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# Effect of bandwidth on seismic imaging of rotating stratified turbulence surrounding an anticyclonic eddy from field data and numerical simulations

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**Abstract:**

The fine resolution of long geoseismic sections should permit the characterization of oceanic turbulence properties over several decades of horizontal scales. The range of horizontal scales actually probed by three different acoustic sources is found to be directly linked to their frequency content. The horizontal inertial range with a spectral slope of $k_h^{-5/3}$ extend up to 3 km wavelength for the most intense acoustic reflectors which surround strong anticyclonic eddies. The in situ data analysis is confirmed by high resolution numerical simulations of oceanic anticyclonic vortices, in a rotating temperature-stratified fluid (no salt), which show the spontaneous emergence of a concentration of acoustic reflectors above and below the eddy. These show an anisotropy and a spectral slope consistent with the framework of stratified turbulence, which differs from that of Garret and Munk for internal waves. The implications are that a direct energy cascade to smaller spatial scales is occurring at the boundaries of energetic oceanic vortices and may provide a mechanism to drive mixing in the ocean interior.

## 1. Introduction

An interesting outcome of the GO (Geophysical Oceanography) experiment [*Hobbs*, 2007] is its successful survey of energetic, long-lived anticyclonic lens-shaped vortices in the Gulf of Cadiz, known as Meddies. They are particularly abundant in the Mediterranean water outflow in the 700-1500 m depth range [*Armi et al.*, 1989]. Such vortices are responsible for a large part of the saltier Mediterranean Water tongue in the North Atlantic and play an essential role for momentum, heat and tracer transport at those depths. In all available seismic observations, the boundaries of Meddies are marked by a concentration of acoustic reflectors, vertically-stacked, with a typical vertical lengthscale of 20-40 m and typical horizontal scales of several tens of kilometers [see detailed review of possible mechanisms in *Biescas et al.*, 2008]. The unprecedented horizontal spatial sampling provided by seismic oceanography invites probing into the nature of the fundamental processes on the route to dissipation and mixing that may occur near strongly energetic vortices such as Meddies. It should permit to characterize the properties of oceanic turbulence over several decades of spatial scales, especially in the horizontal direction.

Evidence of horizontal inertial range spectral behavior of $k_h^{-5/3}$, where $k_h$ is the horizontal wavenumber, from direct ocean observations are available. Among the most recent ones, *Holbrook and Fer* [2005] report geoseismic remote sensing of the internal wave field in both the open ocean and near the continental rise and note a propensity for a $k_h^{-5/3}$ behavior for the spectra of the reflector displacement as the more energetic region of the continental slope is approached. Likewise, in the remote sensing of the internal wave-field off the Iberian peninsula by *Krahmann et al.* [2008], there is a better fit, for the more energetic regions, to $k_h^{-5/3}$ for horizontal wavelengths between 200 m and 1.6 km than to $k_h^{-2}$ characteristic of the Garrett-Munk internal wave spectrum (their Figure 6). Isopycnal displacement spectra near the Hawaian ridge have been collected using a horizontally towed vehicle MARLIN by *Klymak and Moum* [2007] who noted a transition between turbulent regimes. The turbulence inertial-convective subrange corresponding to a -5/3 power law in horizontal energy spectra extends to surprisingly large scales ($>$ 500 m), when compared to the Ozmidov length beyond which the -5/3 power law associated with 3D isotropic Kolmogorov turbulence is expected.

Presently, the interpretation of spectral slopes as due to stratified turbulence versus random internal waves is still under debate. The framework of "stratified turbulence" describing the dynamics of quasi-horizontal, meandering motions dominated by stable density stratification offer a complementary/alternative interpretation to internal waves for such observations of $k_h^{-5/3}$, as elaborated by *Riley and Lindborg* [2008]. The most recent numerical simulations [reviewed in *Brethouwer et al.*, 2007] as well as scaling arguments [*Billant and Chomaz*, 2001] have clearly established that a strong downscale transfer of energy exists in the horizontal and, along with this, that the development of a horizontal spectral inertial range can occur. A salient result is that the spectra of kinetic and potential energy display a $k_h^{-5/3}$ power-law behaviour.

