An assessment of information on the shear-velocity profile at Coyote Creek, San Jose, from SPAC processing of microtremor array data

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This paper is an extract from

Asten, M.W., and Boore, D.M., eds., Blind comparisons of shear-wave velocities at closely spaced sites in San Jose, California: U.S. Geological Survey Open-File Report 2005-1169. [available on the World Wide Web at http://pubs.usgs.gov/of/2005/1169/].

2005

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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CONTENTS

Editors note: This paper is from a report dated December 2002. In keeping with the principles applicable to a blind study, the report has not been updated other than with formatting changes.

ABSTRACT

Microtremor data acquired with three four-station arrays at Coyote Creek, San Jose, can be analysed by the SPAC method to yield useful layered-earth models of shear velocity and thickness. The range of inter-station distances available from the array design is 35 to 300 m. The analysis uses direct visual matching of theoretical azimuthally-averaged coherencies with azimuthally-averaged coherencies of field data, where the theoretical curves are computed from fundamental-mode Rayleigh-wave phase-velocity dispersion curves of layered-earth models. Discrepancies which may be associated with higher-mode propagation are noted but not analysed in this report.

Layer thicknesses resolved by the coherency matching method range from 10 m at the surface, (resolved with frequencies of order 15 Hz), to a thickness of 2000+ m, extending down from depth 420 m (resolved with frequencies 0.3-1 Hz). For layers to 500 m depth, resolution by visual matching of theoretical coherencies with observed azimuthally-averaged coherencies, appears to be between 10% and 20%.

Horizontal/vertical spectral ratio (HVSR) plots from three-component records show three spectral peaks, at periods 3 sec, 1.1-1.5 sec, and 0.3-0.4 sec. The shortest period is not universal across the array, and appears to be longer at two of the seven stations, suggesting there is thickening of softer sediments at these sites. However SPAC analysis does not provide evidence to support any lateral variations across the study area.

The longest-period HVSR peak of 3 sec appears from modelling studies, to be controlled by depth to hard rock. A hypothetical depth of order 920 m to hard rock appears to be needed to match this long-period spectral peak (model PkDec3), but such a model is not consistent with SPAC velocity data. The best fit of azimuthally-averaged coherencies indicates depth to hard rock at this site to be 2000+ m (model PkDec2).

This interpretation was intentionally performed without knowledge of borehole logs or other studies performed at the site, as part of an objective comparison by the USGS of the merits of different seismic techniques for characterisation of sediments in earthquake-prone areas.

INTRODUCTION

The microtremor survey method (MSM) relies on two paradigms foreign to the practice of conventional seismic exploration. These are (a) the property of seismic surface waves that their penetration into the earth is frequency dependent, hence the dispersion curve (phase velocity vs frequency) for observed data can be inverted to yield a layered-earth model of the sub-surface, and (b) the variation of phase velocity with frequency can be measured using array-processing methods.

The MSM applied to the study of near-surface geology has had a fascinating history over the last 50 years. Aki (1957, 1965) laid the foundation for the Spatial Auto-Correlation (SPAC) method which has become the key to successful extraction of phase-velocity information from surface-wave microtremors. This particular contribution from Aki appears to have been largely ignored in Western literature on the study of microtremors up until the last three* years; the great strides in seismic array data processing of the 1960s and 1970s were spurred by the need to locate *direction* to seismic sources, and hence beam-forming (or *f-k*) methods (e.g. Capon, 1967) received the greatest emphasis.

Indeed, the very nature of high-frequency microtremors has been a source of significant debate; some authors in past decades attributed them to P-wave energy, and marketed the use of engineering-seismic studies based on comparing spectral peaks of microtremors with P-wave resonances, while others attributed the same energy, and the same spectra, to Rayleigh-wave propagation. See the exchanges by Asten (1979) and Katz (1979) following Asten (1978) for examples where the debate generated heat as well as light (with somewhat more vigorous debate occurring in unpublished notes sent to the Editor of the day!). More recently, literature originating in the Western Hemisphere has debated whether microtremors are dominated by S-wave resonances or by Rayleigh-wave propagation (eg., Ibs-von Seht and Wohlenburg, 1999 and references therein; Liu et al, 2000).

The study and use of **spectra** of microtremors for engineering-scale studies has developed into a separate and mature science, largely due to the efforts of Japanese seismologists in the last 20 years (Nakamura, 1989; Konno and Ohmachi, 1998). The study and use of phase-velocity dispersion curves of microtremors has developed separately, also in Japan, largely as a result of the diligence of Prof. Okada and his students (Okada,1997), and considerably assisted by use of the SPAC technique pioneered by Prof. Aki 45 years ago.

The SPAC technique is worthy of an additional observation. Whereas array beam-forming delivers estimates of wave velocity and direction, and is subject to bias in velocity estimates when waves from multiple directions are incompletely resolved, the SPAC technique has the delightful property that, since the wave *direction* is not sought, estimates of wave *scalar velocity* are unaffected by the super-position of waves from multiple directions (Aki, 1965; a principle subsequently overlooked in some literature, e.g. Douze and Laster (1979), but then reiterated by Asten, 1983). In fact, the more omni-directional the wave energy (assuming single-mode propagation), the better the estimate of scalar velocity. The SPAC technique thus has the serendipitous property of giving its best results when seismic sources are many. This is why the technique has enormous potential in built-up areas, where microtremor noise militates against the use of conventional seismic methods, but that same ubiquitous noise generated by urban activity produces an omni-directional wave-field of high-frequency microtremors, ideally suited to the SPAC technique.

A curious feature of microtremor literature is the rarity of studies combining both H/V spectral methods *and* phase velocity methods. Tokimatsu (1997) and Sato et al (2001) are examples. See also Asten, Dhu et al (2002) and Asten, Lam et al (2002).

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* written December 2002

In this study we consider both the H/V spectra and the phase velocity dispersion curves, and show that combination of the two data sets does provide more information than either data set alone. There is a physical explanation for this synergy; microtremor energy propagates primarily as Rayleigh waves, with elliptical particle motion. The H/V ratio becomes large at resonant frequencies where the ellipse at the free surface degenerates into horizontal motion. At these critical resonant frequencies, the phase velocity method will not return useful data since the basic SPAC method utilises only vertical-component data from seismic arrays.

ORIGIN AND LOCATION OF DATA STUDIED

This report describes results from re-processing microtremor array data acquired by Dr Hortencia Flores and the US Geological Survey at Coyote Creek, San Jose. The data was supplied to the author by Dr David Boore of the USGS. Documentation on the data acquisition, and the array layout is described in a series of emails and notes between Dr Boore and Dr Flores, and this author. Details are summarised in Appendix 2. The planned layout is depicted in Figure 1, and actual layout is plotted from GPS coordinates in Figure 2; the latter is probably in error, since the small triangular arrays were laid out symmetrically with compass and tape and are believed to be symmetric (unlike what is shown on the plotted Figure 2).

There are three four-station triangular arrays in this layout. The PRKL array (also called PKL array in some documentation) and the CLR array are each 60 m side length, while the PRK array is 300 m side length. Each triangle contains a centre geophone; the radial distance from centre to apices of the triangle is 34.6 m for the small arrays, and 173.2 m for the large array.

A borehole exists near the centre of the small CLR array. Data from this borehole has not been sighted by this author during the preparation of this analysis and report, hence the layered-earth interpretations presented here are deduced solely from the surface array observations. This separation of borehole and surface data has been maintained at the request of David Boore, USGS, in order to assist in objective assessment of the merits of differing seismic methods in the assessment and characterisation of sediments in earthquake-prone areas.

H/V SPECTRA

We first review the 3-component spectra and horizontal/vertical spectral ratios (HVSR) of selected stations. This data gives a useful overview of possible shear-wave resonances and in many cases can map relative variations in shear-velocity and/or sediment thickness (eg Ibs von-Steht, 1997; Asten and Dhu, 2002).

Figure 3 shows separate horizontal and vertical-component spectra plotted vs frequency, together with a plot of the H/V spectral ratio. The HVSR spectral peaks of most interest in this study are associated with troughs in the vertical spectrum, rather than with peaks in the horizontal spectrum. This fact is consistent with the H/V spectral ratios being a function of Rayleigh-wave particle motion (V goes to zero at frequencies where the particle motion ellipse changes from retrograde to prograde motion).

From here on, we use the convention of plotting spectra relative to **period**. Figures 4 and 5 show spectra of HVSR for two sets of seismometers chosen to provide sections across two axes of the array. Spectral peaks are relatively weak at this site, but two persistent peaks are evident, with periods which seem virtually constant across the array. The long period peak is 3.0 sec, and the shorter period peak is broad over the range 1.1 to 1.4 sec. A third spectral peak is evident at 0.3 sec on PKLC and CLR1, and at a longer frequency of 0.38 sec at CLRM and PRK2; this last peak is absent in the south at PRK1.

The shortest-period peak corresponds to Rayleigh wavelengths of order 90 m (see next section) and is therefore may be an indicator of thickening of soft sediments within the top 30 m of sediments, in the vicinity of CLRM and PRK2. This hypothesis is however **not** supported by the limited (due to noise and instrument limitations) data available from array CLR.

The middle peak of 1.1-1.4 sec corresponds to wavelengths of order 1000 m, and appears to be sensitive to the interface at depth 130 m. The long-period peak at 3 sec appears associated with a hypothetical hardrock interface at depth 920 m, but this interpretation is **not** consistent with results of SPAC analysis below.

INITIAL INTERPRETATION OF A SHALLOW EARTH BELOW THE SMALL PKL ARRAY

The four-station triangular array allows estimates of azimuthally-averaged coherency to be made over two distances, r1 = (r / 1.73), and r2 = r, where r is the side length of the outer equilateral triangle. For the small PKL and CLR arrays, the two inter-station distances used for azimuthal averaging are r1=34.6 m and r2 = 60 m.

Figure 6 shows averaged coherencies for a sample of 150 sec of data from the PKL array, for the two station separation distances. The observed coherencies are fitted to theoretical coherencies computed using the relationship

$$ave\ c(f) = J_0\,(kr) = J_0\,(2\,\pi\ f\,r\,/\,V(f)\,), \qquad \text{-----}(1)$$

where *ave c(f)* is azimuthally-averaged coherency,
f = frequency, J_0 is the Bessel function of zero order,
k is the scalar wavenumber, $V(f)$ is the computed fundamental Rayleigh-wave phase velocity dispersion curve, and r is the station separation in the sub-array.

Rayleigh-wave phase and group velocities are computed for a chosen layered-earth velocity model using the forward-modelling algorithm and FORTRAN code of Herrman (2001). A process of manual iteration is used to obtain the best visual fit of field coherencies with model coherencies for the fundamental Rayleigh mode. The model used in Figure 6 is labelled “PkInit”. For reference purposes, the plots in Figure 6 also show modelled coherencies for the first and second higher Rayleigh modes. In this report I do not consider the presence of higher modes, but as shown in Asten (2001), it is likely that higher modes are in general present at some frequencies, and with suitable array design and processing, it is possible that such higher modes may be identified.

With the small PKL array alone, three layers of sands or silts can be identified (Figure 7). Two basement layers with velocities equivalent to competent sandstone, and granitic basement are added in order to give stable computation. I have no information on the geology of the San Jose area; parameters for these two hypothetical basement layers are taken from numbers used at the base of the Sydney basin in Asten (1976).

Figures 8 and 9 show modelled phase velocities, modelled particle-motion H/V ratios, and the observed HVSR spectrum for station PKLM at the centre of the array. Note however that this model “PkInit” is not complete; it is a partial result defining near-surface layers, for input into the next stage of interpretation.

INTERPRETATION OF A LAYERED EARTH BELOW THE PRK ARRAY

The previous section achieved useful fitting of coherency data in the frequency band 3-15 Hz, and resolved three upper layers extending down to 120 m. We now use coherency data from the large PRK array, and add deeper layers in an effort to fit frequencies in the range 0.3-3 Hz. As before two hypothetical basement layers of sandstone and granite are also included.

As before, we attempt to fit field coherencies to the theoretical azimuthally-averaged coherencies for the fundamental Rayleigh-mode phase velocity curve. We also plot theoretical coherencies for the first and second higher modes, for reference. Figures 10, 11 and 12 show the results; the low shear velocity of 1400 m/sec is needed down to 3000 m, in order to match the coherency curve from 0.3 Hz to 1 Hz**.** This model is labelled “PkNov”. **(This is the interim earth model emailed to David Boore on 1 Nov 2002 – see Appendix 1).** While the low frequencies match well, it is apparent that coherencies at mid frequencies 2-5 Hz are not adequately matched.

Figures 13, 14, 15 show an improved model, labelled “PkDec2” for purposes of reference. This model provides a visually optimum fit of field and model coherencies for the PKL array. It is slightly different from the layered-earth model for the top 120 m as derived with data from the small PKL array, but probably not significantly different. The velocity-depth profiles are plotted for comparison in Figure 26.

Figure 22 shows the field coherencies for the small PKL array compared with model coherencies for the “PkDec2” model. The fit can be compared with Figure 6; this model is seen as adequate to fit both the large PRK and small PKL array data.

ATTEMPT TO FIT BOTH VELOCITY AND HVSR DATA FOR ARRAY PRK

Figure 16 shows the theoretical H/V ratios for the model "PkDec2", which has a hard-rock basement at 3420 m depth. It is evident that this model has a broad theoretical H/V peak at period 1.1-1.5 sec which correlates with an observed peak, but there is no H/V peak correlating with the longer-period observed HVSR peak at 3 sec. In order to create a model H/V peak at 3 sec, it appears necessary to invoke a hypothetical hard-rock basement at 920 m depth, shown in Figures 17, 18, 19, 20 as model "PkDec3". This alternative model demonstrates the two H/V peaks desired, but it is also visually apparent that the fit to coherencies in the low-frequency band 0.3-1 Hz is inferior. Without recourse to independent geological information it is not possible to consider the relative merits of these two models further.

COMPARISON OF MODEL "PkDec2" WITH DATA FROM THE SMALL ARRAY CLR

As shown in Figure 2, the centre of the CLR array is 200 m north-west of the centre of the PKL and PRK arrays. Figures 23 and 24 show theoretical coherencies for model PkDec2 plotted with field coherencies for array CLR, for segments of two separate data files. Two features are immediately apparent: (a) The data using the centre station CLRM is corrupt. I suspect this is probably due to incorrect synchronization of CLRM, since the HVSR plots and individual spectra for the centre station CLRM (Figure 25) are similar to those for the PKL array. (b) Observed azimuthally-averaged coherencies computed for the outer stations of array CLR (Figures 23, 24) are markedly more noisy than the equivalent for array PKL for the first file studied (Figure 23), and somewhat more noisy than the equivalent for the second file studied (Figure 24).

Within the limitations of noise levels, there is no evidence in the velocity data for concluding that the geology at the centre of array CLR is any different from the geology at the centre of array PKL This result therefore does **not** support the hypothesis of thicker soft surficial (top 20 m) sediments at this site, a hypothesis suggested by a study of HVSR previously in this report.

