

Higher modes in the near surface: the influence of gradients

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Abstract Higher modes of surface waves are more sensitive to the details of the wavespeed distribution with depth than the fundamental modes, and in particular to the wavespeed gradients within layers and the transition between layers. The character and dispersion of the various modal branches are readily envisaged with the aid of calculations of frequency–phase speed spectra for surface sources. Colour-coding of the three-component response is helpful in assessing the nature of the modes and the way that they interact with recording systems. The near-surface can have very variable wavespeed gradients, from slight in the presence of recent sediments to quite strong under compaction. In the presence of gradients the dispersion properties of higher modes are not well represented by models with just a few uniform layers even though this may be adequate for the fundamental mode. Where gradients are expected, direct parametrisation is beneficial, even if implemented with sequences of uniform layers.

Non-technical summary The immediate near surface zone frequently contains gradients in seismic wavespeed associated with sediment accumulation and compaction. Such gradients have a strong influence on the character of higher modes of seismic surface waves that are increasingly revealed as the density of seismic observations improves. The behaviour of these higher modes as a function of frequency and propagation speed provides strong clues as to the character of the wavespeed distribution with depth.

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1 Introduction

Surface waves are well excited by shallow seismic sources, and their dispersion properties provide a convenient tool for characterising the structure of the near-surface. Most work has concentrated on the properties of the fundamental modes, but it has long been recognised that the higher surface wave modes provide additional constraints on structural properties, if they can be observed (e.g., [Nolet and Panza, 1976](#)).

As observation systems have become denser the opportunities for extracting higher modes have improved for both passive deployments (e.g., [Ma et al., 2016](#)) and active-source experiments (e.g., [Guo et al., 2023](#)). Correlation methods have been particularly effective for isolating fundamental-mode dispersion at high frequencies from dense deployments, with well developed procedures for analysing ambient noise (e.g., [Jiang and Denolle, 2020](#)). In favourable circumstances, higher-mode dispersion can also be extracted (e.g., [Nayak and Thurber, 2020](#); [Takagi and Nishida, 2022](#); [Xie et al., 2025](#)). The advent of distributed acoustic sensing (DAS) with very high spatial sampling has opened the way for more consistent observations of higher modes and the potential for enhanced structural analysis (e.g., [Yang et al., 2024](#)).

Certain classes of environment have proved to be very rich in higher mode energy. On ice sheets, the sur-

face firn layer where snow steadily compacts to form ice at depth has strong gradients, and surface sources have produced very clear observations of higher-mode Rayleigh waves with networks of instruments ([Chaput et al., 2022](#)) and DAS cables ([Fichtner et al., 2023](#); [Yang et al., 2024](#)).

The near surface is a highly variable geological environment. The variations in modal dispersion across a network of stations or DAS cable can therefore provide a means of mapping different classes of structure. Such classification can be significantly enhanced when higher-mode dispersion is taken into account. For example, the study of [Lai et al. \(2024\)](#) not only demonstrates substantial variation along an approximately 20-km-long profile from inversion of fundamental-mode dispersion, but also presents full observed modal dispersion spectra that reinforce the contrasts between different locations.

The shape of the modal dispersion curves as a function of frequency and phase velocity provide strong constraints on the distribution of shear wavespeed, with weaker dependence on P-wave speed and density. For inversion of dispersion information, often models comprising a few uniform layers have been employed even where the actual number of layers is allowed to be an inversion parameter (e.g., [Hallo et al., 2021](#); [Magrini et al., 2025](#)). Effective inversion including higher modes requires correct identification of the modal branches, which is itself a function of structure.

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Although simplified models can be effective, the near-surface zone frequently contains strong gradients, and the nature of modal dispersion depends strongly on the character of such gradients. Aspects of higher-mode dispersion can be helpful in disentangling the nature of the wavespeed variation with depth for structures that have similar fundamental-mode dispersion.

The complication of working with higher modes at close distances from a source is that the arrivals from different modes overlap in time and do not have the class of distinct arrival associated with the Airy phase of the fundamental Rayleigh wave. The higher modes can also be viewed as arising from constructive interference of multiple reflections from the subsurface (e.g., Kennett, 1983). Their frequencies relate to the delay times for S-wave passage that have a strong dependence on the depth profile. As a result, the higher-mode spectrum shows a strong sensitivity to the presence of gradients in wavespeed and the contrasts at interfaces. For the same frequency, the higher modes penetrate deeper than the fundamental mode. But, for the same phase speed, the depth zone sampled is comparable across the modes.

For a perfectly elastic medium varying in depth, the dispersion of seismic surface waves can be calculated working directly with the solution of a suite of differential equations in depth, as developed by Takeuchi and Saito (1972). A separate solution is needed for each frequency and mode. But, with care, the full suite of modal dispersion can be extracted for models with arbitrary gradients and then be employed in inversion for structure with depth. This approach has been combined with Backus-Gilbert inversion by Kaplunov et al. (2025) to investigate multi-mode inversion for both the shear wavespeed and density profiles in a strong-gradient scenario on the Greenland Ice Sheet.

Here I use the approach of Kennett (2023), working directly with the seismic response at the surface in frequency–phase speed space. This produces the full modal response for Rayleigh and Love waves, including leaking modes and also an indication of the relative excitation of the different components of the wavefield. The seismic response is evaluated using many uniform layers, which forces a discretisation of smoothly varying gradient zones.

I first consider the way in which multi-modal dispersion varies with the character of the wavespeed gradient across a single layer and its dependence on layer thickness. I then look at the way in which near-surface properties modulate the multi-mode dispersion response in a scenario with a common structure at depth.

The principal tool used is the seismic response in the frequency–phase speed domain that allows the capture of all mode branches. As in Kennett (2023), the three-component response for a surface source is evaluated on a grid with even sampling in frequency and phase speed. With colour-coding of the components, the relative excitation of modal branches can be clearly displayed.

In this study, gradients are simulated using fine sampling with thin uniform layers. This choice allows an investigation of the extent to which a complex gradient structure can be represented by a limited number of

uniform layers, without significant modification of the dispersion structure.

A further important aspect of utilising multi-mode dispersion is the influence of the recording system and the way that this interacts with the components of the wavefield. Certain portions of higher-mode branches can be much stronger on one component than another and so, depending on the recording system, may be well represented or almost absent from the recorded dispersion behaviour.

2 Effect of different styles of gradients

The near-surface is a zone of high variability depending on the geological conditions. Fresh sediments have weak vertical gradient, whereas weathering and compaction tend to produce gradient regimes that are strong at the surface but then reduce with depth.

As an illustration of the way that the wavespeed gradient influences multi-mode dispersion, I consider a transition from shear wavespeed β_0 to β_1 across a single layer parametrised in terms of normalised depth z/h where h is the layer thickness. A sequence of S wavespeed profiles of the form

$$\beta(z) = \beta_0 + (\beta_1 - \beta_0) \left(\frac{z}{h}\right)^\gamma, \quad (1)$$

$$\gamma = 0.25, 0.5, 1.0, 2.0, 4.0$$

are accompanied by a single first-order jump from β_0 to β_1 . In each case, a constant v_p/v_s ratio of 1.74 has been used to produce an equivalent P wavespeed distribution $\alpha(z)$, with density constructed from $\rho(z) = 1.0 + 0.2\alpha(z)$ that provides suitable values for the near-surface scenario with unconsolidated materials that are not covered by the Nafe-Drake relation (Brocher, 2005). The density values are a little low for P wavespeeds greater than 1.5 km/s. Surface-wave dispersion is dominantly controlled by the S-wavespeed distribution $\beta(z)$, and so the form of the accompanying densities makes negligible difference to the response spectra.