A generic feature of stratified turbulence being the presence of quasi-horizontal layers, it is tempting to relate such patterns to the concentrated "layering" revealed by seismic oceanography immediately above and below Meddies. However, the "stratified turbulence" paradigm neglects all rotation effects and the reflectors revealed by seismic oceanography have a long horizontal extension, exceeding tens of kilometers, which is into the range of "balanced" scales of motion. –The balanced motions are described by an approximated set of equations which truncates the horizontal divergence equation –. This begs the question of assessing what is the upper limit of the horizontal inertial range spectral behavior in $k_h^{-5/3}$ in the GO data set? [*Molemaker et al.*, 2009, provide evidence of an extension of the $k_h^{-5/3}$ range to larger, balanced scales that are influenced by rotation, but for flows without quasi-horizontal layers.] Can the layering phenomena be reproduced in direct numerical simulations? Does its formation involve the slow balanced dynamics characterized by the total vorticity component perpendicular to isopycnal surfaces (Potential Vorticity or PV)? Or does the fast dynamics of high frequency unbalanced internal waves come into play [*Riley and Lelong*, 2000]?

## 2. Data

The GO-project acquired a combined seismic and physical oceanography dataset which repeatly crossed a Meddy. Two of the profiles are used in this paper, GO-LR-13 and GO-MR-05 [Fig.1 and Fig.1 of *Krahmann et al.*, 2009]. For GO-LR-13, the 6-airgun source (total volume of 2320 cu in) was towed at a nominal depth of 10 m and the 2.4 km long hydrophone receiver array was towed at 8 m. For GO-MR-05, we used a novel dual source array to provide simultaneous seismic images of the Meddy over two bandwidths. The first 3-airgun 1160 cu in source (Flop) was towed at a nominal depth of 10 m and the second 3-airgun 540 cu in source (Flip) was towed at a nominal depth of 5 m, for both sources the 2.4 km long hydrophone receiver array was towed at 5 m. The frequency of the Flop source is comparable to the original low-frequency GO-LR-13 source with a bandwidth of 5-60 Hz (insert Fig.1(b) and Fig.1(a)), though the amplitude of the Flop source is less as it only used three as opposed to six airguns. The Flip source has a bandwidth of 10-100 Hz (insert Fig.1(c)) and its amplitude is less again because the energy is spread over a wider bandwidth by using a smaller airgun volume and towing less deep which makes the source acoustically less efficient. The main processing steps for the seismic data focused on removing the strong energetic direct wave, preserving signal amplitudes and correcting source and receiver directivity. The processed data were then migrated, a seismic processing tool for geometric repositioning, using a true amplitude 3D time migration algorithm. Figure 1 only reproduces the portion of the water column lying in the 500-1200 m range and shows the presence of stacked reflectors immediately above the lens core.