CONCLUSIONS

Microtremor data acquired with three four-station arrays at Coyote Creek, San Jose, can be analysed by the SPAC method to yield useful layered-earth models of shear velocity and thickness. Thicknesses range from 10 m at the surface, resolved with frequencies of order 15 Hz, to a thickness of 2000+ m, extending down from depth 420 m (resolved with frequencies 0.3-1 Hz). For layers to 500 m depth, resolution by visual matching of theoretical coherencies with observed azimuthally-averaged coherencies, appears to be between 10% and 20%.

HVSR plots from three-component records show three spectral peaks, at periods 3 sec, 1.1-1.5 sec, and 0.3-0.4 sec. The shortest period is not universal across the array, and appears to be longer at stations CLRM and PRK2, suggesting there is thickening of softer sediments at these sites. However SPAC analysis does not provide evidence to support any lateral variations across the study area.

The longest-period HVSR peak of 3 sec appears from modelling to be controlled by depth to hard rock; a hypothetical depth of order 920 m appears to be needed to match this long-period spectral peak (model PkDec3), but such a model is not consistent with velocity data. The best fit of azimuthally-averaged coherencies indicates depth to hard rock to be 2000+ m (model PkDec2). The two models PkDec2 and PkDec3 are compared in a velocity-depth plot in Figure 26.

ACKNOWLEDGEMENTS

The seismic array used for data acquisition was designed by Dr Hortencia Flores of UNAM, Mexico. Data acquisition was carried out by Dr Hortencia Flores and Mr Russell Sell of the US Geological Survey. The raw array data was supplied to the author by Dr David Boore of the USGS. The author is supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 04HQGR0030 and 05HQGR0022. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either express or implied, of the U.S. Government.

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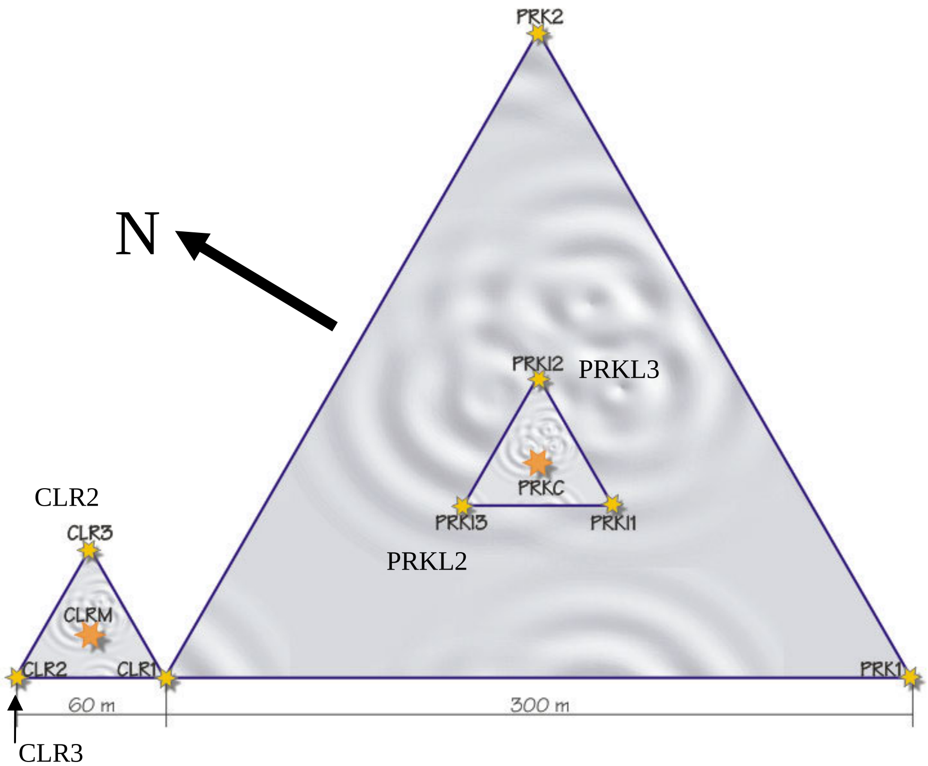


Fig. 1. Planned layout of arrays; large labels show actual station labels applied in the field.

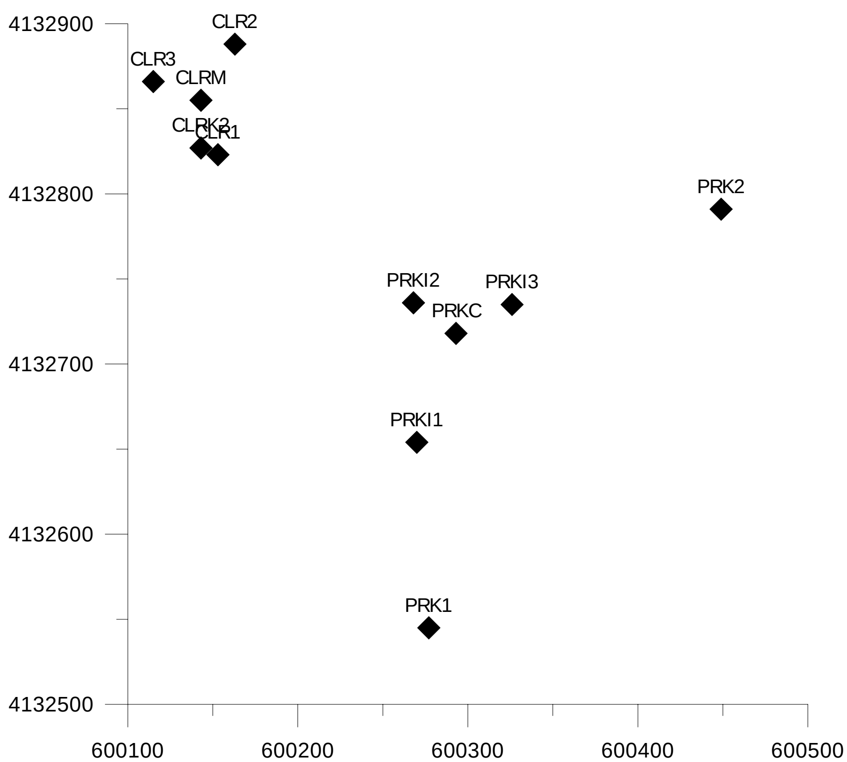


Fig. 2. Station positions as surveyed by GPS. The GPS coordinates for small arrays PKL and CLR are believed to be erroneous, as these arrays were positioned by tape and compass.

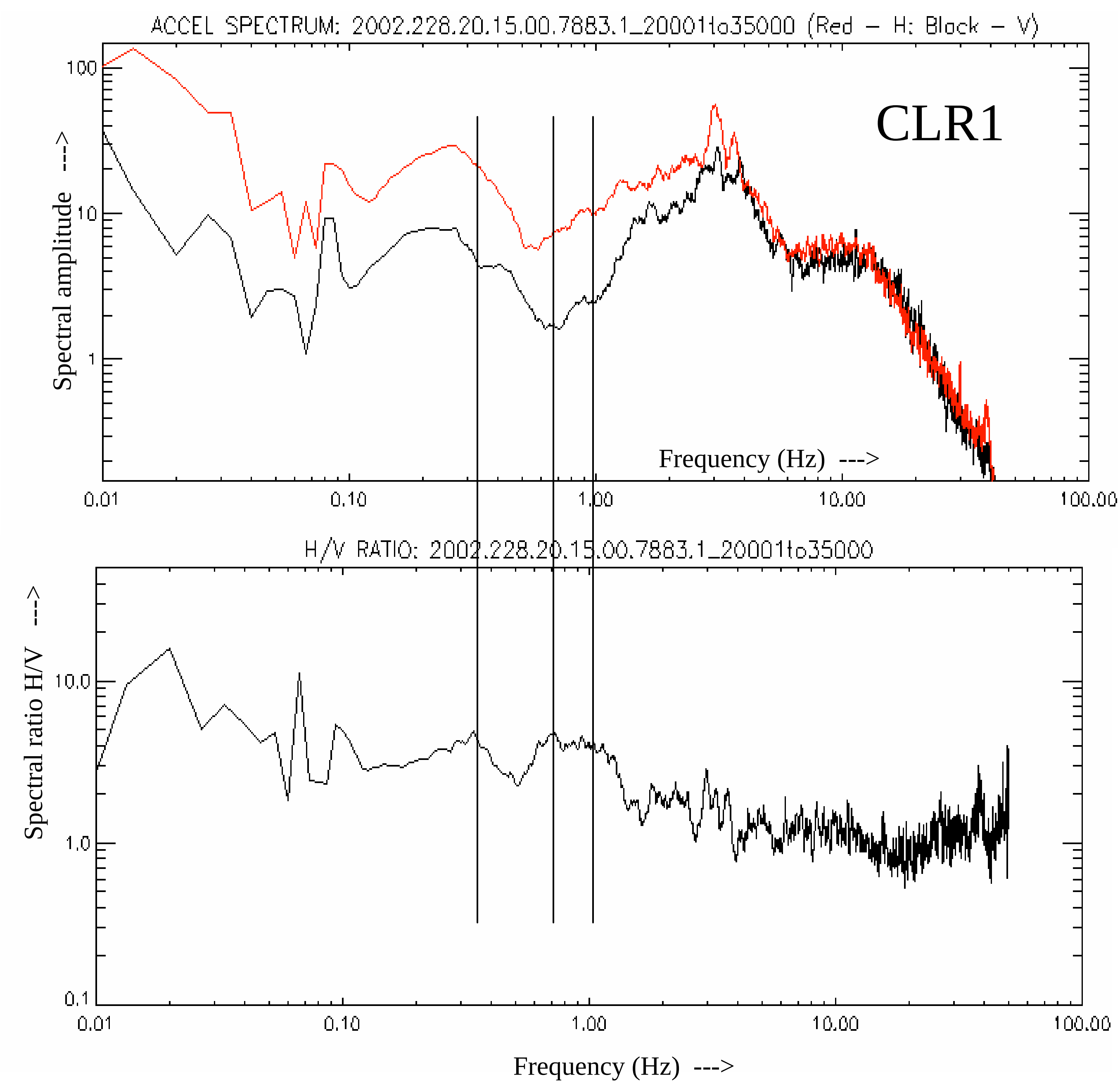


Fig. 3. Separate H and V spectra by frequency for station CLR1, showing that H/V peaks are associated with relative troughs in V, rather than peaks in H.

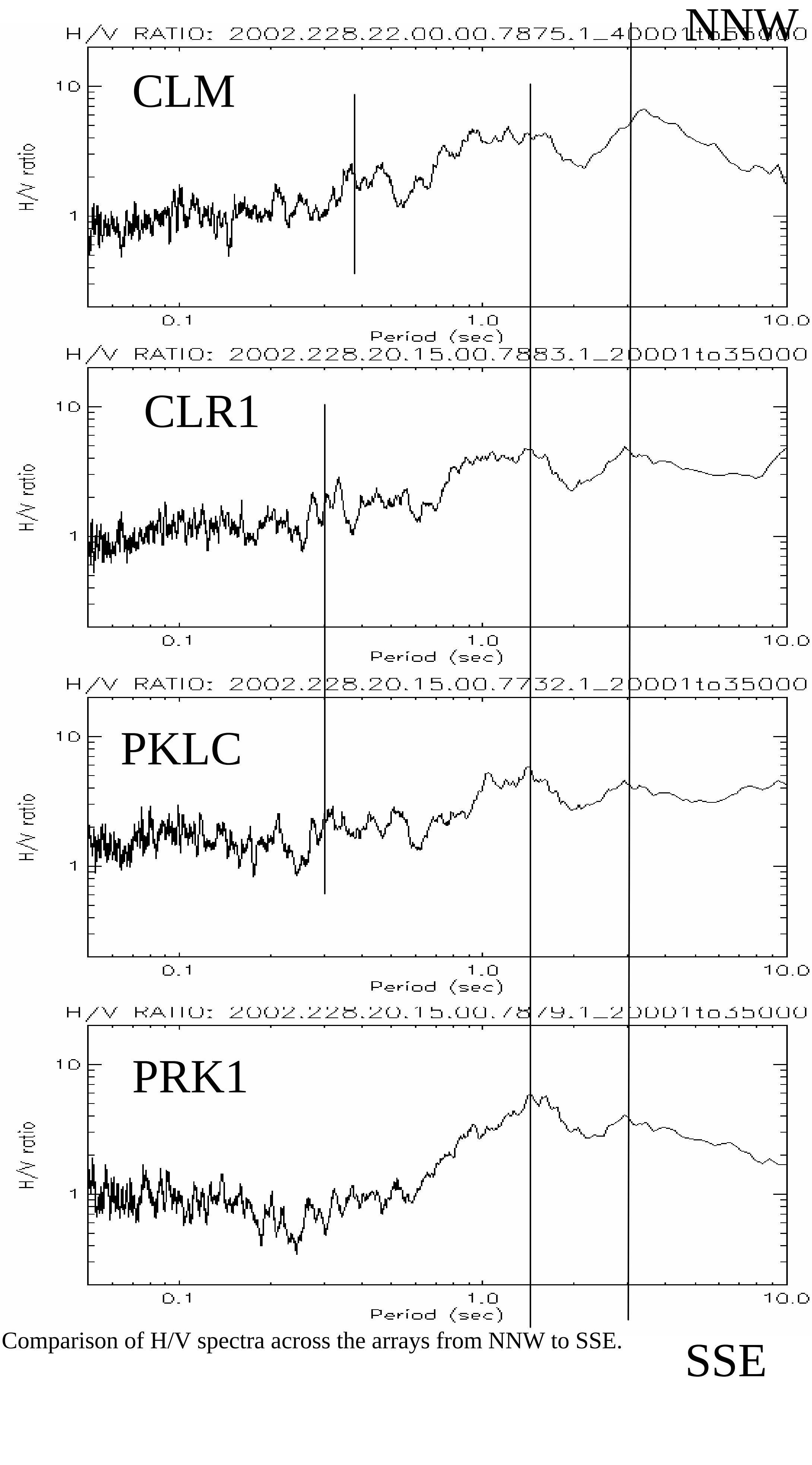


Fig. 4. Comparison of H/V spectra across the arrays from NNW to SSE.