In Figure 1, I consider the case with $\beta_0 = 0.444$ km/s, $\beta_1 = 0.888$ km/s, and a layer thickness h of 40 m. Each of the gradient models is implemented with 0.5-m uniform layers in the top 2.0 m and 1.0-m thick uniform layers below. Weak attenuation is used (Q_α : 100, Q_β : 50) so that all modes are visible. The response spectrum in frequency–phase speed space is calculated for a surface S-wave source using the approach of Kennett (2023). The spectra are displayed in Figure 2 using a 200×200 sampling matrix with the three components indicated by colour. Green is used for the transverse (SH) component corresponding to Love waves. For Rayleigh waves, the radial component is indicated in blue and the vertical component in red. The depth of colour in each pixel displays the amplitude of the seismic response for that frequency–phase speed combination. The modal curves stand out because of their associated large amplitude. The maximum plotted amplitude for all components is set the same and so the relative excitation of the modal branches can be assessed by the apparent width of the mode branch in the plot. The relative balance of the radial and vertical components of the Rayleigh wave

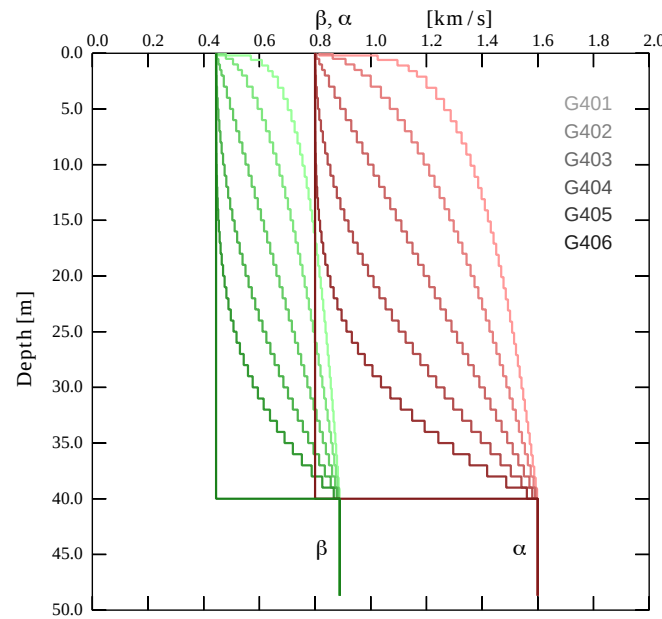


Figure 1 Sequence of P and S wavespeed models constructed using equation (1), with increasing γ : G401: 0.25, G402: 0.5, G403: 1.0, G404: 2.0, G405: 4.0. Model G406 has a simple first-order transition. The density of colour increases with the γ value.

changes the apparent colour to purple mixtures reflecting changes in modal ellipticity at the surface.

For the strongest near-surface gradient (model G401), only the fundamental mode is visible in the frequency range up to 40 Hz. As the gradients become more gentle the higher modes become evident so that for the linear gradient model (G403) four higher Rayleigh modes can be seen, though the first higher mode is poorly excited for phase speeds below 0.8 km/s. As the wavespeed gradient reduces further and the contrasts at the base of the layer are enhanced, osculation points develop where the Rayleigh mode branches start to approach each other. This pattern is most distinct for the scenario with a first-order jump in wavespeed, but is also noticeable for model G405. The fundamental Rayleigh mode is well expressed on both the radial and vertical components, but the first higher mode only acquires strong vertical character once the phase speed exceeds the P wavespeed at the surface (0.80 km/s).

For a continuous wavespeed profile the spacing of the modal branches for Love waves at each phase speed is inversely proportional to the corresponding SH delay time τ_{SH} for the wavespeed model at that phase speed (Kennett, 1983). As a result, when the layer thickness is varied similar features emerge in the dispersion behaviour at higher frequencies for a thinner layer. The situation is more complicated for Rayleigh waves because of P-SV wave coupling, but comparable behaviour is seen in the zone where P waves are strongly evanescent (up to 0.7 km/s). As demonstrated by Kennett and Clarke (1983), in this regime the dispersion properties of higher-mode Rayleigh waves can be expressed in a very similar way to that for Love modes.

In Figure 3, I display three wavespeed profiles for $\gamma = 2.0$ in equation (1) with layer thicknesses of 20, 30 and 40 m. The corresponding dispersion-response spectra

are shown in Figure 4. The shift in the frequency content for comparable features is almost exactly inversely proportional to the layer thickness, and so for both the Love and Rayleigh modes we see a shift to include more mode branches in the frequency window as the layer thickness is increased. The limited number of modal branches for thinner layers means that the recognition of higher-mode dispersion becomes more challenging where reduced near-surface wavespeeds occupy only a thin zone. Indeed, we can see a comparable effect emerging in Figure 2 as the wavespeeds at shallow depth decrease when the exponent γ in equation (1) is increased.

3 Composite zones

So far I have considered a single layer with wavespeed gradients, but a more common scenario is a surficial zone with lowered wavespeeds overlying a basement which itself can contain gradients. In this case we have the scenario of coupled waveguides for surface waves as discussed in Kennett (2023). Individual higher modes alternately partake of the character of the shallow or deep guide leading to strong patterns of osculation (kissing) points where modal branches approach closely.

A set of four wavespeed models are illustrated in Figure 5. Model H200 has constant shear wavespeed of 0.2 km/s in the top 20 m overlying a basement with a steadily increasing wavespeed from 0.5 km/s to 1.7 km/s. The models H201, H202 and H203 have significant wavespeed gradients in the surface layer with a steadily reducing jump in wavespeed into the basement. Once again the gradient models are rendered with thin uniform layers. The dispersion spectra for each of the models are displayed in Figure 6, once again using the