## 3. Model

Direct numerical simulations at resolution up to $1000^3$ grid points have been performed with the Boussinesq, non hydrostatic code of *Aiki et al.* [2006], which has been tailored to accommodate the massively parallel, vectorial architecture of the Earth Simulator. The anisotropic grid is 100 m in the horizontal and 3 m in the vertical directions. A wide range of numerical simulations has been performed to address the free evolution of anticyclonic eddies whose spatial characteristics are close to those observed during the GO cruise (lenses with an inner solid body rotation core of 20-25 km radius, maximal azimutal velocity ranging from 12 to 25 cm/s, height of 400-600 m), which are initialized in cyclogeostrophic balance and for Rossby number ranging from 0.2 to 0.6. Background rotation correspond to a constant $f$-plane, whose inertial period is about 20 hours, typical of the Gulf of Cadiz. We stress that, in all our simulations, the density field variations are assumed to depend on temperature variations alone and to a constant background stratification of $N = 3.3 \cdot 10^{-3}$ s$^{-1}$. No salinity effects are taken into account, so that there is an a priori assumption that prevents double-diffusion and other thermohaline mechanisms. We test the possibility of an energy cascade due to a spontaneous loss of balance of the anticyclonic lens which could involve, as in *Plougonven et al.* [2005], an instability that couples balanced modes and unbalanced waves. [1] In all the simulations we observe the spontaneous evolution of step-like distributions in the initially vertically smooth PV distribution (Fig.2) which occurs between two to four weeks of evolution depending on the strength of the eddy. Such modifications are characterized by slow dynamics and cannot be attributed to fast internal gravity waves *alone* since they do not carry PV [*Riley and Lelong*, 2000].

The corresponding distribution of acoustic reflectivity, induced by vertical variations of the acoustic impedance –which is defined as the product of the fluid density and sound-speed and largely controlled by temperature anomalies–, is plotted in Figure 3(a). One can observe that the vertical derivative of temperature signal shapes the PV field. The convolution of acoustic reflectivity by the Flop and Flip source wavelets yields patterns shown in Figures 3(b) and 3(c) respectively. Both sources image the induced layering though the higher frequency Flip source reveals finer vertical layers (especially in the eddy interior). Moreover, the Flip source also shows a slightly shorter horizontal extension to the reflectors.

## 4. Analysis Method

To probe for the possible existence of the inertial range in the data, our analysis uses second order structure function $S(r)$ (where $r$ is horizontal lag) rather than classical spectral analysis. [2] Since $S(r)$ is in Fourier duality with the power spectrum, if there is a power law in spectrum, $E(k_h) \propto k_h^{-n}$, with $1 < n < 3$, then $S(r) \propto r^{n-1}$. In the present case, a -5/3 (or -2) power law in spectra will correspond to a +2/3 (or +1) power law in structure function.

## 5. Horizontal Inertial Ranges in $k_h^{-5/3}$

We have analysed the GO seismic oceanography data in terms of their second order structure function (Fig.4). Calculations are binned inside horizontal 12 km long boxes, centered on the most intense acoustic reflectors above the Meddy.

The three sections from Figure 1 (GO-LR-13, and GO-MR-05-Flop and -Flip) display a range of horizontal scales with parts of the structure functions scaling close to a 2/3 power law which corresponds to a spectral inertial range in $k_h^{-5/3}$. There is a constant power law over nearly a decade in all three sections, with a 2/3 coefficient for all cases when taking into account error bars. Furthermore, an assessment of the convolution of a known, synthetic dataset by the different sources shows that it induces a decrease of the slope in the structure functions of 0.06 for Flip, 0.02 for Flop and 0.01 for LR. The inertial range found for Flip corresponds to smaller horizontal scales than Flop by 25%: this moderate shift to smaller scales can be attributed to the higher frequency content of Flip. Our evidence is based on reflectivity field which is dominated by the vertical gradient of temperature whereas the theoretical framework of stratified turbulence predicts a -

5/3 power law for potential energy spectrum. Since in simulations both the temperature anomalies and their vertical gradient display horizontal inertial ranges in $k_h^{-5/3}$ for roughly the same range of horizontal scales, it is plausible that observed power laws are consistent with stratified turbulence. This result needs to be rationalized in further studies.