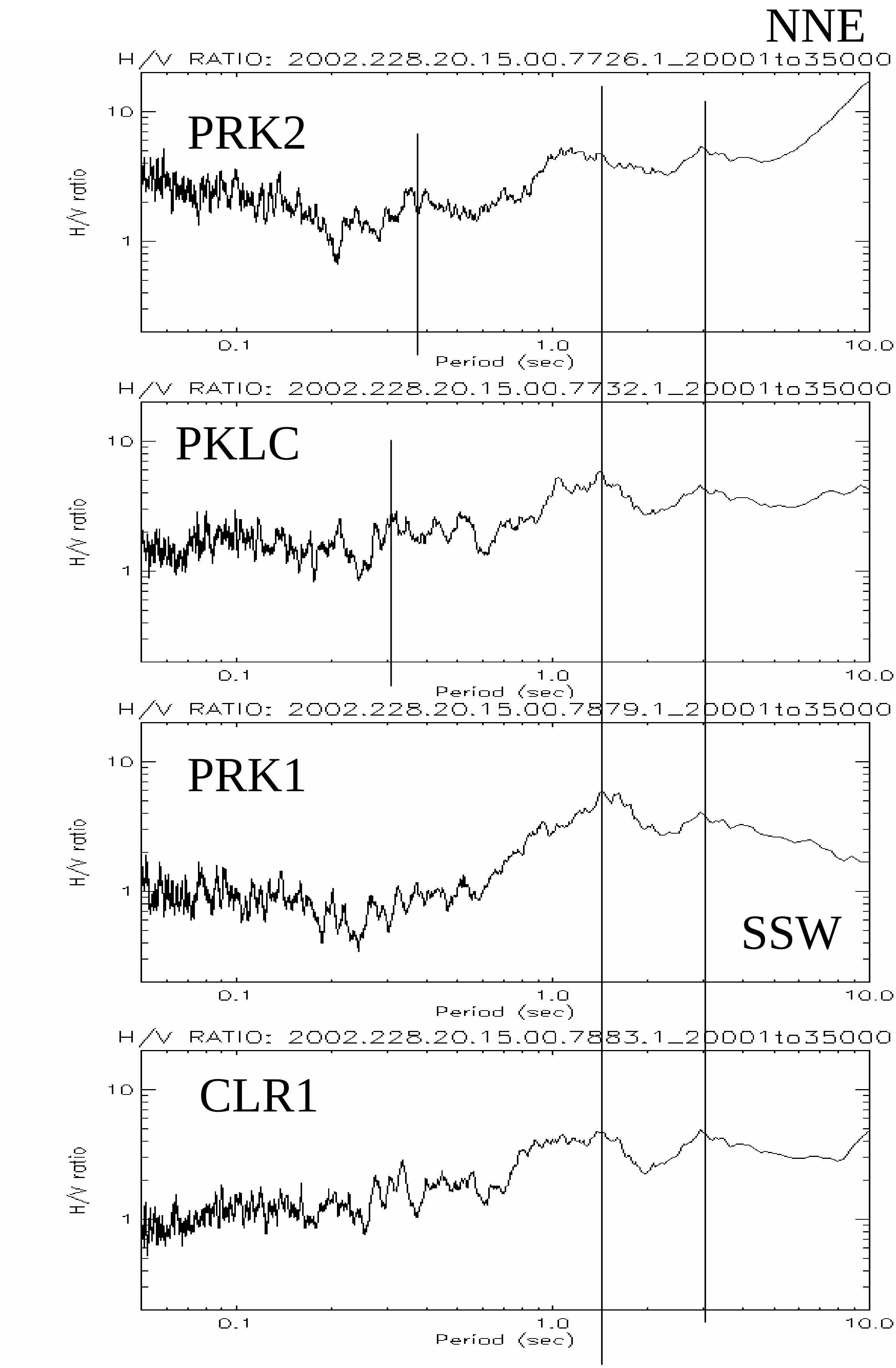


Fig. 5. Comparison of H/V spectra across the arrays from NNE to SSW.

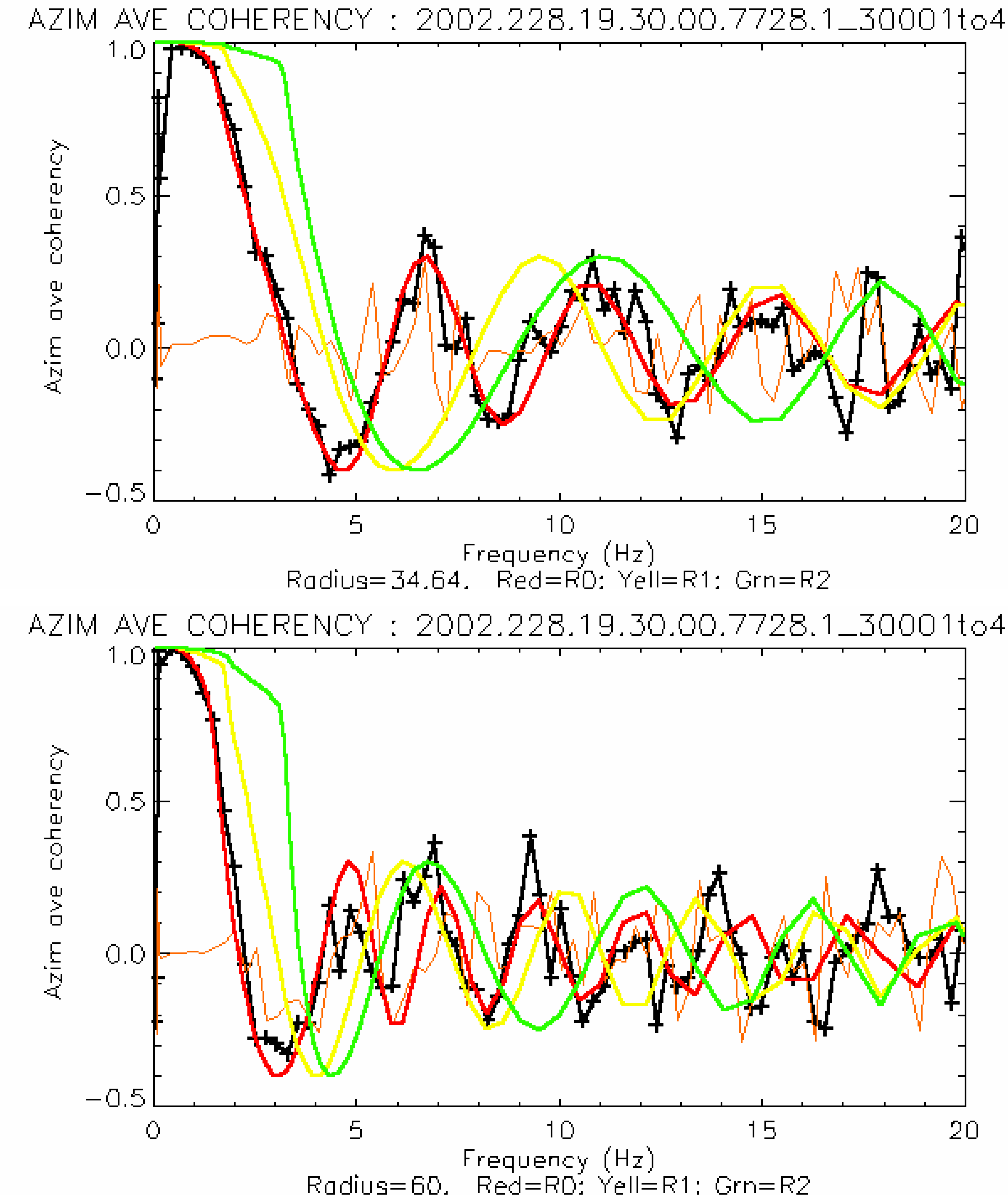


Fig. 6. **Not a final model**. Model PkInit". PKL array only; initial fit of field and model coherencies, using a shallow layered earth of three layers over sandstone & granite basement.

Red: mode R0. Yellow: mode R1. Green: mode R2.

H	VP	VS	RHO	QP	QS	ETAP	ETAS	FREFP	FREFS	
10.	360	180	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
10	1700	250.	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
100	1700	350.	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
1000.	2940	1700	2.39	0.0	0.0	0.0	0.0	1.0	1.0	sandstone
0.	6040	3490	2.8	0.0	0.0	0.0	0.0	1.0	1.0	granitic basement

Fig. 7. Thickness and velocity model “PkInit” derived for the PKL array. The top three layers of this partial model are well resolved in thickness and shear velocity by this small array. Deeper layers are interpreted later, in Figures nn, using data from the large PK array.
(Compressional wave velocities are guesses assuming a water table at 10 m depth, and Poissons ratio of 0.25 for consolidated rock).

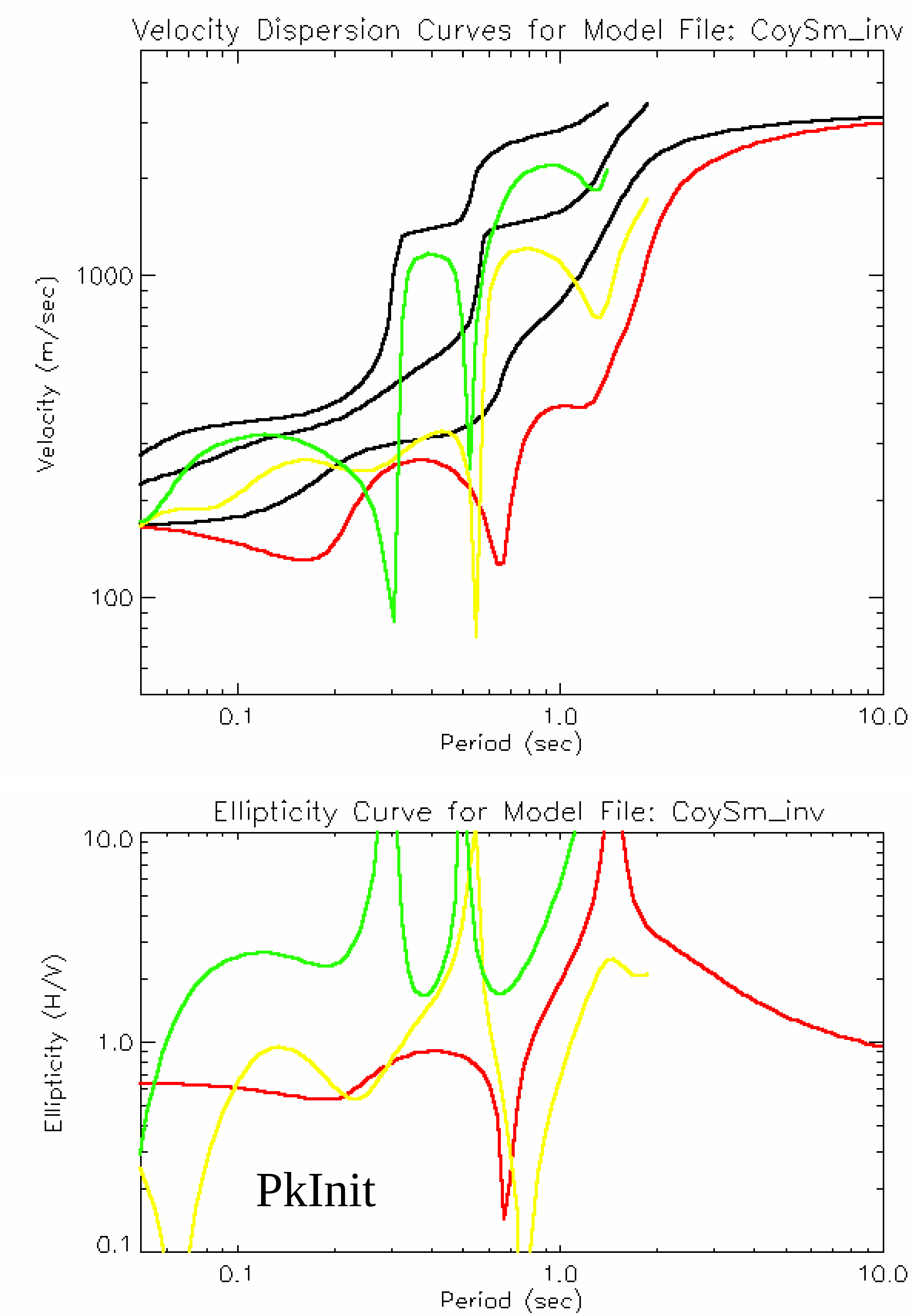


Fig. 8. Phase velocities (black), group velocities and H/V ratio for the initial shallow layered-earth model "PkInit"used in Figure 6.
Red: mode R0. Yellow: mode R1. Green: mode R2.

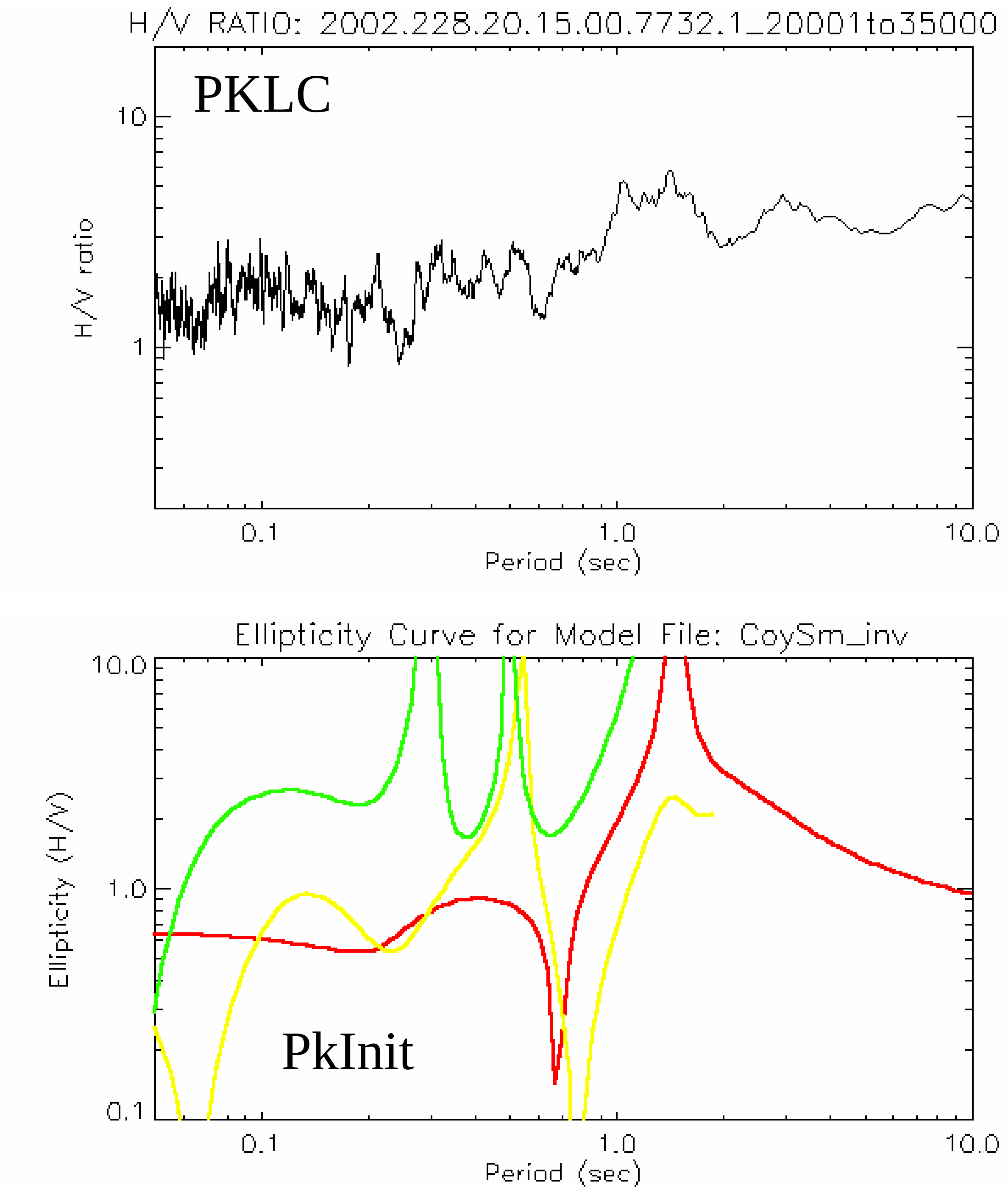


Fig. 9. (Top) HVSR for field data, PKL array.
(Bottom) H/V for model "PkInit, from Fig. 8.
Red: mode R0. Yellow: mode R1. Green: mode R2.