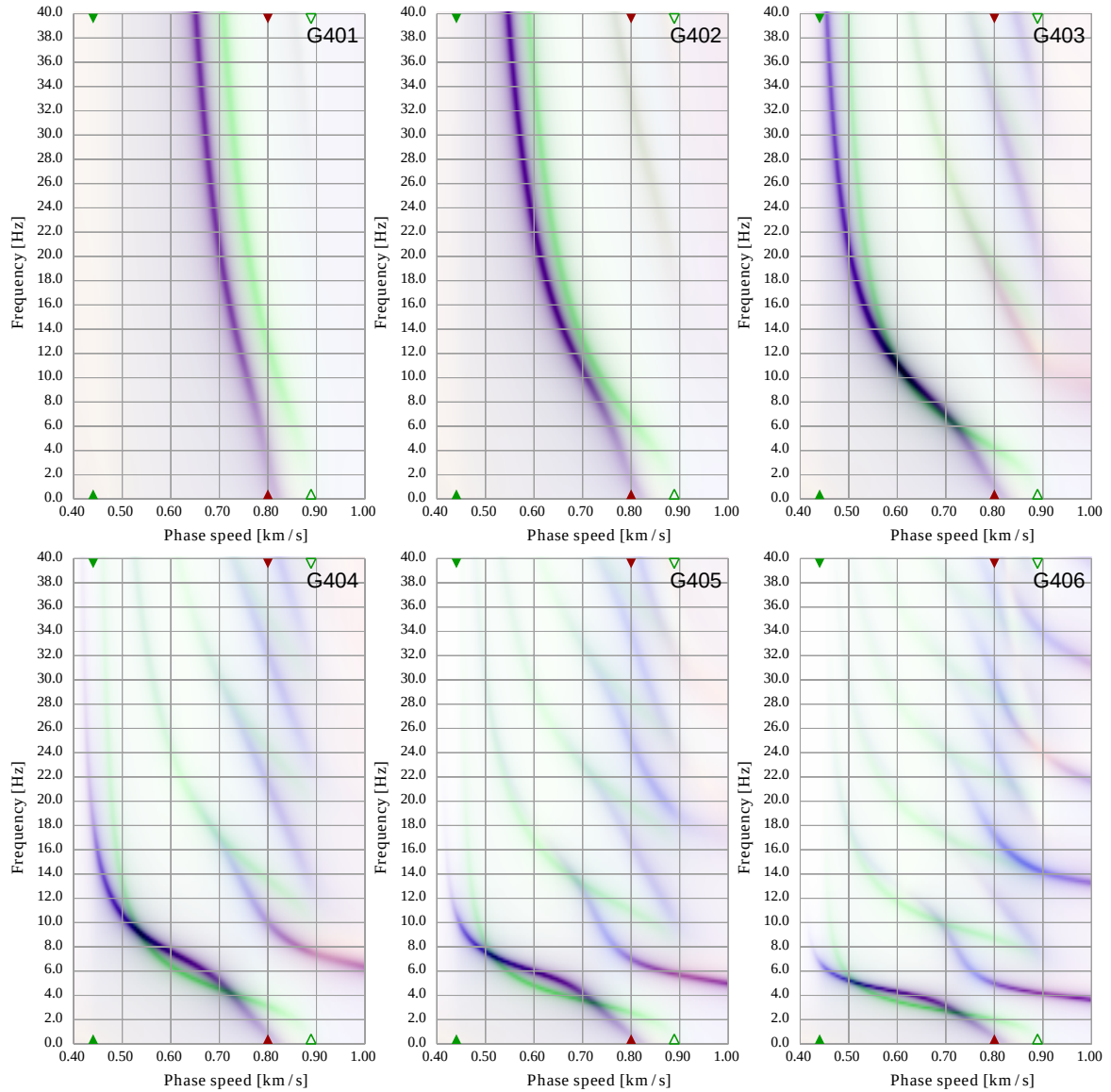


Figure 2 Three component rendering of the surface response in frequency–phase speed for the sequence of models in Figure 1 for a surface S-wave source. The transverse component (Love) is shown in green, with the radial component in blue and vertical component in red for the Rayleigh modes. The maximum plotted amplitude for all components is set the same, and so the relative excitation of the modal branches can be assessed by the apparent width of the mode branch in the plot. The dispersion is the same for the two components of the Rayleigh wave, and so the apparent colour changes with the surface ellipticity. The markers indicate the wavespeeds associated with the different segments of the models (Figure 1) with S structure in green and P in red. The solid symbols mark the wavespeeds at the surface, and the open symbols those at the base.

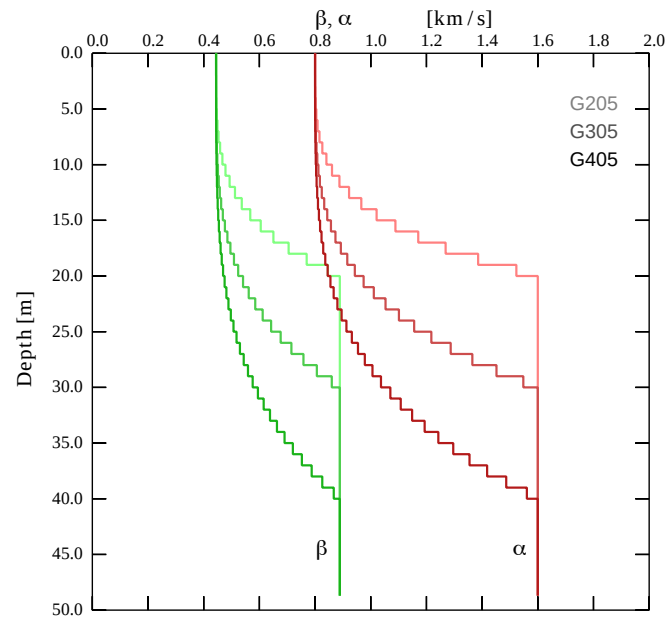


Figure 3 P and S wavespeed models for variable layer thickness (20 m, 30 m, 40 m) constructed from equation (1) with $\gamma = 4.0$. The density of colour increases with the layer thickness.

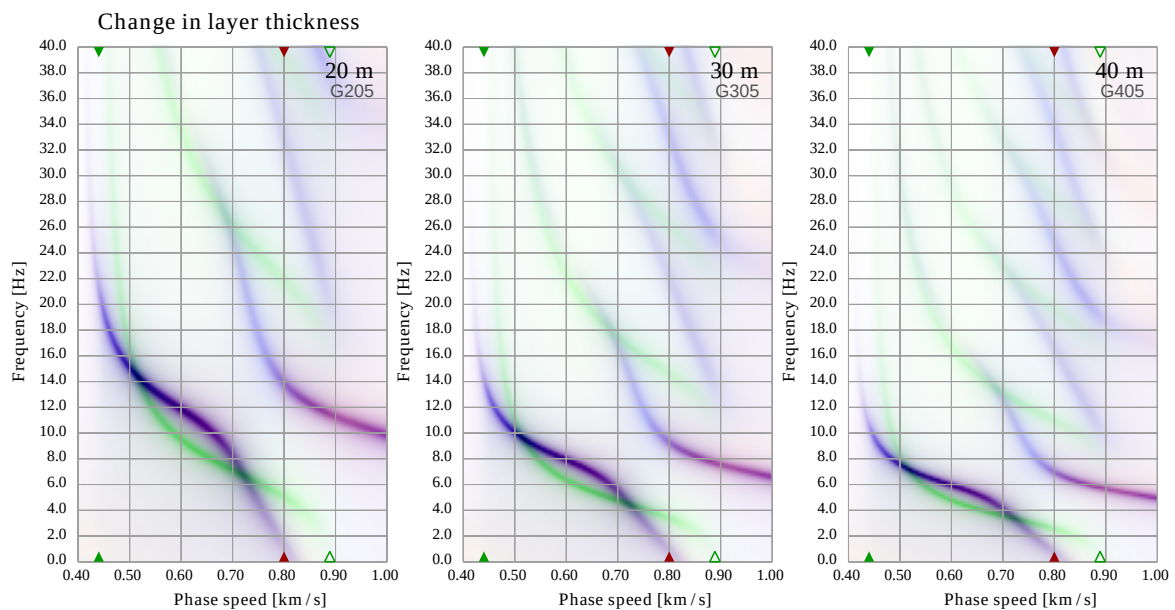


Figure 4 Three-component rendering of the surface response in frequency-phase speed for the sequence of models with variable layer thickness in Figure 3 with a surface S-wave source. The transverse component (Love) is shown in green, with the radial component in blue and vertical component in red for the Rayleigh modes. The maximum plotted amplitude for all components is set the same, and so the relative excitation of the modal branches can be assessed by the apparent width of the mode branch in the plot. The dispersion is the same for the two components of the Rayleigh wave, and so the apparent colour changes with the surface ellipticity. The markers indicate the wavespeeds associated with the different segments of the models (Figure 3) with S structure in green and P in red. The solid symbols mark the wavespeeds at the surface, and the open symbols those at the base.

three colour rendering with Love modes in green, the radial component of the Rayleigh modes in blue and the vertical component in red.

