Optimal resolution seismic tomography with error tracking: imaging the upper mantle beneath Ireland and Britain

Raffaele Bonadio[1], Sergei Lebedev[1], Thomas Meier[2], Pierre Arroucau[3], Andrew Schaeffer[4], Andrea Licciardi[5], Matthew Agius[6], Clare Horan[1], Louise Collins[1], Brian O'Reilly[1], Peter Readman[1], and the Ireland Array Working Group[1]

[1]Dublin Institute for Advanced Studies, School of Cosmic Physics, Dublin, Ireland (raffaelebonadio@gmail.com)

[2]Christian-Albrechts-Universität zu Kiel, Inst. for Geosciences, Kiel, Germany

[3]EDF-DIPNN-DI-TEGG, Aix-en-Provence, France

[4]Geological Survey of Canada, Sidney, Canada

[5]Université Côte d'Azur, Geoazur, Sophia Antipolis, France

[6]Dipartimento di Scienze, Università Roma Tre, Roma, Italy.

Spatial resolution, as the ability to distinguish different features that are close together, is a fundamental concept in seismic tomography and other imaging fields. In contrast with microscopy or telescopy, seismic tomography's images are computed, and their resolution has a complex, non-linear dependence on the data sampling and errors. Linear inverse theory provides a useful resolution-analysis approach, defining resolution in terms of the closeness of the resolution matrix to the identity matrix. This definition is similar to the universal, multi-disciplinary one in some contexts but diverges from it markedly in others. In this work, we adopt the universal definition of resolution (the minimum distance at which two spike anomalies can be resolved). The highest achievable resolution of a tomographic model then varies spatially and depends on the data sampling and errors in the data. We show that the propagation of systematic errors is resistant to data redundancy and results in models dominated by noise if the target resolution is too high. This forces one to look for smoother models and effectively limits the resolution. Here, we develop a surface-wave tomography method that finds optimal lateral resolution at every point by means of error tracking.

We first measure interstation phase velocities at simultaneously recording station pairs and compute phase-velocity maps at densely, logarithmically spaced periods. Multiple versions of the maps with varying smoothness are computed, ranging from very rough to very smooth. Phase-velocity curves extracted from the maps at every point are then inverted for shear-velocity (V_S) profiles. As we show, errors in these phase-velocity curves increase nearly monotonically with the map roughness. Very smooth V_S models computed from very smooth phase-velocity maps will be the most accurate, but at a cost of a loss of most structural information. At the other extreme, models that are too rough will be dominated by noise. We define the optimal resolution at a point such that the error of the local phase-velocity curve is below an empirical threshold. The error is estimated by isolating the roughness of the phase-velocity curve that cannot be explained by any Earth structure.

A 3D V_S model is then computed by the inversion of the phase-velocity maps with the optimal resolution at every point. The estimated optimal resolution shows smooth lateral variations, confirming the robustness of the procedure. Importantly, optimal resolution does not scale with the density of the data coverage: some of the best-sampled locations require relatively low lateral resolution, probably due to systematic errors in the data.

We apply the method to image the lithosphere and underlying mantle beneath Ireland and Britain, using 11238 newly measured, broadband, inter-station dispersion curves. The lateral resolution of the 3D model is computed explicitly and varies from 39 km in central Ireland to over 800 km at the region boundaries, where the data coverage declines. Our tomography reveals pronounced, previously unknown variations in the lithospheric thickness beneath the region, with implications for the Caledonian assembly of the islands' landmass and the mechanism of the magmatism of the British Tertiary Igneous Province.