## 6. Discussion

The regions where the $k_h^{-5/3}$ inertial range is observed coincide with the high concentrations of the most intense acoustic reflectors immediately above and below the anticyclonic lenses. The nonuniform distribution of the reflectors is a signature of strong spatial intermittency. The horizontal scales which are concerned lie in the range of 300 m to 2.8 km for the present acoustic sources and are impacted by the bandwidth of seismic sources. As *Klymak and Moum* [2007], we find a -5/3 power law horizontal inertial range which also extends to quite large horizontal wavelength. Actually, the detailed energy diagnostics of the numerical simulations (not shown) reveal that the upper bound of this -5/3 power law inertial range can be even larger than 3 km and depends on the flow parameters, in particular the strength of the anticyclonic lens. A down-scale potential and kinetic energy transfer to small horizontal scales at the depths coinciding with the concentration of strong acoustic reflectors has been diagnosed. Such results could be interpreted as the manifestation of an instability route to dissipation for the ocean interior away from boundaries [see *Molemaker et al.*, 2009]. Finally, instabilities which occur leads to turbulence with a strong signature in the potential vorticity field, thus involving nonlinear mechanisms other than free internal waves which leave no trace on potential vorticity.

We conclude that seismic oceanography is a significant tool to improve our understanding of the transition in geophysical turbulence regimes between the tens of kilometers scale balanced motions and the intermediate scales that are involved in the route to dissipation and mixing. However, the present analysis shows that the frequency content of acoustic sources has a direct influence on the extension of horizontal inertial range that is actually sampled, e.g. smaller horizontal scales are kept for the Flip source and larger horizontal scales for the Flop source.

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## Notes

1. See additional material for more information.

2. See additional material for further explanations.

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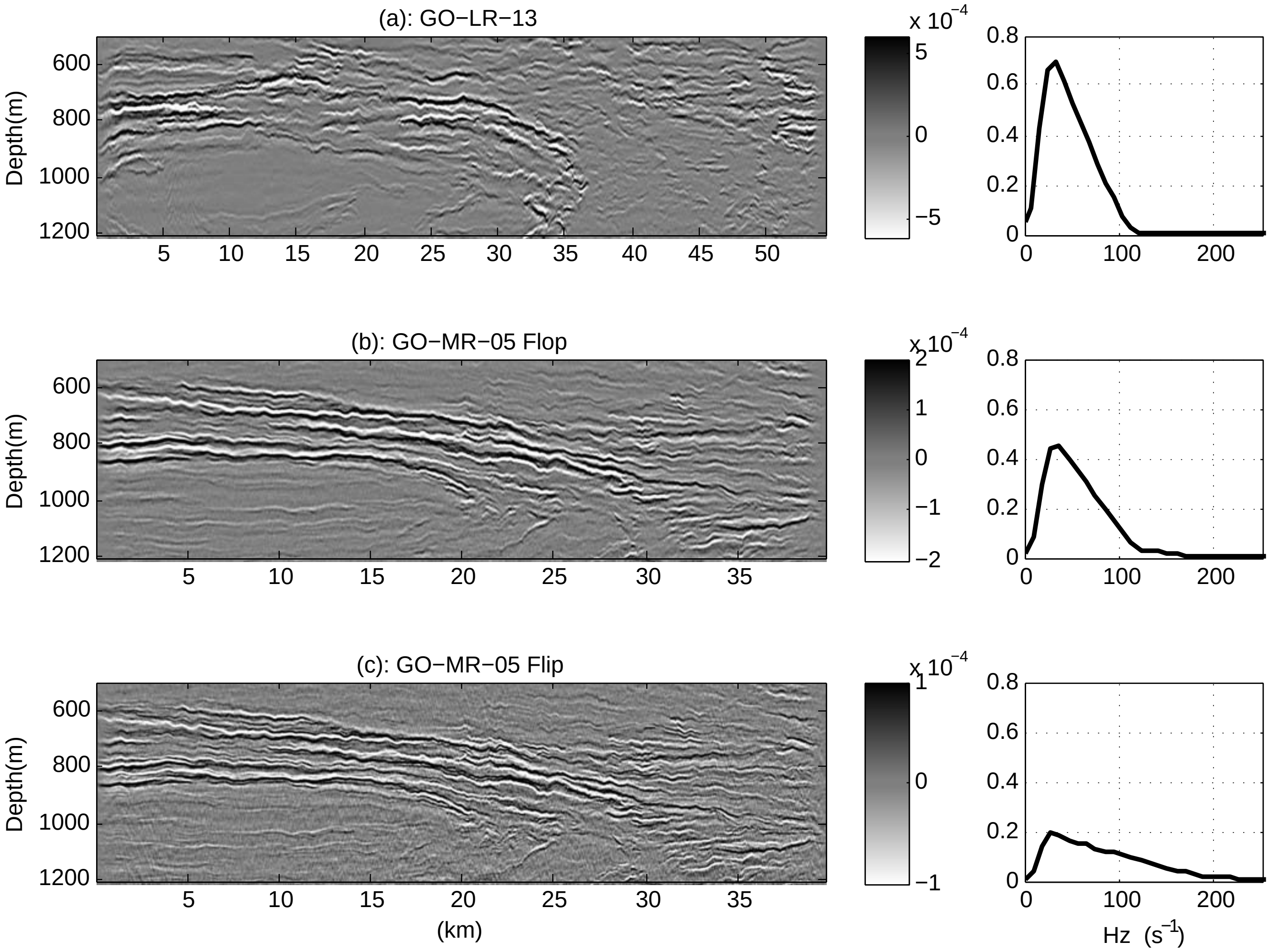