With the lower surface wavespeeds than in the single-layer case, the delay times for S reflections are larger and the modal branches in Figure 6 are shifted to lower frequency than in Figures 2, 4. The presence of the reduced wavespeeds in the surface zone impose a strong

structure on the higher-mode branches. The influence of the shallow waveguide leads to segments with little frequency variation, whereas deeper propagation imposes more rapid variation with frequency.

The strong wavespeed contrasts at the base of the surficial layer in models H200, H201 produce a sharp change in the gradient of alternate mode branches at the phase speed associated with the top of the basement

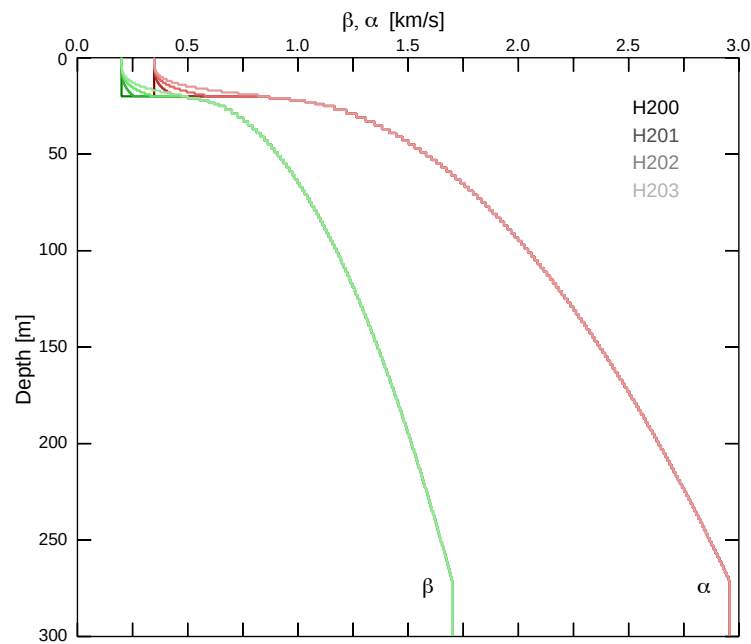


Figure 5 Two layer P- and S-wavespeed models with a 20 m surface layer with low wavespeed overlying a basement with a steadily increasing wavespeed. The contrast at the base of the surface layer steadily reduces from model H200 with a uniform surface layer to H203 that has pronounced gradient, with also a progressively lighter colour for the profiles.

(0.5 km/s). Very little frequency change occurs over the phase speed span up to 1.0 km/s. The steeper branches also tend to show more P-wave character with greater expression on the vertical component. However, we also note that the first higher mode has weak radial motion over a broad span of phase speed (0.5-1.1 km/s) with little frequency dispersion. At higher phase speeds, we see the emergence of a group of P-dominated modes on the vertical component.

In the models H202, H203 with stronger gradients in the top layer and less contrast at the base, the sharp changes in modal slope are reduced. The P-dominated modes also become more distinct, cutting across S-dominated modes because P waves can be trapped for phase speeds less than 1.7 km/s. This means that in addition to the multiple waveguides for S wave propagation we have interaction with P waves as well (see, e.g., Kennett, 2023)

The differences in the character of the modal dispersion depending on the gradient structure in the surface layer offers the potential for discriminating between potential structures in inversion, if sufficient higher modes are observed and correctly identified. Such inversion will require a parameterization of wavespeed flexible enough to provide an effective rendering of gradients.

4 Simplifying structures

In the analysis of the influence of gradients I have used a fine discretization to ensure that the wavespeed profile is well rendered. In the absence of direct knowledge of the actual wavespeed distribution, how far can a structure be simplified without perceptible modification of the dispersion spectrum?

In Figure 7, I illustrate a P- and S-wavespeed profile

G523 with modest gradients in depth represented by 1 m thick layers with a total of 55 layers. This is accompanied by two simplified structures with coarser discretisation. Model G512 with 8 layers is arranged to keep S-wavespeed jumps at the minor layer boundaries below 0.12 km/s, whilst model G511 with 7 layers has larger steps up to 0.2 km/s.

Figure 8 compares the dispersion spectra for G523 and G512. Even though the number of layers has been significantly reduced in G512, the dispersion spectra are very close. Careful inspection reveals slight shifts in the dispersion branches for the fourth Rayleigh higher mode and above, but these almost lie within the width of the trace for the mode.

In contrast, if we compare the dispersion spectra for G512 with G511, as in Figure 9 we see that even a slight reduction in the number of layers with larger inter-layer contrasts has led to clear changes in the modal patterns for both Love and Rayleigh modes. The higher Love modes have shifted to higher frequency, and the osculation point between the third and fourth Rayleigh modes has shifted to smaller phase speed and higher frequency. There are also changes in the inflection of the different modes for model G511 produced by the larger inter-layer jumps in wavespeed, e.g., for the fifth and higher Rayleigh modes for phase speed around 0.6 km/s. The P-dominant mode above 0.8 km/s phase speed has also shifted upwards by more than 2 Hz and changed its shape. There is little difference in the character of the fundamental and first Rayleigh modes, but higher modes are increasingly affected.

In this example with modest gradients it was possible to achieve a substantial reduction in the number of layers employed without changing the character of the modal spectrum. Typically, keeping wavespeed jumps at layer boundaries small (below 0.1 km/s) preserves