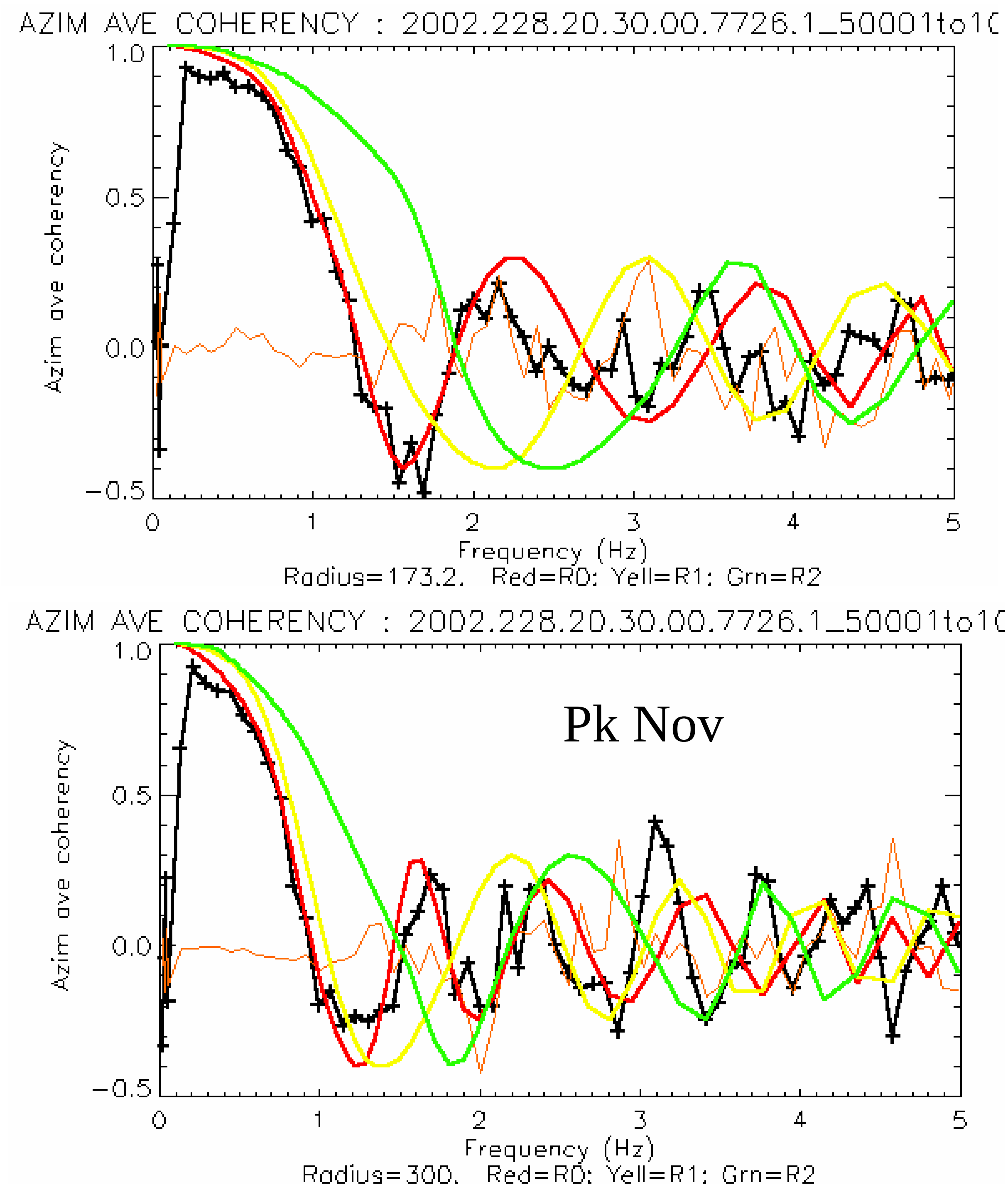
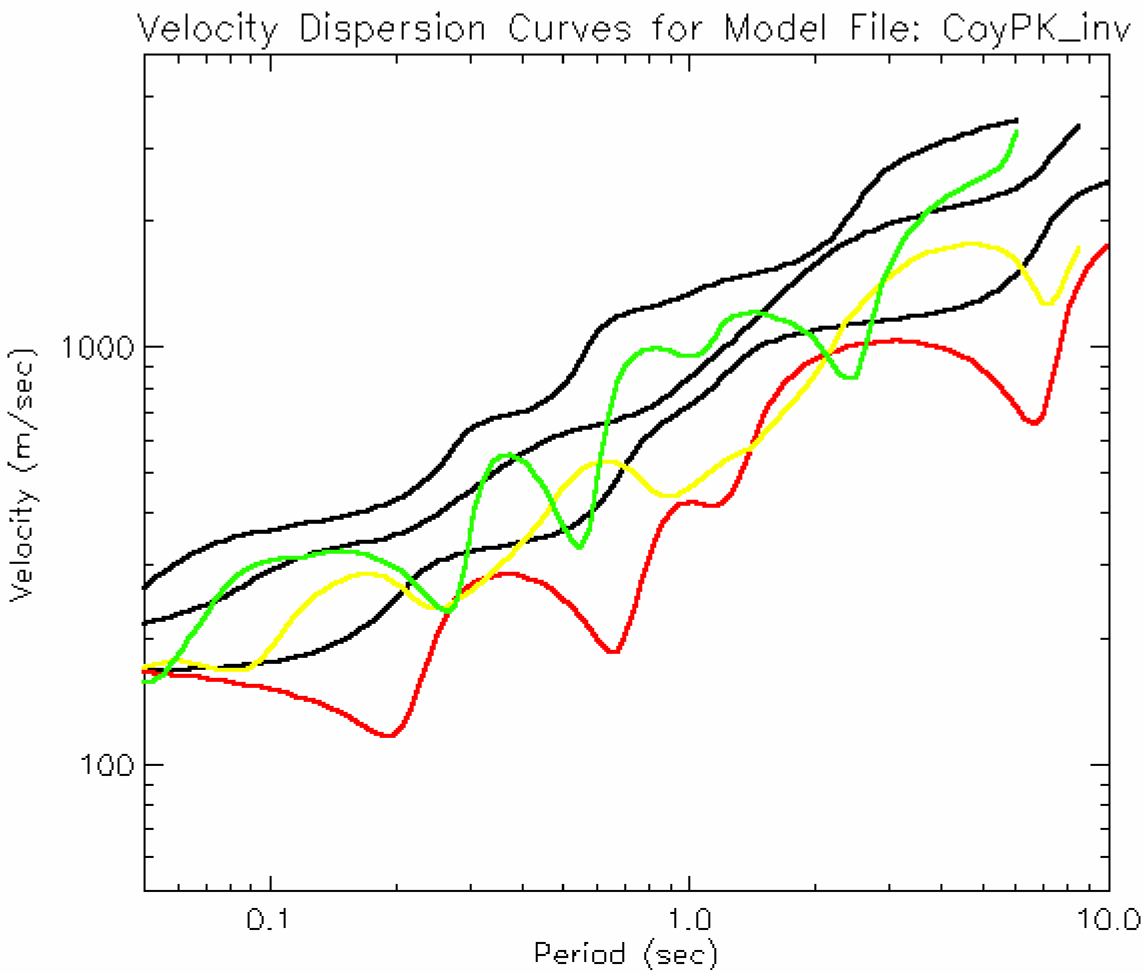


Fig. 10. **Not a final model.** Model “PkNov” . PRK array fit of field and model coherencies, using a shallow layered earth from Fig. 6., plus two deeper layers over sandstone & granite basement.
Red: mode R0. Yellow: mode R1. Green: mode R2.

H	VP	VS	RHO	QP	QS	ETAP	ETAS	FREFP	FREFS	
10.	360	180	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
10	1700	230.	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
100	1700	380.	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
300	1800	750	2.0	0.0	0.0	0.0	0.0	1.0	1.0	
3000	2380	1400	2.0	0.0	0.0	0.0	0.0	1.0	1.0	
1000.	2940	1700	2.39	0.0	0.0	0.0	0.0	1.0	1.0	sandstone
0.	6040	3490	2.8	0.0	0.0	0.0	0.0	1.0	1.0	granitic basement

Fig. 11. **Not a final model** . Model "PkNov". Thickness and velocity model used in Fig. 10, derived for the large PRK array, using upper layers previously derived from the small PKL array. The field data does not resolve the thickness of layer 5, but does appear to resolve the Vs to order 10%.

(Compressional wave velocities are guesses assuming a water table at 10 m depth, and Poissons ratio of 0.25 for consolidated rock).



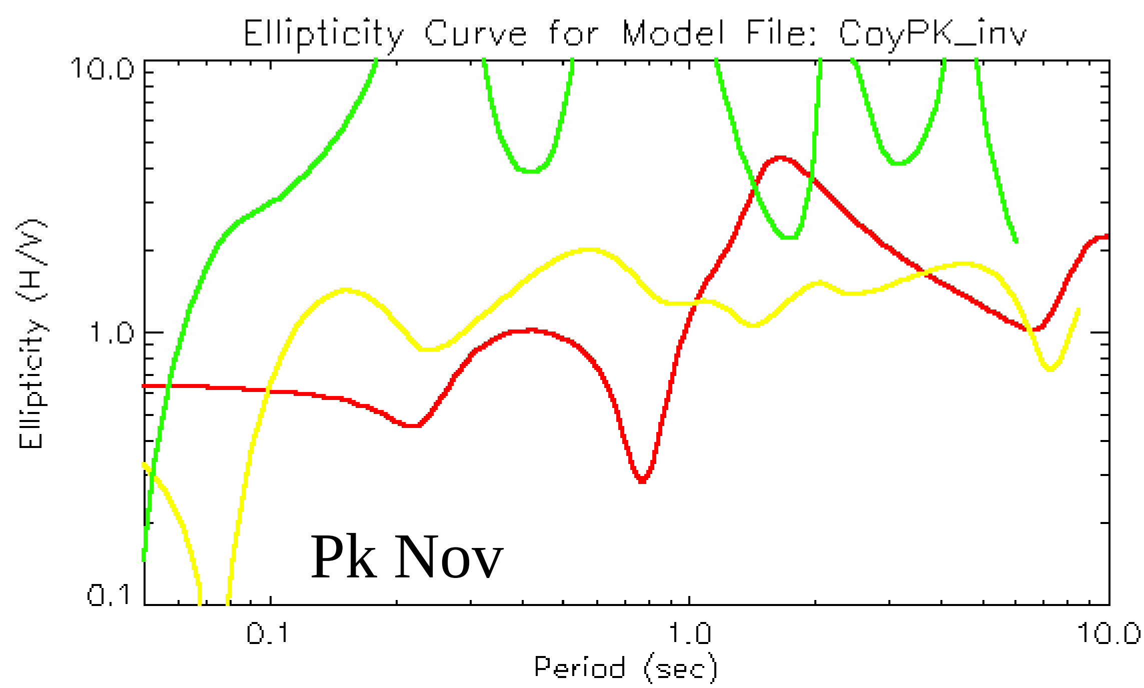


Fig. 12. **Not a final model.** Model “PkNov”. Phase velocities (black), group velocities and H/V ratio for the layered-earth model used in Figures 10,11. Red: mode R0. Yellow: mode R1. Green: mode R2.

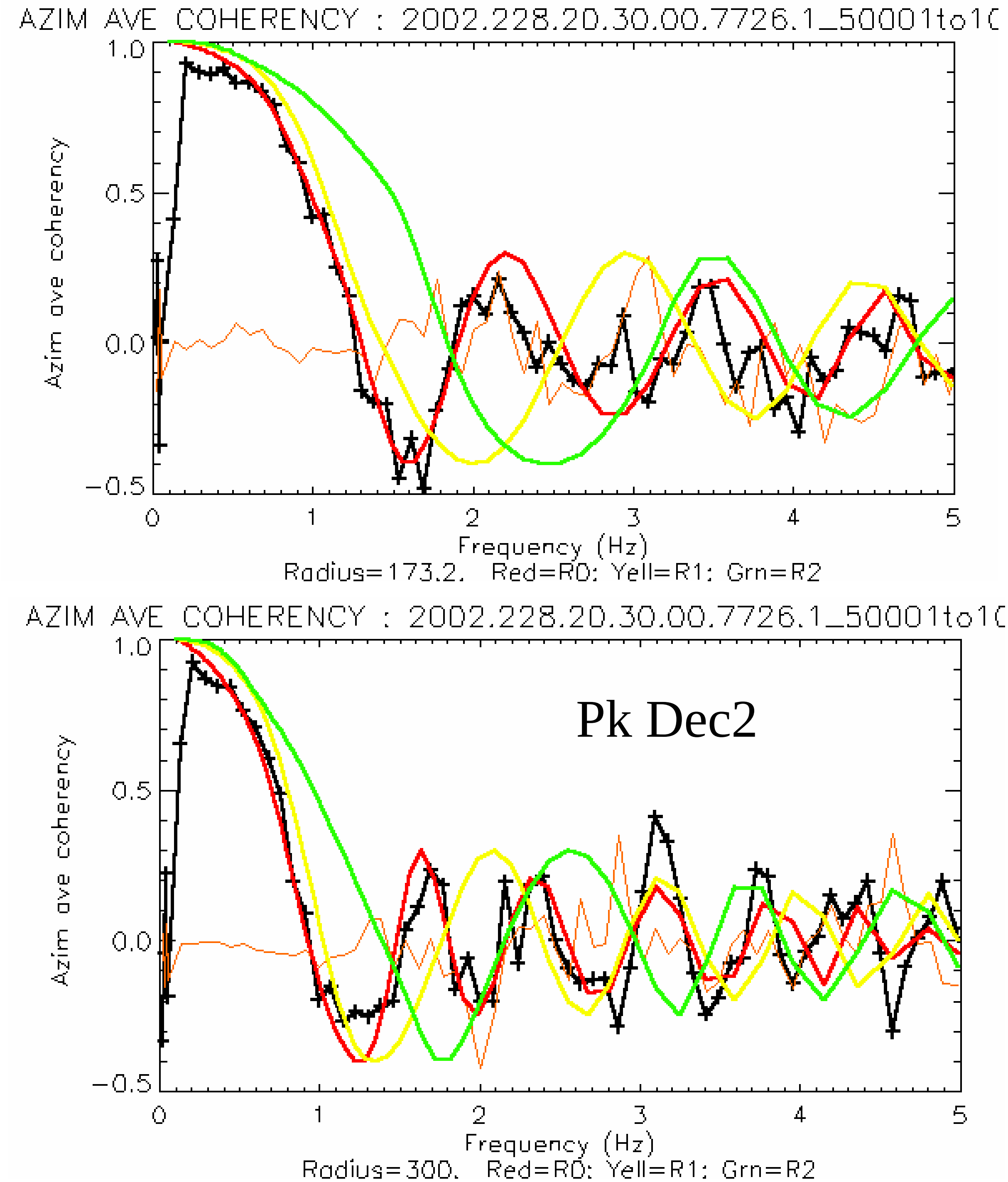


Fig. 13. A possible final model "PkDec2". PRK array fit of field and model coherencies, using a shallow layered earth from Fig. 6., plus four deeper layers fitting this data, over a hypothetical sandstone & granite basement.