**Figure 1.** Seismic sections of reflexion coefficients (unitless) convolved with: **(a)** LR-13, **(b)** Flop **(c)** Flip, with the source wavelet spectrum (right) indicating the approximate relative amplitude of the different air gun sources.

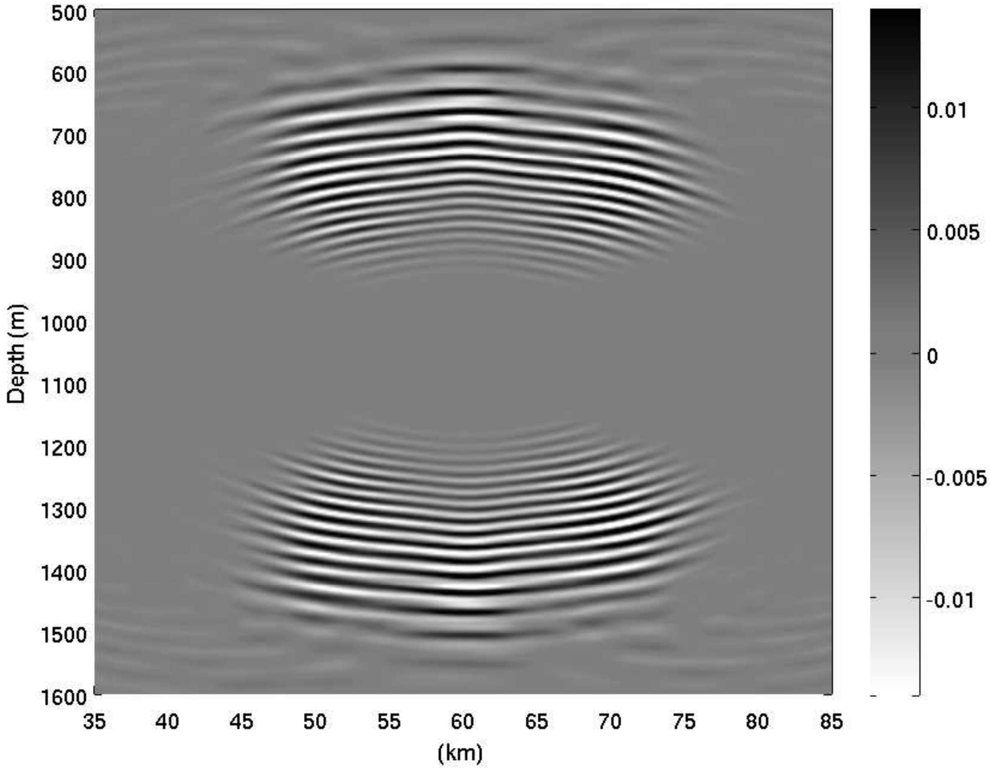


**Figure 2.** Numerical simulations of an anticyclonic eddy with maximal azimuthal velocity of 1 cm/s and a solid body rotation core radius of 20 km: potential vorticity field across the eddy center.