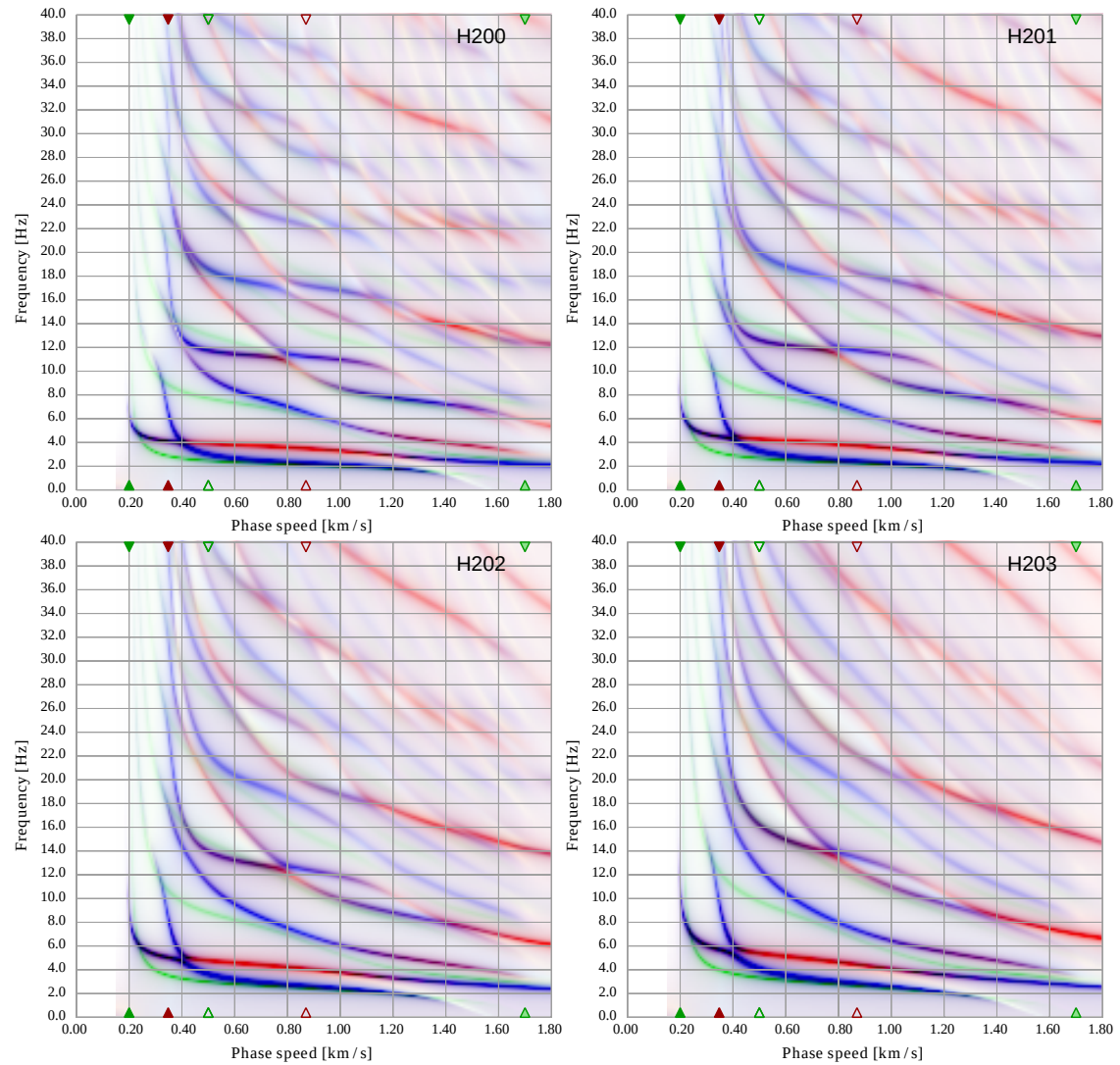


Figure 6 Three component rendering of the surface response in frequency–phase speed for the sequence of two layer models in Figure 5 with a surface S-wave source. H200 has a full jump in P and S wavespeed, and the contrast at the interface is progressively reduced with the inclusion of gradients in the models H201–H203. The transverse component (Love) is shown in green, with the radial component in blue and vertical component in red for the Rayleigh modes. The maximum plotted amplitude for all components is set the same, and so the relative excitation of the modal branches can be assessed by the apparent width of the mode branch in the plot. The dispersion is the same for the two components of the Rayleigh wave, and so the apparent colour changes with the surface ellipticity. The markers indicate the wavespeeds associated with the different segments of the models (Figure 5) with S structure in green and P in red. The solid symbols mark the wavespeeds at the surface, and the open symbols those at the base of the upper layer.

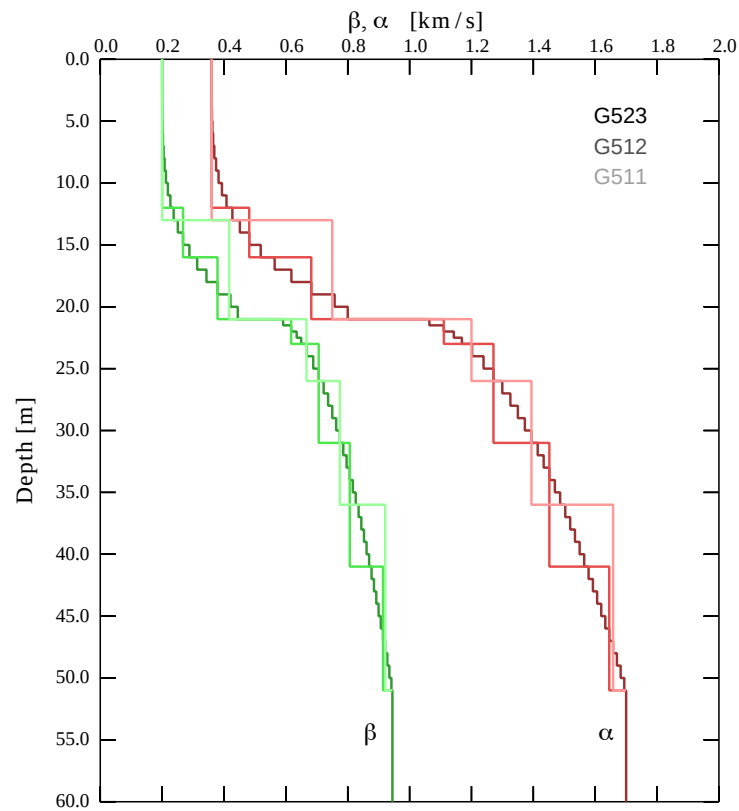


Figure 7 Gradient model G523 and more coarsely discretised versions G511, G512. Lighter colours are used for the simplified models.

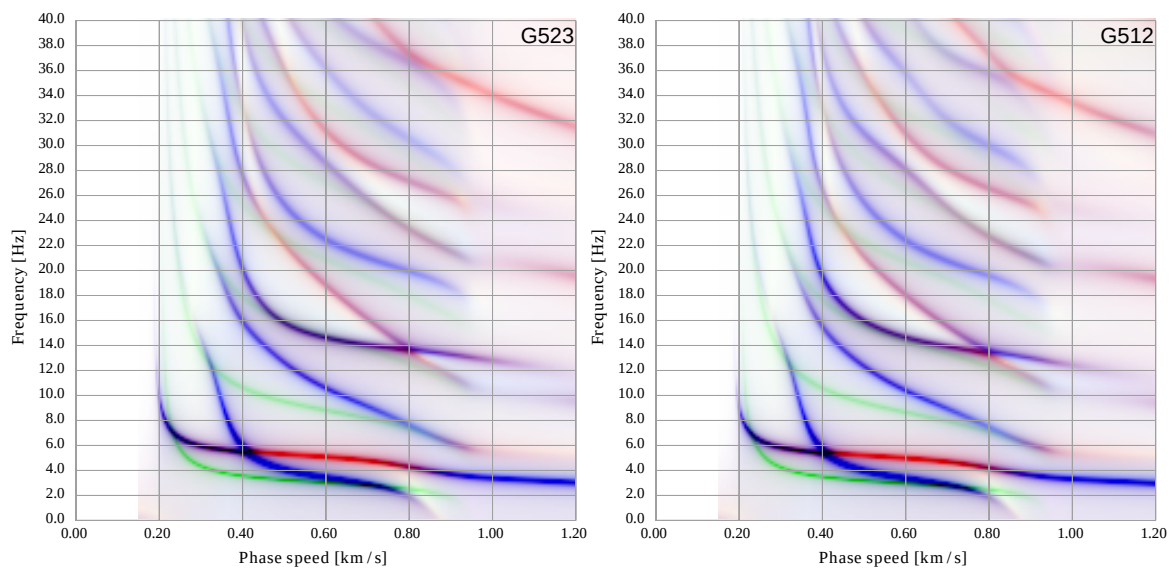


Figure 8 Three component rendering of the surface response in frequency–phase speed with a surface S-wave source for the models G523 with 55 layers and G512 with 8 layers. The transverse component (Love) is shown in green, with the radial component in blue and vertical component in red for the Rayleigh modes. The maximum plotted amplitude for all components is set the same, and so the relative excitation of the modal branches can be assessed by the apparent width of the mode branch in the plot. The dispersion is the same for the two components of the Rayleigh wave, and so the apparent colour changes with the surface ellipticity.