Red: mode R0. Yellow: mode R1. Green: mode R2.

H	VP	VS	RHO	QP	QS	ETAP	ETAS	FREFP	FREFS	
10.	360	180	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
10	1700	230.	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
50	1700	340.	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
60	1700	440.	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
100	1800	750	2.0	0.0	0.0	0.0	0.0	1.0	1.0	
190	1800	750	2.0	0.0	0.0	0.0	0.0	1.0	1.0	
3000	2380	1200	2.0	0.0	0.0	0.0	0.0	1.0	1.0	
1000.	2940	1700	2.39	0.0	0.0	0.0	0.0	1.0	1.0	sandstone
0.	6040	3490	2.8	0.0	0.0	0.0	0.0	1.0	1.0	granitic basement

Fig. 14. Model “PkDec2”. Thickness and velocity model used in Fig. 12, derived for the large PRK array, using upper layers previously derived from the small PKL array. The field data does not resolve the thickness of layer 7, but does appear to resolve the Vs to order 20%.

(Compressional wave velocities are guesses assuming a water table at 10 m depth, and Poissons ratio of 0.25 for consolidated rock).

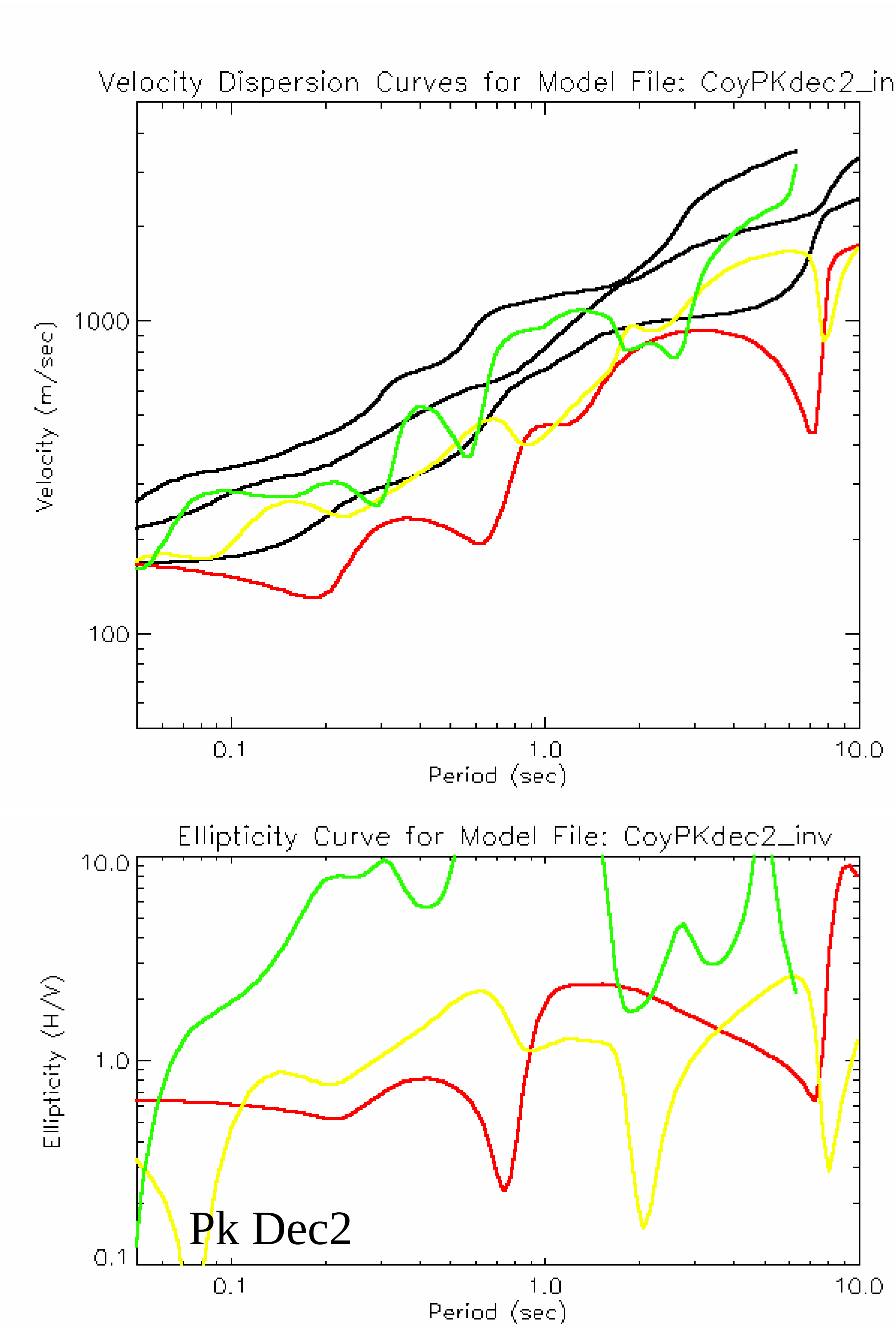


Fig. 15. A possible final model "PkDec2". Phase velocities (black), group velocities and H/V ratio for the layered-earth model used in Figures 13,14.
Red: mode R0. Yellow: mode R1. Green: mode R2.

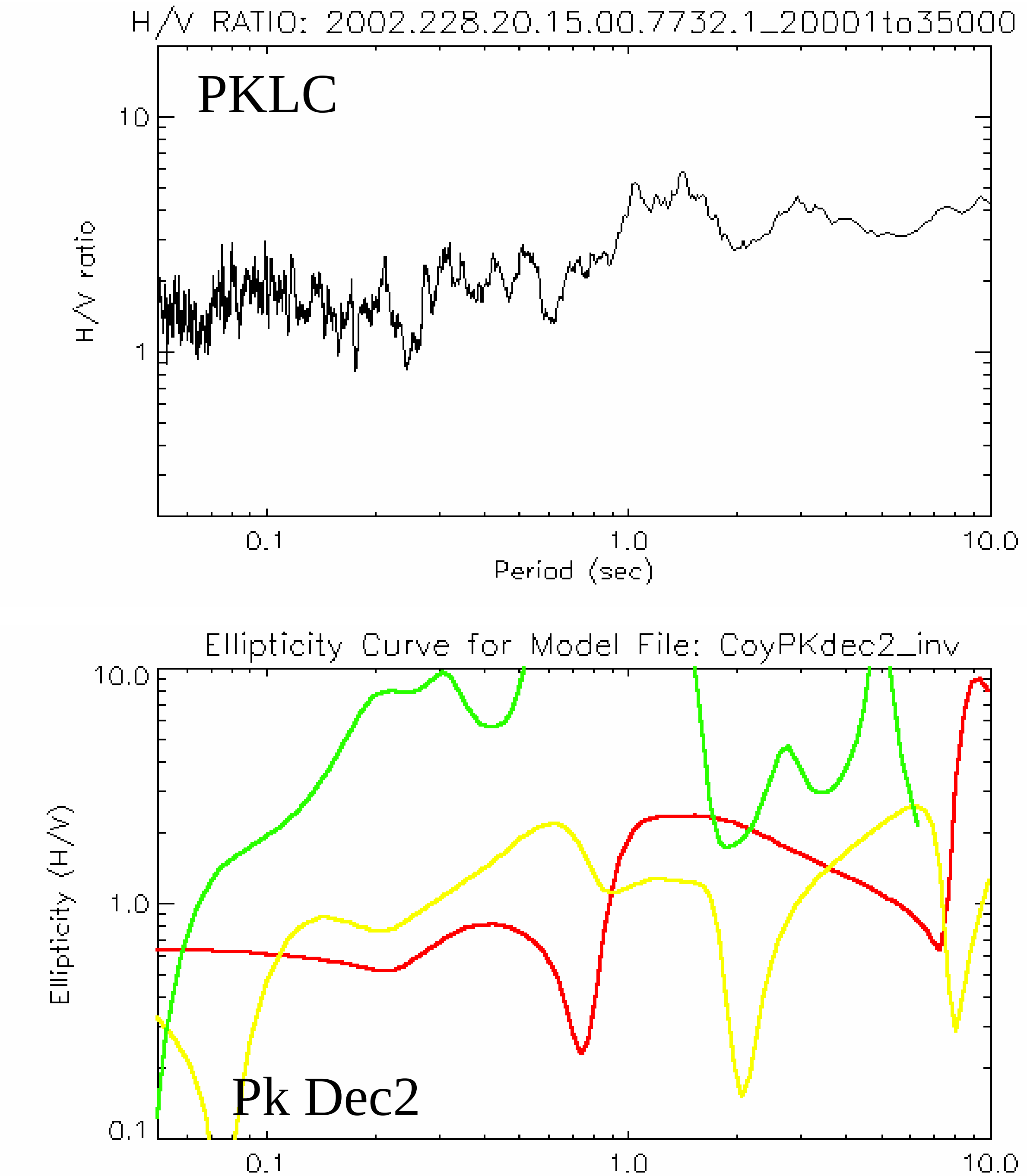
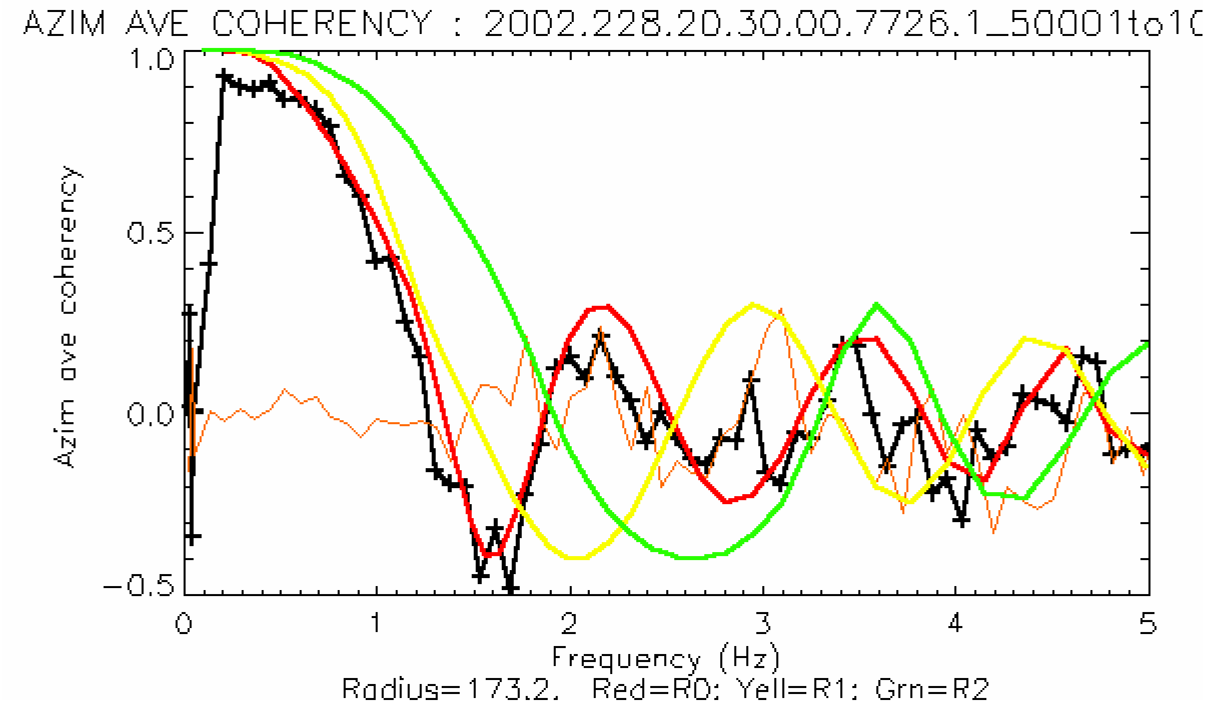


Fig. 16. (Top) HVSR for field data, PKL array.
(Bottom) H/V for model"PkDec2", from Fig. 15.
Red: mode R0. Yellow: mode R1. Green: mode R2.



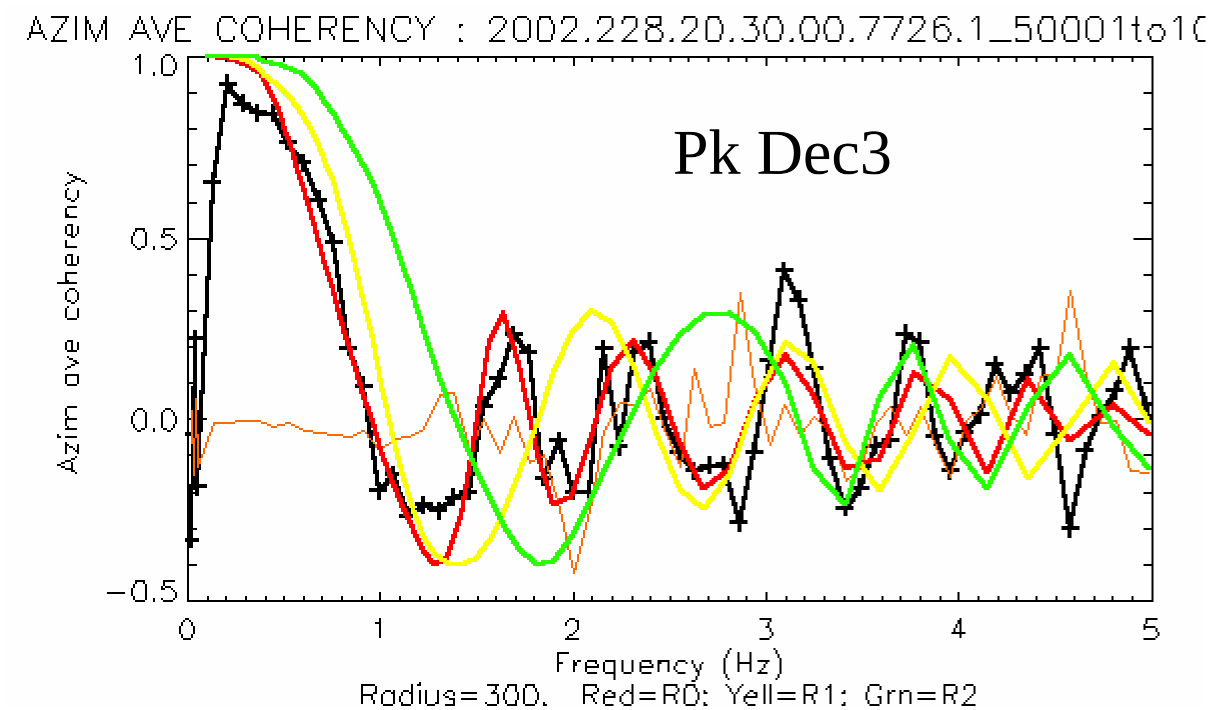


Fig. 17. A alternate possible final model “PkDec3”. PRK array fit of field and model coherencies, with improved fit to HVSR spectra. The model has a reduced depth to a hypothetical sandstone & granite basement.
Red: mode R0. Yellow: mode R1. Green: mode R2.