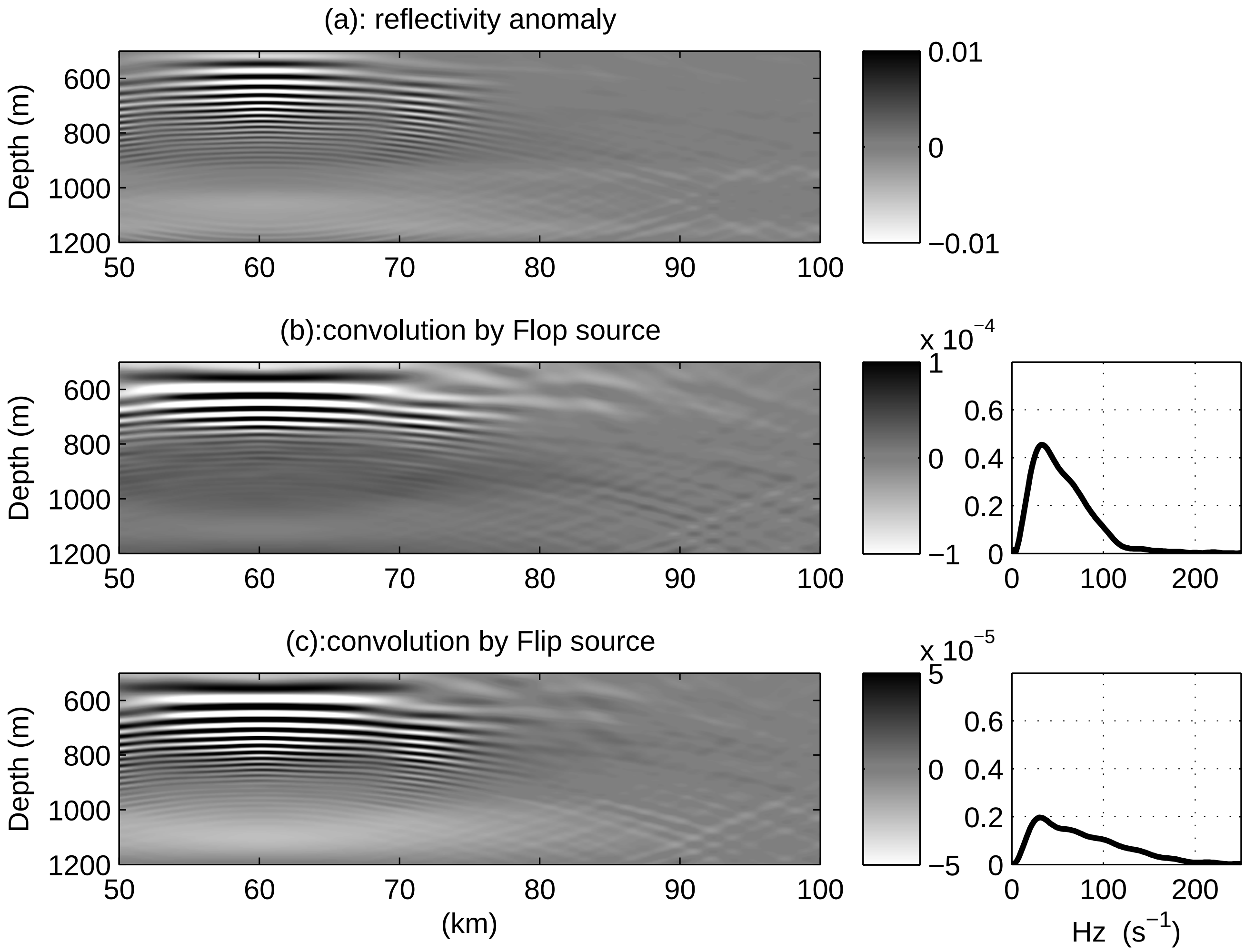


**Figure 3.** Numerical simulations of an anticyclonic eddy with maximal azimuthal velocity of 21 cm/s and a solid body rotation core radius of 20 km: **(a)** Reflectivity anomaly, **(b)** Reflectivity convoluted by Flop wavelet **(c)** Reflectivity convoluted by Flip wavelet, with on the right the spectrum of the corresponding source wavelet.

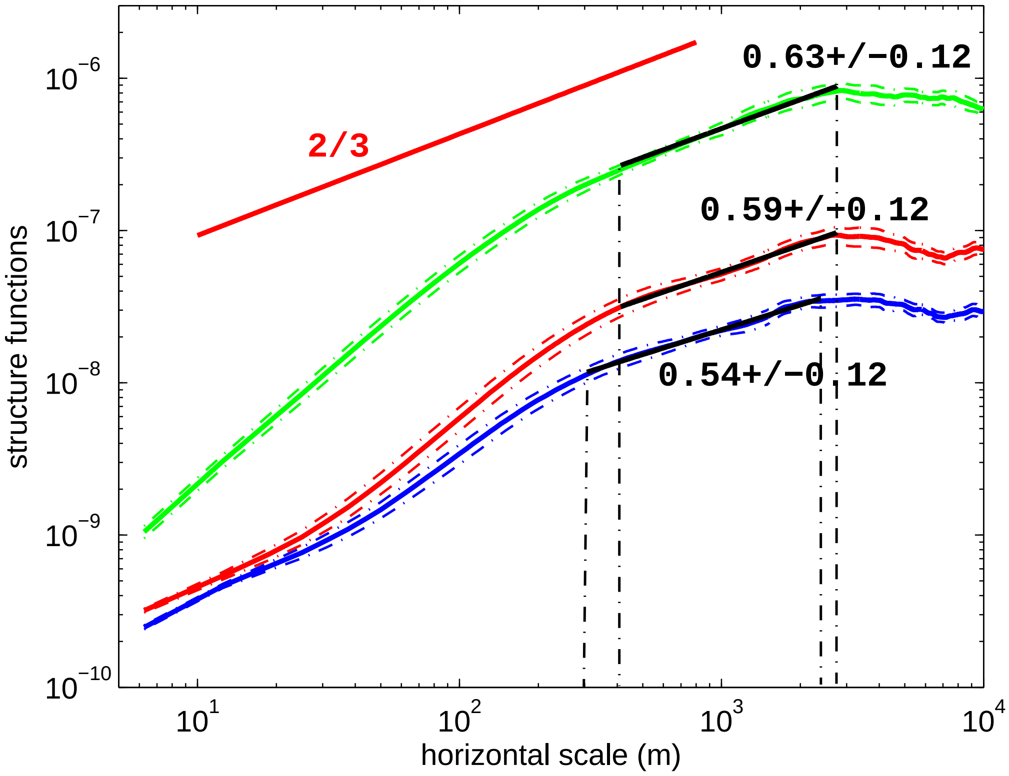


**Figure 4.** Second order structure functions for the different geoseismic sections of Figure 1 (green: LR-13, red: Flop, blue: Flip), with standard deviation in colored dash lines. Black lines are best power law fits whose exponent is to be compared with 2/3. For all three cases, the +2/3 power law lies within the error bars of the structure functions. The difference in magnitude between the three different curves is due to differences in the intensity of the air gun sources.