the modal behaviour. This means that the discretisation employed has to be model adaptive if maximum simplification is to be achieved. A reduction of layer count by a factor of 3–4 is usually possible, but cannot be guaranteed. A model comprising a few layers with major jumps

in wavespeed is unlikely to provide a good match to the modal spectrum once gradients in wavespeed are significant.

In an inversion where the character of the model is not known it is tempting to employ approaches with a

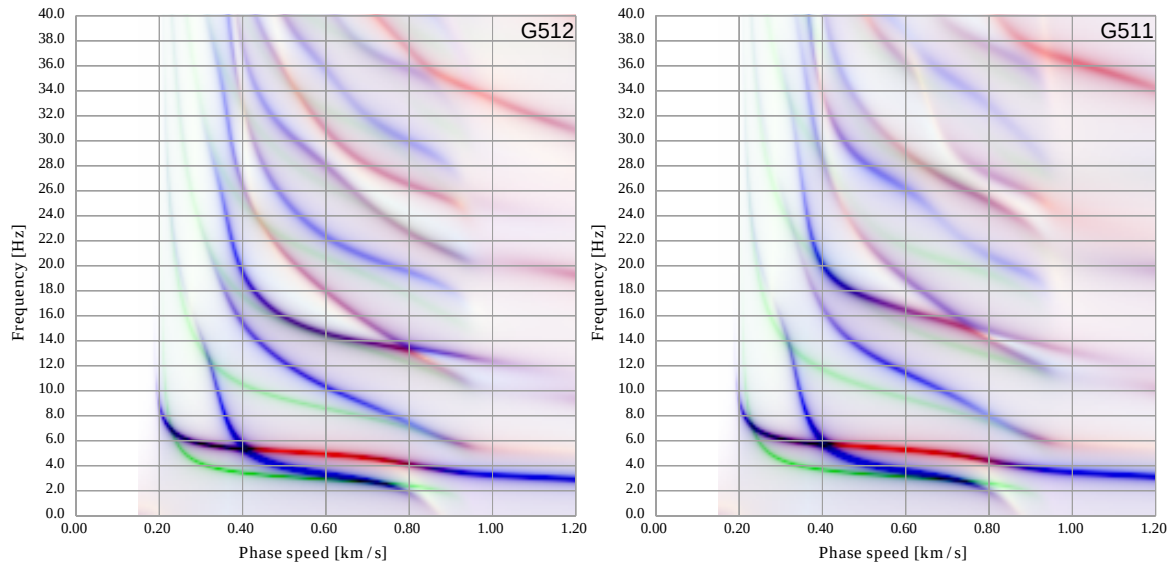


Figure 9 Three component rendering of the surface response in frequency–phase speed with a surface S-wave source for the models with coarse discretisation of a gradient structure. Model G512 has 8 layers with modest contrasts within layers, whilst G511 has 7 layers but larger wavespeed jumps. The transverse component (Love) is shown in green, with the radial component in blue and vertical component in red for the Rayleigh modes. The maximum plotted amplitude for all components is set the same, and so the relative excitation of the modal branches can be assessed by the apparent width of the mode branch in the plot. The dispersion is the same for the two components of the Rayleigh wave, and so the apparent colour changes with the surface ellipticity.

simple parametrisation based on uniform layers. When the number of layers is itself an inversion variable, good results can be achieved with few layers for matching the dispersion of fundamental Rayleigh and Love waves (e.g., [Magrini et al., 2025](#)). As higher-mode information is added, the dispersion behaviour imposes stronger constraints on the details of the wavespeed distribution with depth, and so effective models will need to become more complex.

5 Influence of recording system

So far I have presented examples with the full three-component dispersion spectrum, but a further consideration is the way that the recording systems can modify the character of the observable spectrum. Until recently the density of recording stations has been such that the extraction of higher-mode information at high frequencies required fortunate circumstances. The advent of dense nodal systems and distributed acoustic sensing (DAS) has provide much denser spatial sampling, and observations of higher modes are becoming more common.

Cross-correlation approaches have been extensively used to extract dispersion information from networks of instruments and have been effective in extracting fundamental mode properties, since this generally well excited for the virtual source-receiver pair. There can be hints of higher modes, but often these are only visible over limited bands in frequency and phase speed. The tighter spacing of channels in DAS systems means that spatial aliasing is avoided and the potential for extracting higher modes is enhanced. Even in urban environments, rich observed dispersion spectra can be ex-

tracted (e.g. [Lai et al., 2024](#)) with clear higher Rayleigh modes.

In Figure 10, I present the three-component dispersion spectrum for the model H201, shown in Figure 5, together with the modifications introduced with different styles of recording. If only vertical component instruments are available some modal branches almost disappear, e.g., the second higher Rayleigh mode. There are also complications for the fundamental and first higher mode – since segments of the two branches almost join to give an apparently continuous dispersion curve that is dominated by the first mode. The weak expression of the true fundamental mode on the vertical component is a consequence of the rather slow surface wavespeeds.

For DAS recording the dispersion spectrum is modulated by the inverse of the phase speed with inclination factors $\cos^2 \psi$ for Rayleigh waves and $\sin \psi \cos \psi$ for wavetrains crossing the DAS cable at an angle ψ (see, e.g., [Kennett, 2022a](#)). Love waves are suppressed for in-line recording ($\psi = 0$) and have the highest chance of being visible when the waves cross the cable at 45 degrees (e.g., [Ji et al., 2024](#)). The weighting factor for phase speed concentrates higher-mode information into lower phase speeds, and so such features as the sharp change in slope of mode branches, due to the large wavespeed jump into the basement, can resemble the truncation of a branch. Multi-mode observations in DAS are favoured when the surface wavespeeds are low. The detailed character of the higher-mode branches can then provide useful additional constraints to fundamental-mode dispersion. There remains the difficulty of correctly identifying the mode branches, because incorrect association will result in distortions of the inferred wavespeed profile with depth. Issues

