3D collection of Point Spread Functions (PSFs) computed using the modeling/migration of a coarse grid of point scatterers.

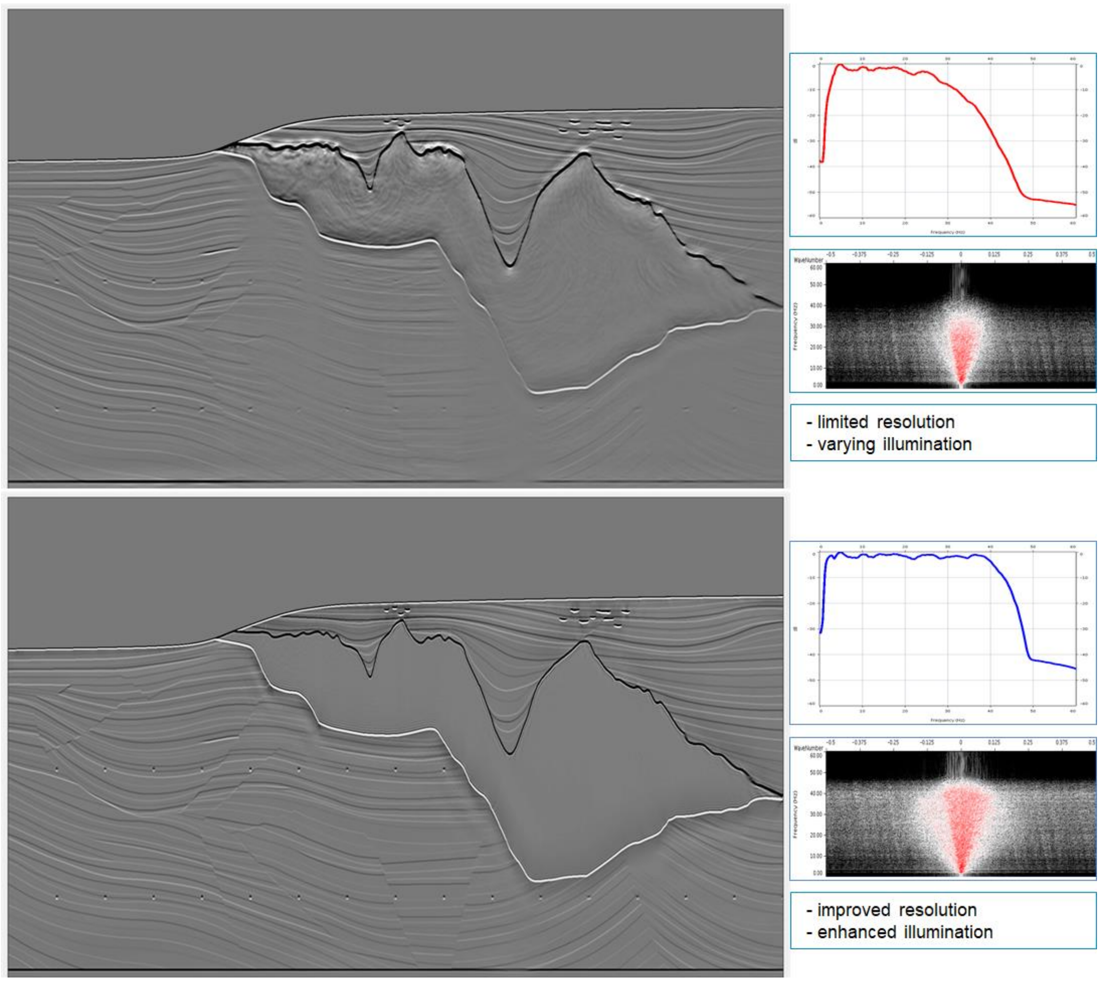

Figure 4. (upper) PSDM image of the Sigsbee synthetic model, the associated temporal frequency spectrum, and the associated wavenumber frequency spectrum; (lower) LSM equivalent results.