H	VP	VS	RHO	QP	QS	ETAP	ETAS	FREFP	FREFS	
10.	360	180	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
10	1700	230.	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
50	1700	340.	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
50	1700	400.	1.78	0.0	0.0	0.0	0.0	1.0	1.0	
300	1800	850	2.0	0.0	0.0	0.0	0.0	1.0	1.0	
500	2380	1000	2.0	0.0	0.0	0.0	0.0	1.0	1.0	
1000.	2940	1700	2.39	0.0	0.0	0.0	0.0	1.0	1.0	sandstone
0.	6040	3490	2.8	0.0	0.0	0.0	0.0	1.0	1.0	granite

Fig. 18. Model “PkDec3”. Thickness and velocity model used in Fig. 14, derived for the large PRK array, with effort to obtain a match between modelled and observed HVSR.

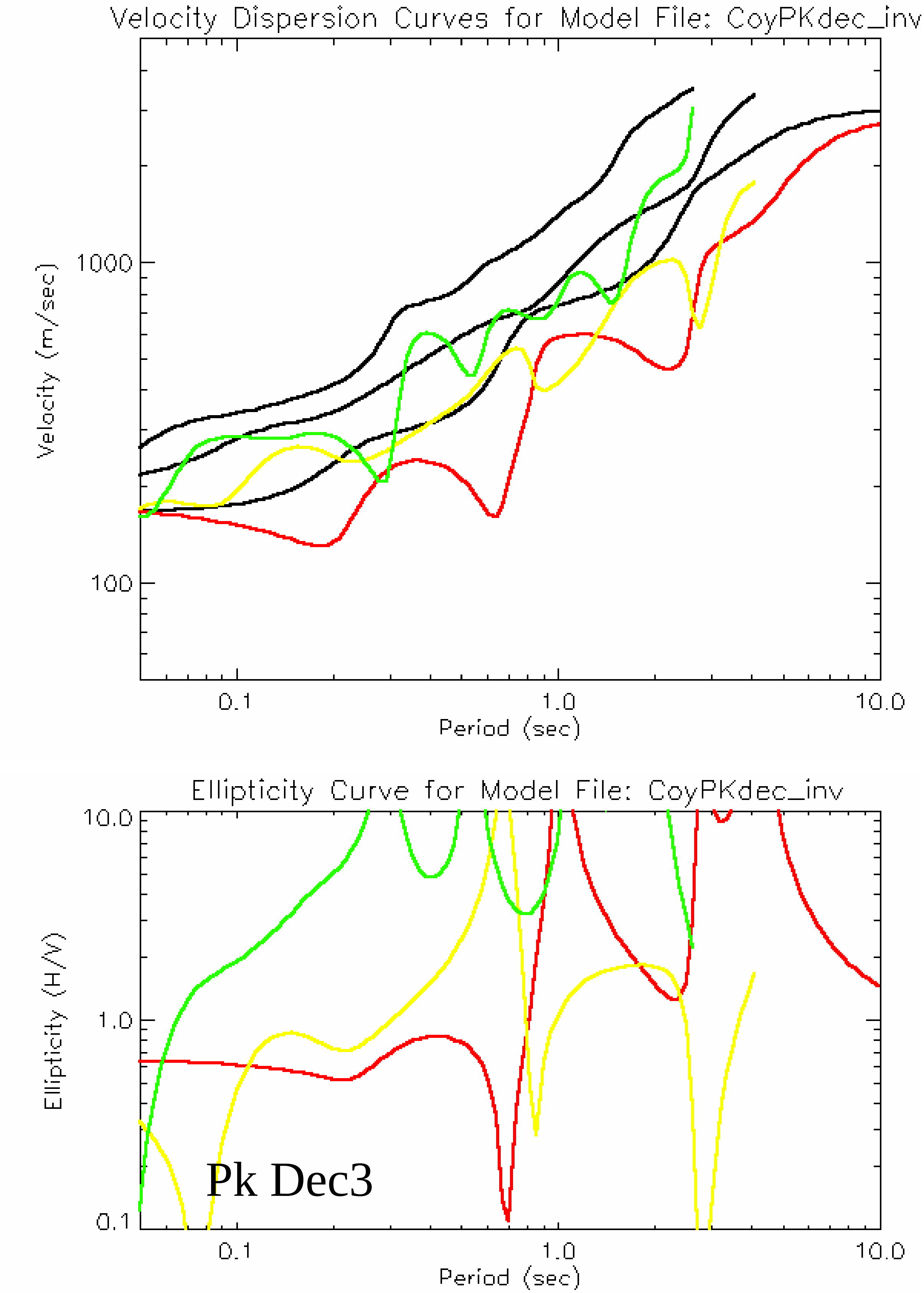


Fig. 19. Phase velocities (black), group velocities and H/V ratio for the alternative layered-earth model "PkDec3" used in Figure 17.
Red: mode R0. Yellow: mode R1. Green: mode R2.

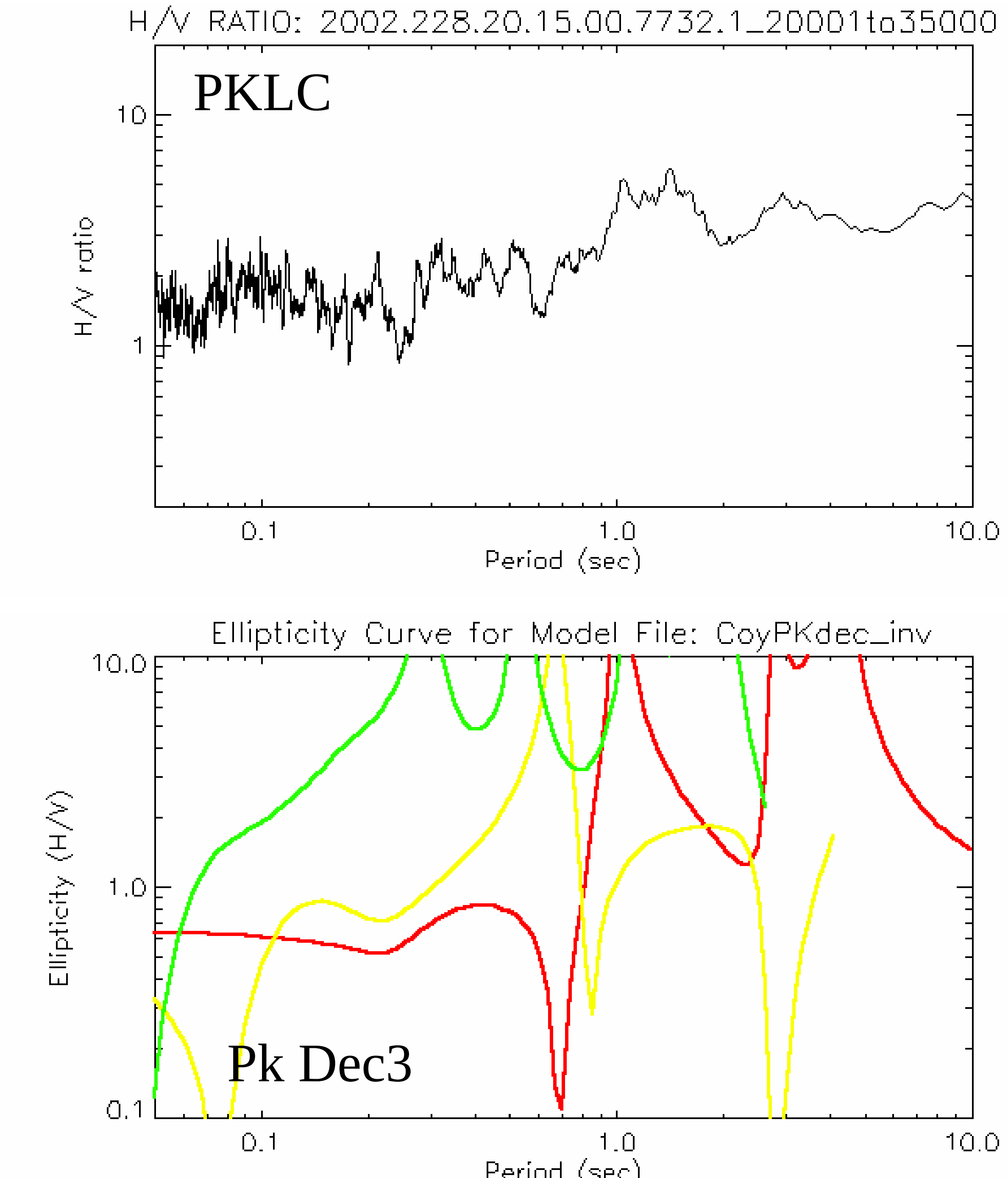


Fig. 20. (Top) HVSR for field data, PKL array.
(Bottom) H/V for model "PkDec3", from Fig. 18.
Red: mode R0. Yellow: mode R1. Green: mode R2.

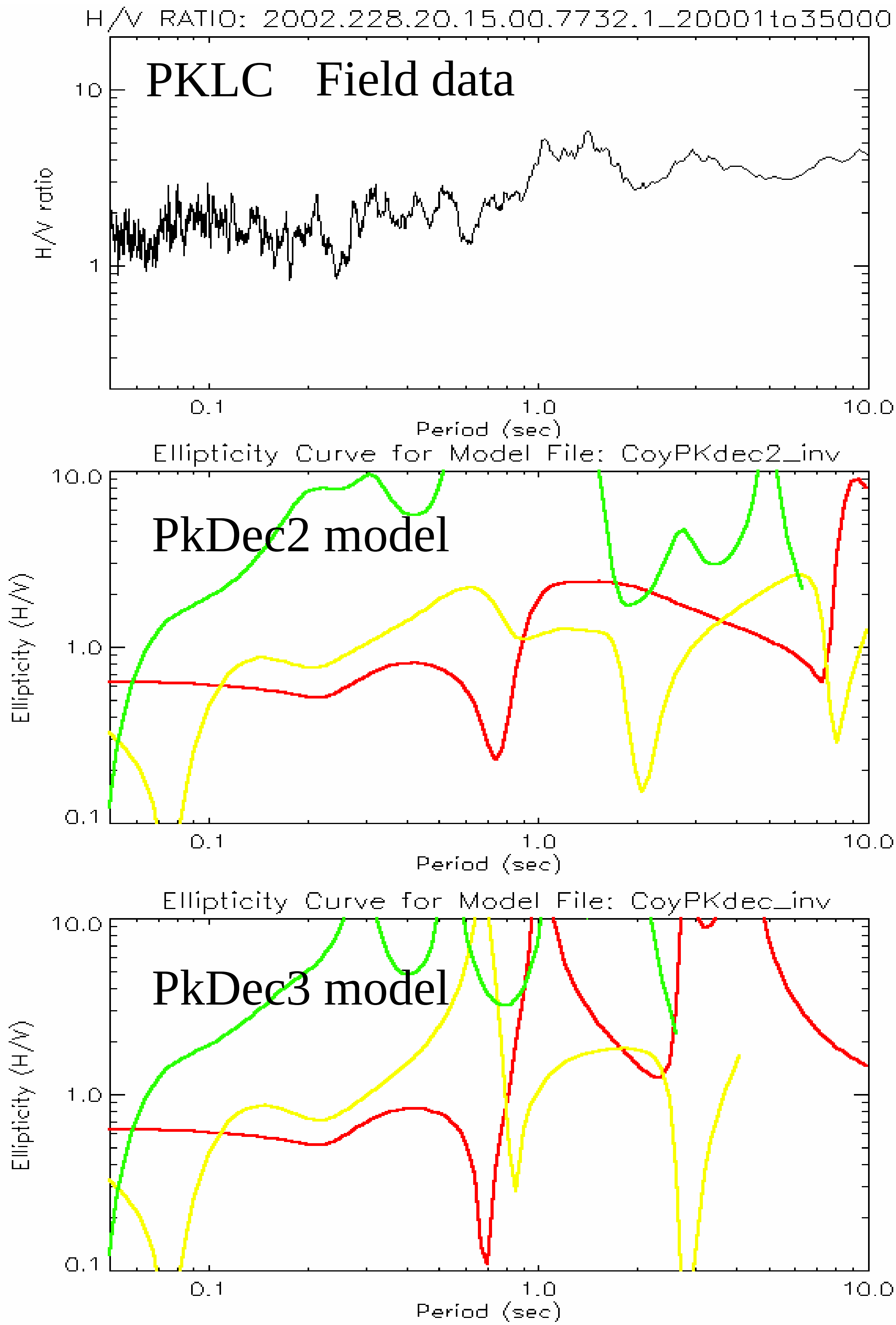


Fig. 21. Direct comparison of (top) field data HVSR, (middle) modelled H./V for model "PkDec2", and (bottom) model "PkDec3".
Red: mode R0. Yellow: mode R1. Green: mode R2.