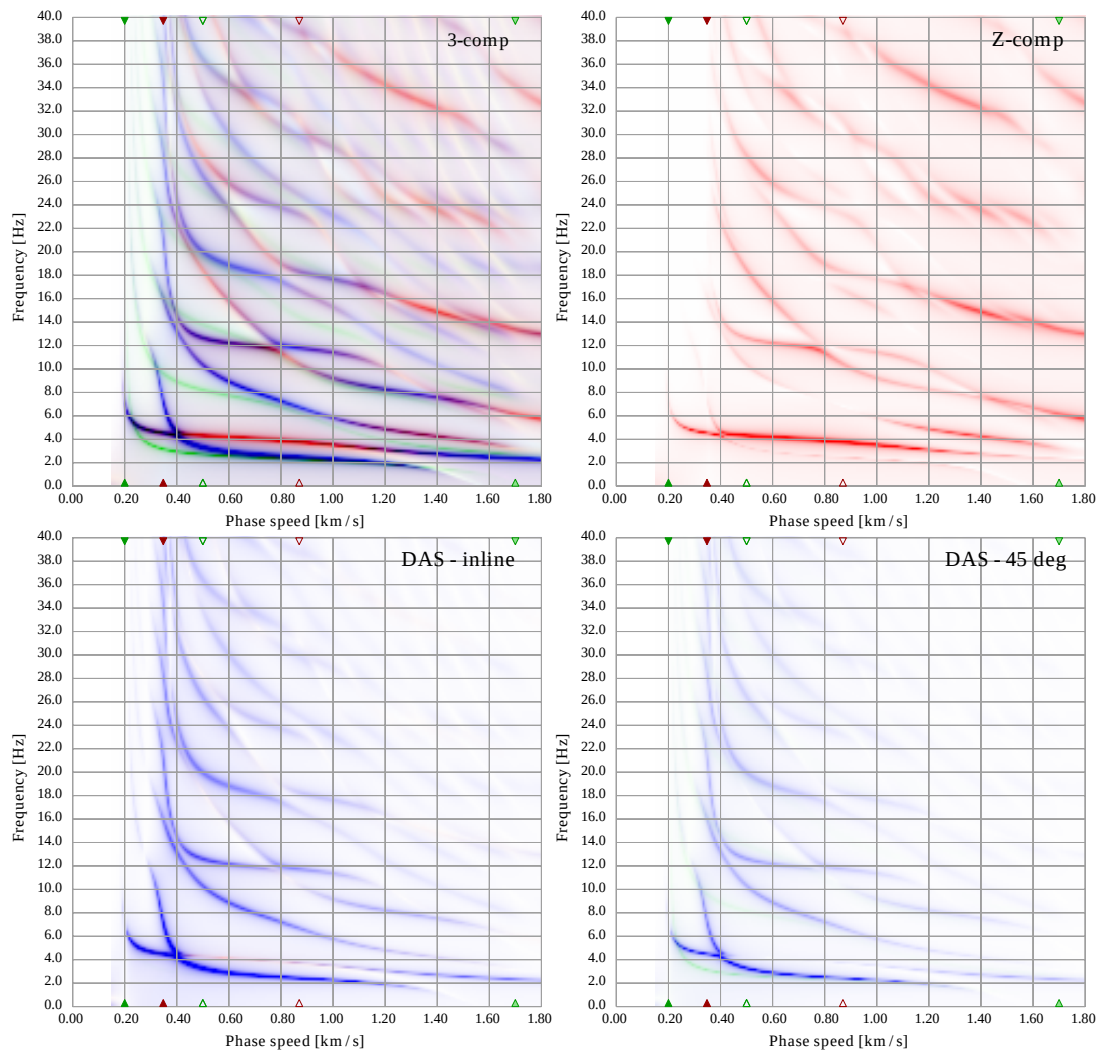


Figure 10 The modification of the three-component dispersion spectra for model H201, shown in Figure 5, with different modes of recording. (a) Full response spectrum, (b) vertical component only, (c) DAS system with waves travelling directly along the cable, (d) DAS cable with waves crossing at 45 degrees. The transverse component (Love) is shown in green, with the radial component in blue and vertical component in red for the Rayleigh modes. The maximum plotted amplitude for all components is set the same, and so the relative excitation of the modal branches can be assessed by the apparent width of the mode branch in the plot. The dispersion is the same for the two components of the Rayleigh wave, and so the apparent colour changes with the surface ellipticity.

can arise where a mode has poor expression on the radial strain response of DAS. This can be seen for the first higher Rayleigh mode in Figure 10. A comparable effect was encountered in work on the Greenland icesheet (Fichtner et al., 2023) with again the first Rayleigh higher mode almost absent from the DAS results, though the second higher mode was very clear.

6 Discussion and Conclusions

The presence of wavespeed gradients has a strong influence on the character of the modal spectrum, both for the fundamental mode and for the pattern of higher modes. The effects of gradients are stronger for Rayleigh waves than for Love waves. With the aid of frequency–phase speed dispersion spectra all modes, both fully trapped and leaking, are represented with an indication of their relative excitation. Colour coding of the three components of the spectrum is helpful for

assessing the observability of mode branches, particularly when the influence of the recording system is included.

Fundamental-mode dispersion shows strong dependence on the thickness of surficial layers and the contrasts at interfaces. The pattern of higher modes has more sensitivity to gradients because it depends on the interference of multiple passages of S waves through the structure. Where available, the additional sampling provided by the higher modes can significantly improve inferences about the wavespeed distribution with depth. In particular, the details of higher-mode behaviour can be helpful in disentangling the nature of the wavespeed variation with depth for structures that have similar fundamental-mode dispersion. However, effective exploitation of higher modes requires flexible parametrisation of the wavespeed profile with depth and correct identification of higher-mode branches, taking into account the nature of the recording system

employed.

In situations where gradients are anticipated it can be useful to employ suitable physical models as a basis for inversion for structure. For example, [Yang et al. \(2024\)](#) have examined structure at the South Pole using DAS data from a 8-km-long cable with excitation by controlled sources. Higher Rayleigh modes to order 8 and 6 P-dominated leaking modes were extracted from the records. At the South Pole there is annual snow accumulation without melt so that the structure with depth is almost entirely controlled by compaction. [Yang et al. \(2024\)](#) used parametrised compaction models together with calculated frequency–phase speed spectra to invert for the controlling parameters and achieved an excellent fit to the dispersion behaviour of the observed modes. In contrast, on the Greenland Icesheet there is more melting in the summer, and the shallow ice profile is more complicated. [Fichtner et al. \(2023\)](#) used DAS observations of a landing aircraft to extract the properties of 5 higher Rayleigh modes and a couple of P-dominated leaking modes. A compaction model did not prove adequate to fit the higher mode dispersion, and more complex structures were needed in the top 20 m of the wavespeed profile.

It is common for inversions of even multi-mode dispersion data to employ just a few uniform layers. Tests with a variety of models suggest that adequate representation of the full dispersion spectra of gradient scenarios requires more layers than might be anticipated, since contrasts at secondary interfaces need to be kept small (< 0.1 km/s). The fundamental mode is less affected by the model parametrisation, and higher-mode information over a fair span of phase speed is needed to fully characterise gradient behaviour. Even where only a limited segment of higher-mode branches are recoverable their behaviour can be diagnostic. For example, sharp changes in the slope of higher mode dispersion branches are suggestive of the presence of strong contrasts in wavespeeds between layers but do not preclude the presence of significant gradients within layers.