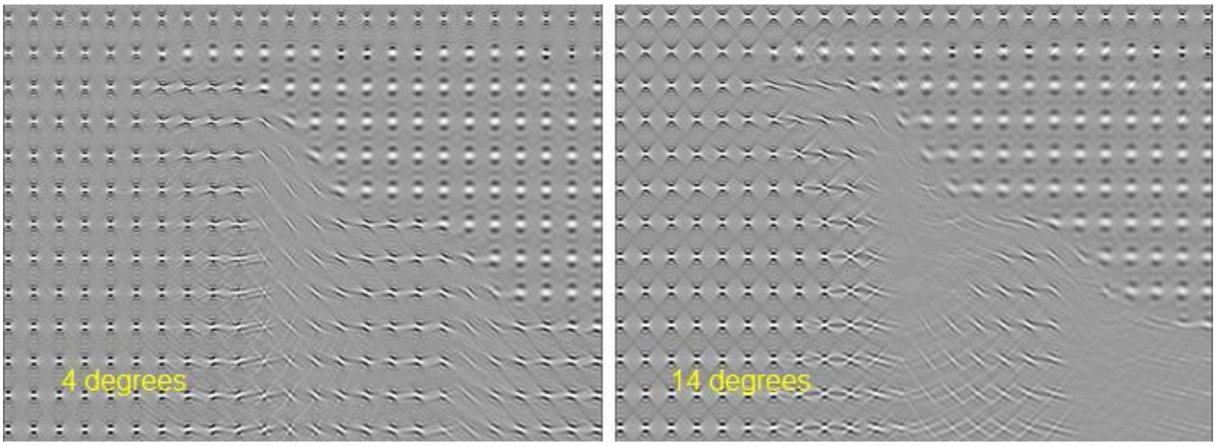

Figure 5. PSFs computed below the Sigsbee synthetic salt model for incidence angle of 4° (left) vs. 14° (right).

Recent applications of LSM with FWM have produced data suitable for geohazard assessment on conventionally-acquired OBS (and deep tow multisensor streamer) data, mitigating the additional time, expenditure, and environmental impact associated with performing this kind of analysis using site survey acquisition and processing Improvements in shallow spatial resolution at depths where conventional (primaries-only) PSDM is corrupted by acquisition footprint effectslargely derives from the complementary illumination provided by all orders of surface multiples. At larger depths the improvements in reflectivity and spatial resolution commonly observed (notably the sharper focusing of fault truncations) derives from the benefits of LSM.

The ability of LSM to compensate for deficiencies in acquisition geometry can also be exploited (within limits) to achieve quite different ambitions:

- Compensate for different acquisition geometries and/or shooting directions in time-lapse (4D) reservoir monitoring (e.g. Lecerf and Besselievre, 2018; Lecerf, 2019). Figure 2 is also relevant.
- Deliberately reduce the acquisition effort and cost without unacceptably compromising the migrated image quality and resolution (e.g. van der Burg et al., 2018).

What's Next

In the next article, I will consider one of the most prominent themes at this year's SEG conference: 'Sparse Nodes'. As the cost of densely-sampled Ocean Bottom Node (OBN) acquisition remains prohibitively expensive to the widespread adoption of the methodology, the rhetorical question is being asked whether 'sparse' OBN deployment is acceptable for various survey ambitions. LSM may be a valid solution to augment the value of OBN surveys with larger separation that may otherwise be geophysically acceptable…

Additional Reading Material

- Arasanipalai, S., Lebit, H., Ollagnon, P., Virlouvet, B., and Tilton, J., 2019, Enhanced presalt imaging using iterative least-squares migration: A case study in Santos Basin, Brazil. SEG Expanded Abstracts, 4216-4220. https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/pgs_arasanipalai_etal_seg2019_presalt-lsm-brazil.pdf
- Korsmo, Ø, Arasanipalai, S., and Greplowski, Z., 2019, Application of iterative least-squares migration in different geological settings. EAGE Extended Abstracts, We_R04_11. https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/eage2019_korsmo_etal_lsm_casestudies.pdf
- Lecerf, D., and Besselievre, M., 2018, A new approach to compensate for illumination differences in 4D surveys with different individual acquisition geometries. First Break, 36(2), 71-77. https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/fb_lecerf_etal_feb2018_4dsynthetic.pdf
- Lu, S., Liu, F., Chemingui, N., Valenciano, A., and Long, A., 2018, Least-squares full-wavefield migration. The Leading Edge, 37(1), 46-51. https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/tle_lu_et_al_jan2018_ls-fwm.pdf
- Valenciano, A.A., Orlovich, M., Klochikhina, E., and Chemingui, N., 2019, Least-squares migration with gathers. SEG Expanded Abstracts, 4206-4210. https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/pgs_valenciano_etal_seg2019_lsm-gathers.pdf
- van der Burg, D., Martin, T., Asnaashari, A., Perrier, S., Fasterling, J., and Musser, J., 2018, Separated Wavefield Imaging for ocean bottom surveys – Feasibility study of receiver decimation on a North Sea dataset. EAGE Extended Abstracts, Tu A10 11. https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/eage2018_pgs-maersk_vanderberg_etal_june2018_swim-obn-decimation.pdf