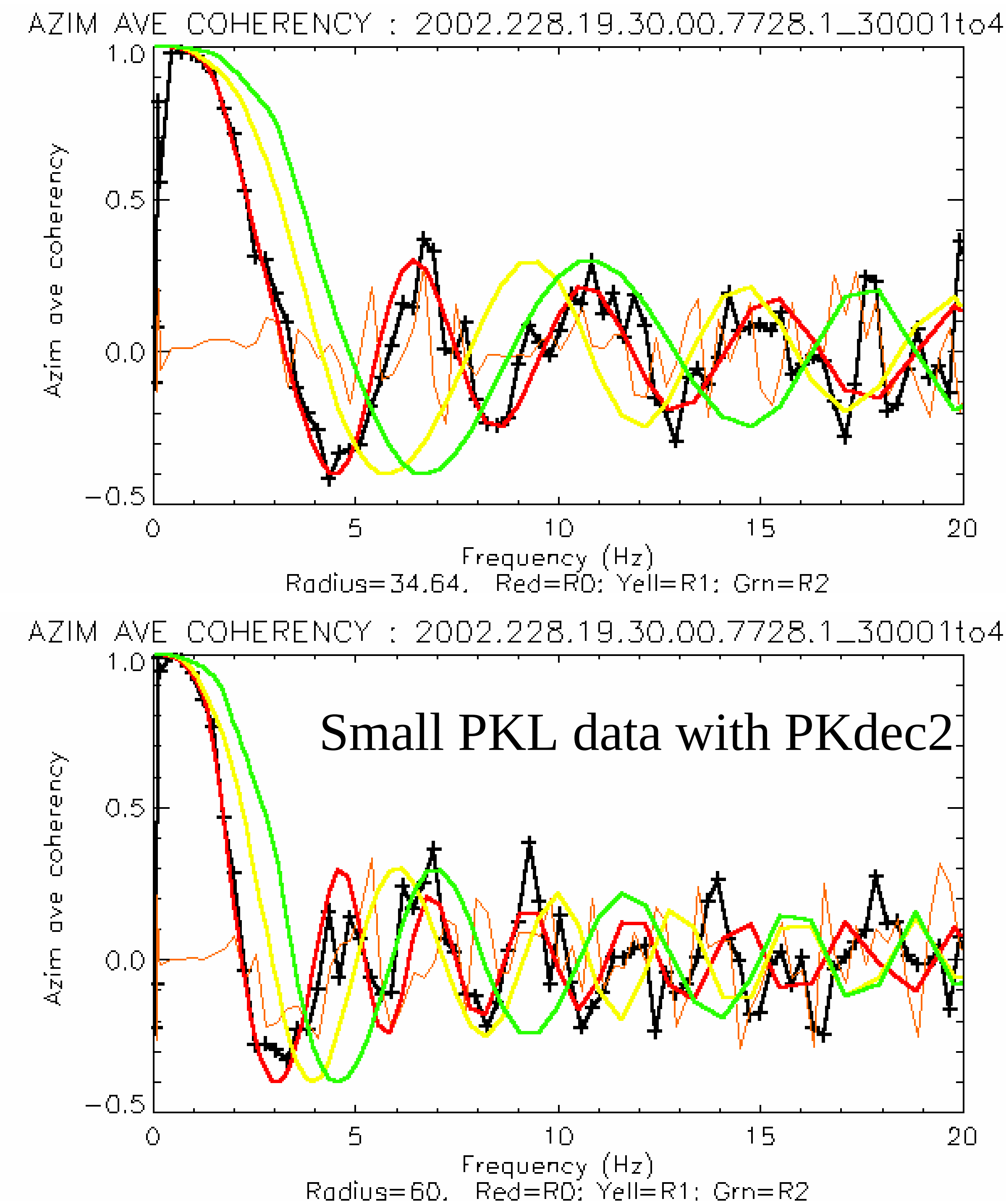
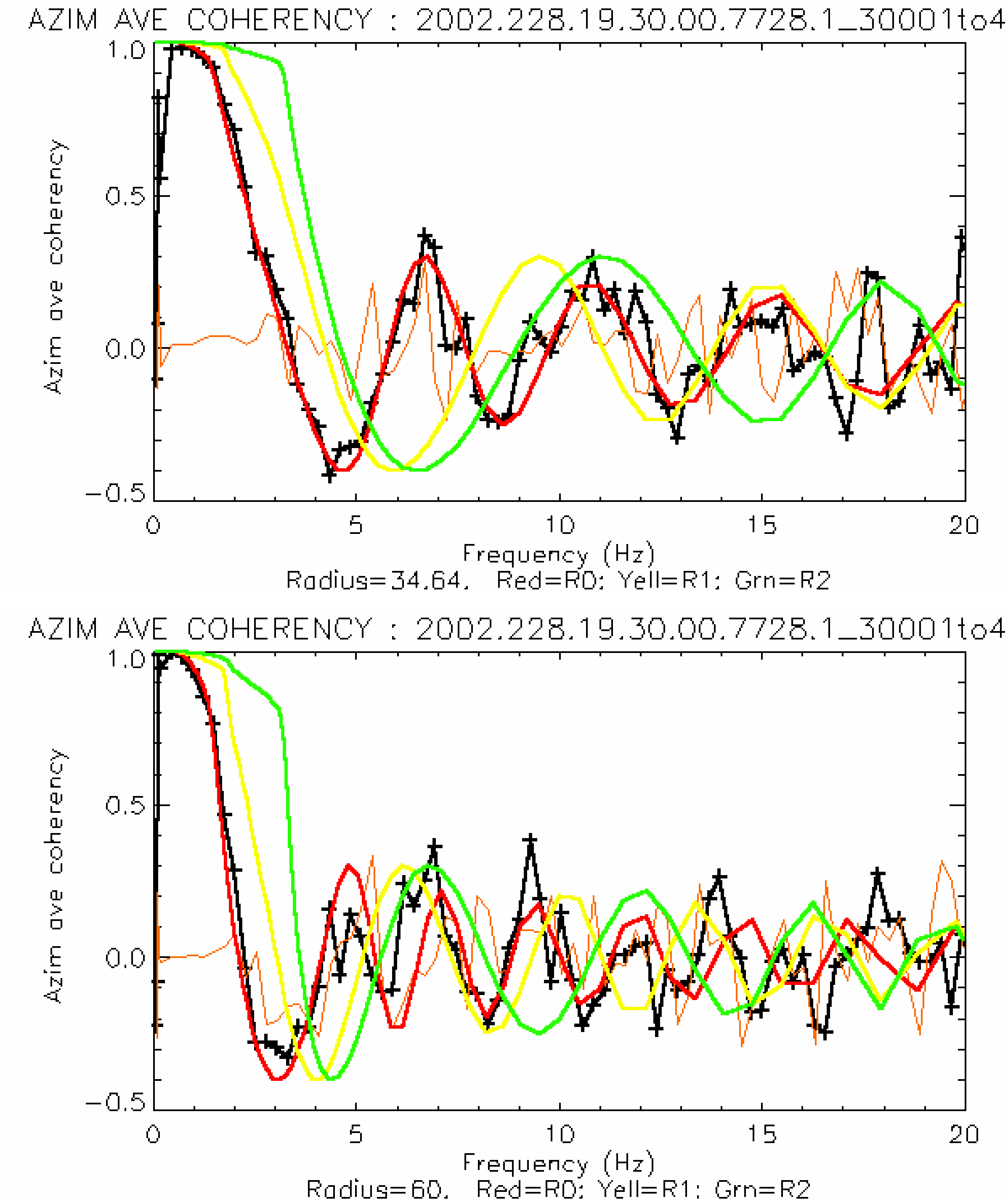


Fig. 22. Theoretical coherencies for the model "PkDec2" plotted with field coherency data for the small PKL array. Red: mode R0. Yellow: mode R1. Green: mode R2.



Repeat of Fig. 6. The initial fit of upper layers (model "PkInit") data from the small PKL array.
Red: mode R0. Yellow: mode R1. Green: mode R2.

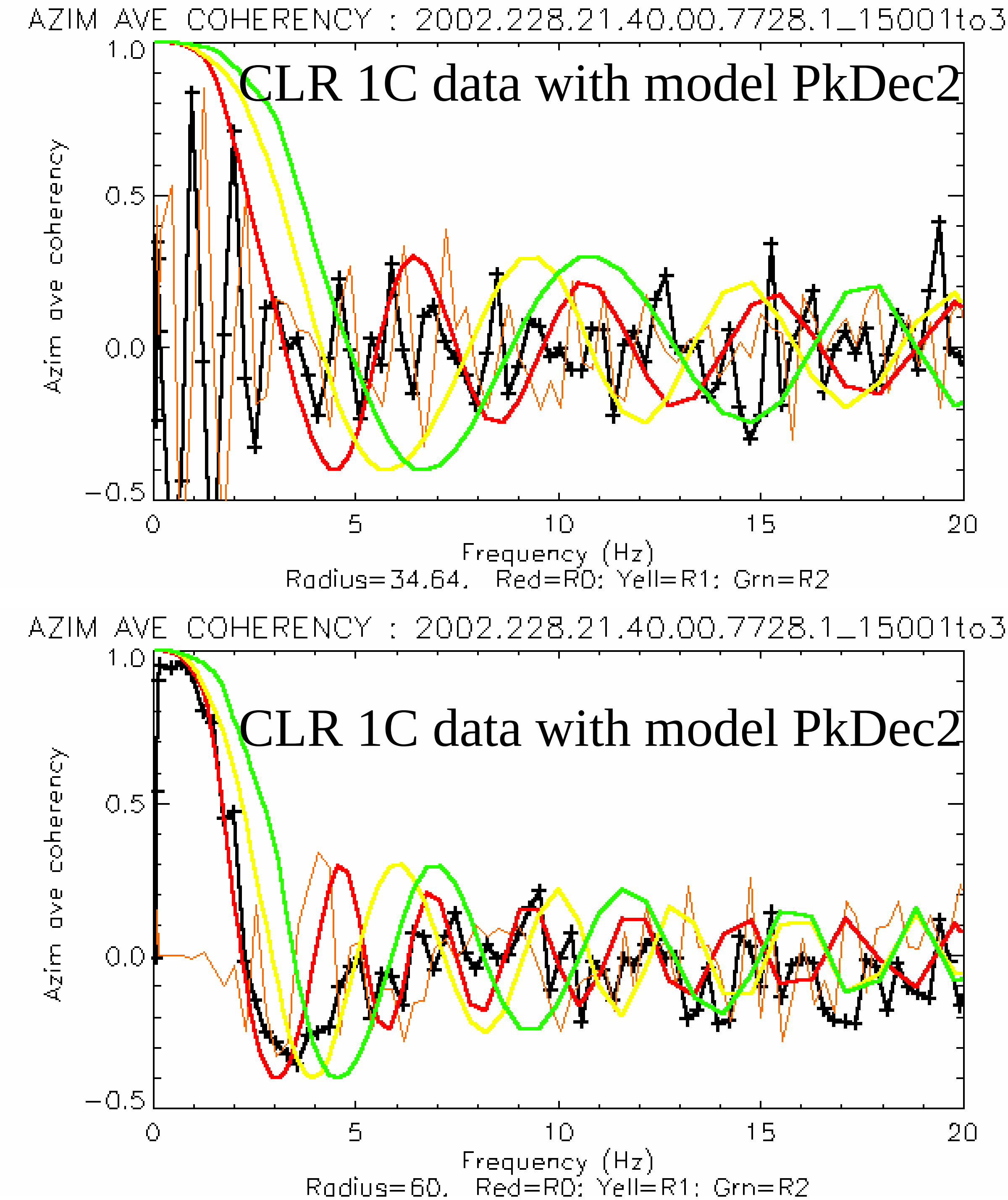


Fig. 23. Theoretical coherencies for the possible final model "PkDec2"; with the field coherency data from a sample from the small array CLR.
Red: mode R0. Yellow: mode R1. Green: mode R2.

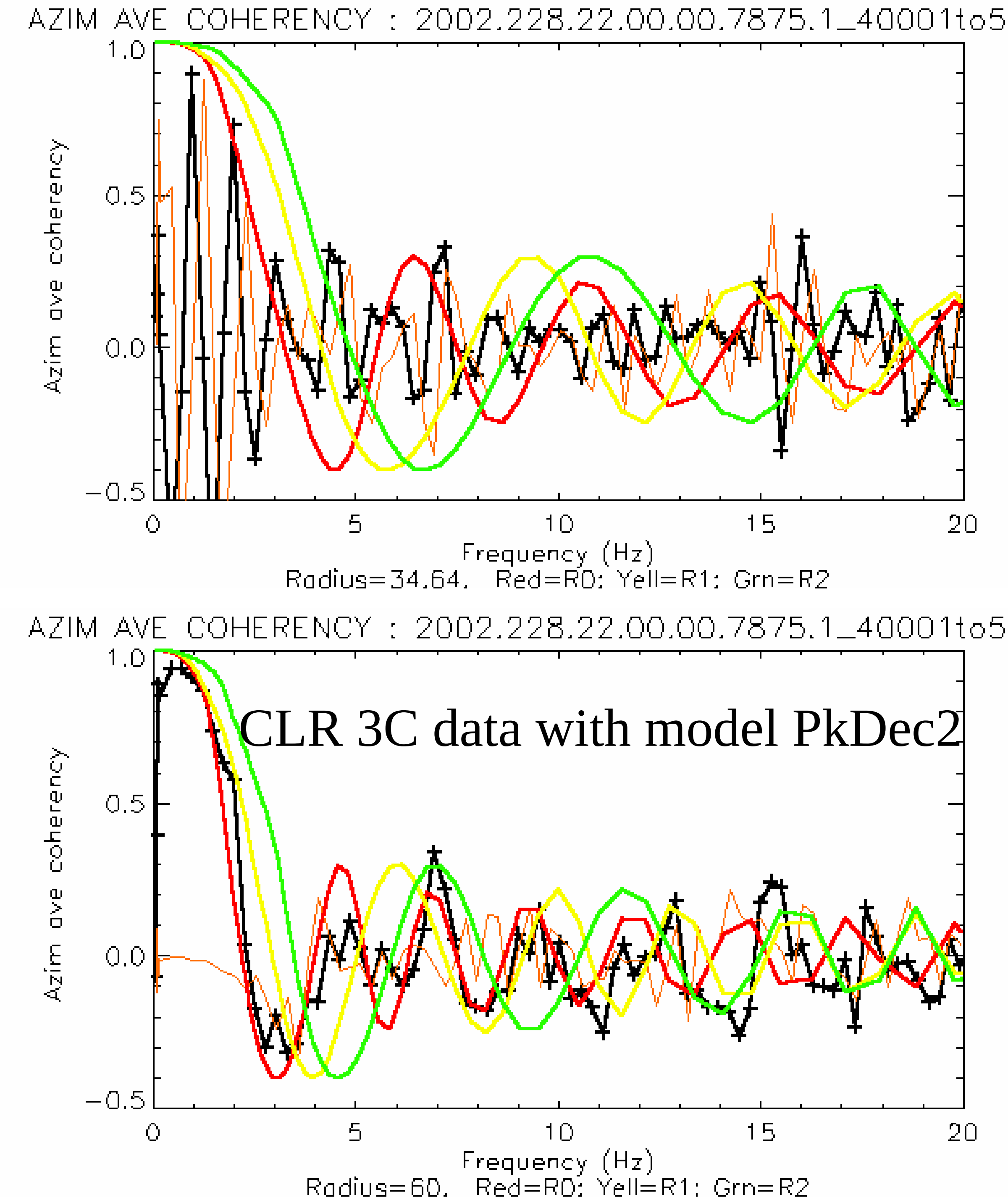


Fig. 24. Theoretical coherencies for model "PkDec2"; with the field coherency data from another sample from the small array CLR.
Red: mode R0. Yellow: mode R1. Green: mode R2.