Gradient structures can be described in terms of just a few parameters, and so do not present barriers to inversion. Such models have, e.g., been used in receiver function inversion (e.g., [Sambridge, 1999](#)). A gradient zone may well be implemented with a sequence of uniform layers, and then it can be advantageous to use some structural simplification to reduce computational cost. As noted above a reduction of a factor of 3 is usually possible without noticeable modification of the dispersion pattern.

I here present results for models without any horizontal variation in properties so that the various higher modes propagate independently. When the local structure varies slowly compared to the wavelengths of the surface waves, independent mode propagation is maintained. The modal dispersion can still be represented effectively by a structure varying solely with depth. Differences in the modal structure for well separated sampling sites can then provide indications of changes in structure even where only limited portions of higher modes are extracted. As noted by [Kennett \(2023\)](#), the effect of stronger lateral heterogeneity is to introduce

coupling between mode branches that will be most important when branches are closely spaced. The broad behaviour of the modal branches associated with gradients will therefore be maintained even in the presence of near-surface variations. The complications will be confined to the neighbourhood of osculation points linked to major structural boundaries. Their influence will tend to be damped by both the presence of attenuation in sedimentary structures and the influence of recording and processing observations.

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Data and code availability

Fortran codes for frequency–phase speed synthesis and display are made available at Zenodo ([Kennett \(2022b\)](#)); doi: 10.5281/zenodo.7384357).

Competing interests

None.

References

- Brocher, T. M. Empirical Relations between Elastic Wavespeeds and Density in the Earth's Crust. *Bulletin of the Seismological Society of America*, 95(6):2081–2092, 2005. doi: 10.1785/0120050077.
- Chaput, J., Aster, R., Karplus, M., and Nakata, N. Ambient high-frequency seismic surface waves in the firn column of central west Antarctica. *Journal of Glaciology*, 68(270):785–798, 2022. doi: 10.1017/jog.2021.135.
- Fichtner, A., Hofstede, C., N. Kennett, B. L., Nymand, N. F., Lauritzen, M. L., Zigone, D., and Eisen, O. Fiber-Optic Airplane Seismology on the Northeast Greenland Ice Stream. *The Seismic Record*, 3(2):125–133, 2023. doi: 10.1785/0320230004.
- Guo, W., Li, Z., Zhao, S., and Chen, X. Characterizing the shallow structure with the multimodal dispersion curves and the body wave refraction traveltimes from deep seismic sounding data. *Frontiers in Earth Science*, Volume 10 - 2022, 2023. doi: 10.3389/feart.2022.1025935.
- Hallo, M., Imperatori, W., Panzera, F., and Fäh, D. Joint multi-zonal transdimensional Bayesian inversion of surface wave dispersion and ellipticity curves for local near-surface imaging. *Geophysical Journal International*, 226(1):627–659, 2021. doi: 10.1093/gji/ggab116.
- Ji, Q., Luo, B., and Biondi, B. Exploiting the Potential of Urban DAS Grids: Ambient-Noise Subsurface Imaging Using Joint Rayleigh and Love Waves. *Seismological Research Letters*, 95(3): 1794–1811, 2024. doi: 10.1785/0220230104.
- Jiang, C. and Denolle, M. A. NoisePy: A New High-Performance Python Tool for Ambient-Noise Seismology. *Seismological Research Letters*, 91(3):1853–1866, 2020. doi: 10.1785/0220190364.

- Kaplunov, N., Hofstede, C., Zigone, D., Eisen, O., Kennett, B. L. N., and Fichtner, A. Probabilistic multiparameter Backus–Gilbert method—Application to density inversion. *Geophysical Journal International*, 240(2):1064–1078, 2025. doi: 10.1093/gji/ggae430.
- Kennett, B. L. N. *Seismic Wave Propagation in Stratified Media*. Cambridge University Press, 1983.
- Kennett, B. L. N. The seismic wavefield as seen by distributed acoustic sensing arrays: local, regional and teleseismic sources. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 478(2258):20210812, 2022a. doi: 10.1098/rspa.2021.0812.
- Kennett, B. L. N. Construction of Frequency-Slowness and Frequency-Phase speed diagrams, 2022b. doi: 10.5281/zenodo.7384357.
- Kennett, B. L. N. Interacting Seismic Waveguides: Multimode Surface Waves and Leaking Modes. *Seismica*, 2(1), 2023. doi: 10.26443/seismica.v2i1.282.
- Kennett, B. L. N. and Clarke, T. J. Seismic waves in a stratified half-space – IV: P–SV wave decoupling and surface wave dispersion. *Geophysical Journal International*, 72(3):633–645, 1983. doi: 10.1111/j.1365-246X.1983.tb02824.x.
- Lai, V. H., Miller, M. S., Jiang, C., Yang, Y., Magrini, F., Zhan, Z., and McQueen, H. Passive Seismic Imaging of Urban Environments Using Distributed Acoustic Sensing: A Case Study from Melbourne, Australia. *The Seismic Record*, 4(4):308–317, 2024. doi: 10.1785/0320240031.
- Ma, Y., Clayton, R. W., and Li, D. Higher-mode ambient-noise Rayleigh waves in sedimentary basins. *Geophysical Journal International*, 206(3):1634–1644, 2016. doi: 10.1093/gji/ggw235.
- Magrini, F., He, J., and Sambridge, M. BayesBay: A Versatile Bayesian Inversion Framework Written in Python. *Seismological Research Letters*, 96(3):2052–2064, 2025. doi: 10.1785/0220240275.
- Nayak, A. and Thurber, C. H. Using multicomponent ambient seismic noise cross-correlations to identify higher mode Rayleigh waves and improve dispersion measurements. *Geophysical Journal International*, 222(3):1590–1605, 2020. doi: 10.1093/gji/ggaa270.
- Nolet, G. and Panza, G. F. Array analysis of seismic surface waves: Limits and possibilities. *pure and applied geophysics*, 114(5):775–790, 1976. doi: 10.1007/BF00875787.
- Sambridge, M. Geophysical inversion with a Neighbourhood Algorithm—I. Searching a parameter space. *Geophysical Journal International*, 138(2):479–494, 1999. doi: 10.1046/j.1365-246X.1999.00876.x.
- Takagi, R. and Nishida, K. Multimode dispersion measurement of surface waves extracted by multicomponent ambient noise cross-correlation functions. *Geophysical Journal International*, 231(2):1196–1220, 2022. doi: 10.1093/gji/ggac225.
- Takeuchi, H. and Saito, M. Seismic Surface Waves. In BOLT, B. A., editor, *Seismology: Surface Waves and Earth Oscillations*, volume 11 of *Methods in Computational Physics: Advances in Research and Applications*, pages 217–295. Elsevier, 1972. doi: 10.1016/B978-0-12-460811-5.50010-6.
- Xie, Y., Luo, Y., Tong, P., Xie, J., Wu, S., and Yang, Y. Separation of Fundamental- and Higher-Mode Surface Waves in Ambient Noise Cross Correlations. *Seismological Research Letters*, 96(5):3166–3178, 2025. doi: 10.1785/0220240477.
- Yang, Y., Zhan, Z., Karrenbach, M., Reid-McLaughlin, A., Biondi, E., Wiens, D. A., and Aster, R. C. Characterizing South Pole Firn Structure With Fiber Optic Sensing. *Geophysical Research Letters*, 51(13):e2024GL109183, 2024. doi: 10.1029/2024GL109183.

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