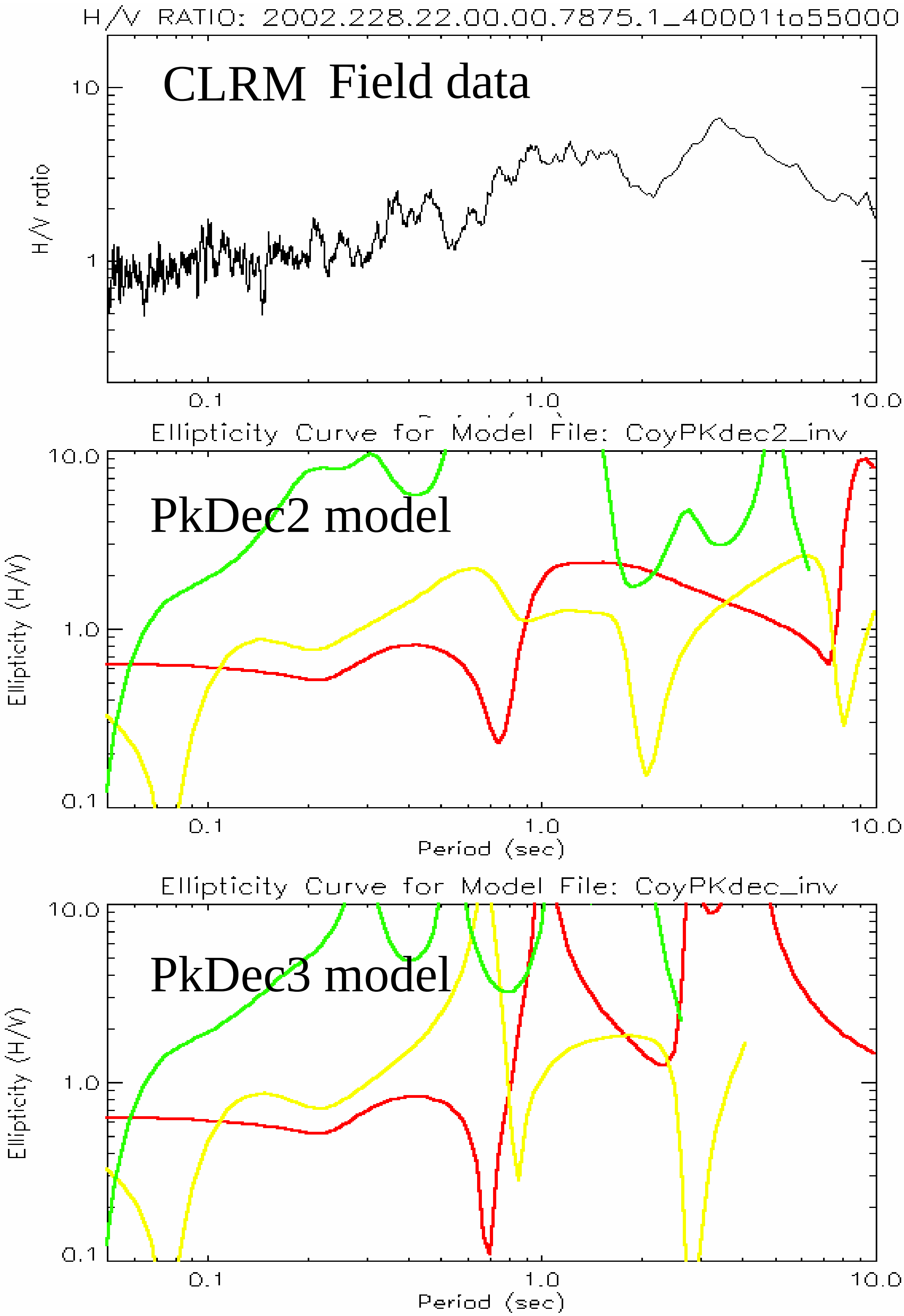


Fig. 25. Direct comparison of (top) field data HVSR for small array CLR, (middle) modelled H./V for model "PkDec2", and (bottom) model "PkDec3".
Red: mode R0. Yellow: mode R1. Green: mode R2.

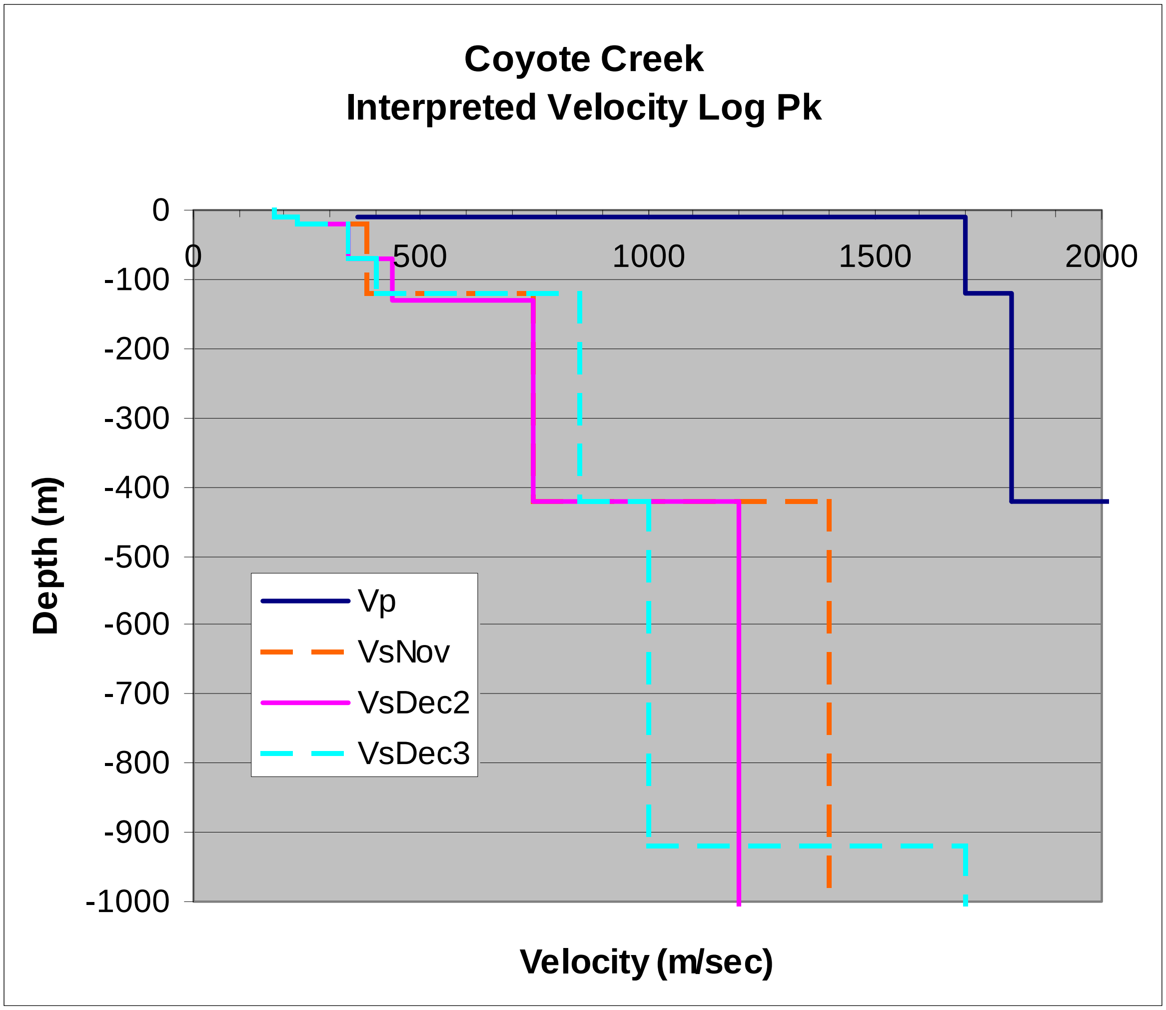


Fig. 26. Velocity-depth profiles for the preliminary model "PkNov" (of Fig. 10), and final models "PkDec2" and "PkDec3". The Vp data is assumed, and constant for all models (assuming a water table at depth 10 m). The Vs data and layer thicknesses for each model are resolved by the combination of azimuthally-averaged coherencies from the small PKL and large PRK arrays.

Vs Dec2 is the preferred model giving the best fit of coherencies to a layered model (Figs. 13 and 22).

Vs Dec3 is the alternative model which gives a poorer fit to field data coherencies at low frequencies 0.3-1 Hz, but it gives theoretical H/V ratios which correlate better with peaks in the HVSR spectra of field data (Figs. 17, 20, 21). The major difference of this alternative model is that hard-rock basement is placed at depth 920 m (compared with order 3400 m for the preferred model).

See Figs. 7, 11, 14, 18 for Tables of velocity data.

APPENDIX 1

PRELIMINARY INTERPRETATION – COYOTE CREEK VERTICAL-COMPONENT DATA

Subject:
Re: Fw: coords of Coyote Ck stations
Date:
Fri, 01 Nov 2002 14:11:34 +1100
From:
Michael Asten <michaelasten@flagstaff-geoconsultants.com.au>
Organization:
Flagstaff GeoConsultants
To:
"David M. Boore" <boore@usgs.gov>
References:
1 , 2 , 3

A few interesting results.
The following is a composite "manual inversion" for Coyote Park PRK Array (300m side) plus small Park PKL Array (60
m side). I havent looked at the borehole small array CLR as yet.

```
======
MODEL.01
Coyote Large array
ISOTROPIC
MGS
FLAT EARTH
1-D
CONSTANT VELOCITY
LINE08
LINE09
LINE10
LINE11
H       VP VS      RHO QP QS ETAP ETAS FREFP FREFS
10.  360   180   1.78    0.0 0.0 0.0 0.0 1.0 1.0
10  1700   230.  1.78    0.0 0.0 0.0 0.0 1.0 1.0
100 1700   380.  1.78    0.0 0.0 0.0 0.0 1.0 1.0
300 1800   750  2.0   0.0 0.0 0.0 0.0 1.0 1.0
3000 2380 1400   2.0  0.0 0.0 0.0 0.0 1.0 1.0
1000. 2940  1700   2.39   0.0 0.0 0.0 0.0 1.0 1.0
0.    6040  3490   2.8    0.0 0.0 0.0 0.0 1.0 1.0
============
```

The density and VP parameters are pure guesses.
For the top 4 layers, thickness and velocity for each layer appear to be resolvable to order 10%. Better than I would have
expected, but we have a spread of wavelengths from 10 m to 2200 m and 4 different array station spacings to work with.

The 5th layer is effectively "basement" to the big array, since the lowest useful freq is 0.45 Hz,
with Vphase 1000 m/sec, ie wavelength is order 2200 m. The low freq limit for a SPAC array is an array station
separation is order wavelength/8.

I have made no attempt to consider higher Rayleigh modes, but expect some improvement in fit if I do (but that wont be
soon - there is a fair bit of work involved in that step).

I have assumed the array geometry as per the original diagrams; if the GPS coords as supplied in recent email are in fact
correct, then it will be surprising that a distorted small PKL array can deliver results for the upper layers with the resolution
that this appears to have achieved.

It is curious that this continually increasing Vs model predicts a very poor Nakamura-type H/V spectrum (no
retrograde-prograde ellipse conversions) hence I expect that H/V spectra for the site do not show distinct resonance peaks
other than a broad peak at T=1.5 sec. I dont have the horiz data so cant test this hypothesis. Have you had any success in
recovering it yet?

I have not attempted to model Vs inversions; a layer of silt under sand could certainly produce such an inversion, and I think
the method would resolve a thick case of inversion, but I dont know for sure. This data thus far does not seem to warrant
use of any low veloc layers.

Does this mumbling have any ring of truth? Worth continuing?

Regards,
Michael Asten
Principal Research Fellow, Monash University

APPENDIX 2

SPECIFICATIONS OF DATA ACQUISITION

Subject: RE: Fw: coords of Coyote Ck stations
Date: Fri, 08 Nov 2002 11:07:26 -0600
From: Hortencia Citlali Flores Estrella <HFloresE@iingen.unam.mx>
To: Michael W Asten <Michael.Asten@sci.monash.edu.au>
CC: David Boore <boore@usgs.gov>

The CLR small array was around the borehole laid out at a different time and with a diiferent corner location. The CLR1 station was the
closer one to the borehole.

Both of the small triangles were measured with tape and compass, so tou can consider them as equilateral traingles of 60m.

The station numbering on the small PKL triangle is clockwise as shown by the plotted GPS coordinates.

Regards

Hortencia Flores

-----Mensaje original-----
De: Michael W Asten [mailto:masten@mail.earth.monash.edu.au]
Enviado el: MiÃ© 06/11/2002 09:59 p.m.
Para: Hortencia Citlali Flores Estrella
CC: David Boore
Asunto: Re: Fw: coords of Coyote Ck stations

Thanks for this. Unfortunately I am still not clear on the
station positions.

Hortencia Citlali Flores Estrella wrote:

> I`m sorry for not answering you before, I was on the
> field. I think there is no problem with the coordinates.
> The plot I sent was jus schematic, and the station CLRK2
> is the one corresponding to the K2 instrument located at
> the "open classroom"

So was the K2 station the same site as the CLR1 station? Or
was the CLR small array around the borehole laid out at a
different time and with a diiferent corner location?
>
> The coordinates I sent you were the average from the GPS

> of the REFTEK, so maybe the errors were due to the GPS we
> used to locate the big triangle.

The coordinates of the big triangle plot as a symmetric and
equilateral
triangle, using the coordinates you supplied, so I dont have
a problem with this one.

> The small triangle at the
> park was measured with tape and a compass, so maybe the
> coordinates from the station PRKI1 are wrong.

1)Based on these compass and tape measurements, I will take
the small PKL triangle as being a correct equilateral
triangle of side length 60 m.

2)Can you recall whether the station numbering on the small
PKL triangle is anticlockwise (as on the original sketch) or
clockwise (as shown by the plotted GPS coordinates for the
PKL triangle only). The difference does not affect
application of the SPAC technique, but in order that
beamforming can also be applied in future, it would be good
to confirm which coordinates should be used.

3) Can you recall whether the small borehole array CLR1-2-3
was also surveyed by compass and tape? If yes, then I will
assume an equilateral triangle for this array too, but the
GPS coordinates do seem to show CLR2 in the wrong place.

>Now, can you
> tell me how you use the coordinates of the station to make
> the SPAC analysis, please?

Numbering the centre station as S1, the triangle corners as
S2,S3,S4,
the distance R1=(s2-S1), and distance R2=(S2-S3)= sidelength
of triangle,
I compute the matrix of interstation complex coherencies ,
then compute azimuthally averaged coherencies
ave_c(R1)= (coh12+coh13+coh14)/3 , and
ave_c(R2)= (coh23+coh34+coh42)/3. This seems to be what you
have also done in your recent paper on SPAC processing of
data from Mexico (David gave me a copy of your preprint).

For the SPAC method to work we obviously want distances R1
and R2 to be constant around the triangle, so we need to be

sure the triangle is equilateral. Absolute coordinates are
not needed, but note my comment above that it would be good
to confirm the absolute coordinates so HR beamforming can
also be used as part of the comparison of methods.

Many thanks,
Regards,
Michael Asten

>Thank you Hortencia Flores
>
> -----Mensaje original-----
> De: Michael W Asten
> [mailto:Michael.Asten@sci.monash.edu.au]
> Enviado el: Mar 29/10/2002 06:21 p.m.
> Para: David M Boore; Hortencia Citlali Flores
> Estrella
> CC:
> Asunto: Re: Fw: coords of Coyote Ck stations
> I am having some difficulty with these
> coordinates.
> The attached plot shows the original geometry,
> but at the right is a plot of stations taken
> from the coordinates file.
> Even after allowing for the rotation to
> east-north, the array seems distorted. PRKI1
> and PRKI2 appear to be interchanged.   CLRK2 is
> a "new" station, separate from CLR1, but it
> shows as being coincident with CLR1 on the
> original plot.
> Is it possible the GPS coordinates are in
> error? Did the survey in fact use different
> sites for the east end of the CLR (borehole)
> array, and the west end of the PRK (big) array?
>
> Regards,
> Michael Asten
> Principal Research Fellow, Monash University
>
>
> David M Boore wrote:
>
> > ÃƒÆ’Ã‚Â¯Ãƒâ€šÃ‚Â»Ãƒâ€šÃ‚¿
> > ----- Original Message -----
> > From: Hortencia Citlali Flores Estrella
> > To: David M. BooreSent: Monday, October 14,

> > 2002 9:44 AMSubject: RE: coords of Coyote Ck
> > stations
> >
> >
> > Hi Dave: I'm sorry for the delay but here the
> > net has not been working okay. I send you an
> > excell file with the coordinates and also an
> > image with the distribution of the
> > instruments. Hortencia
> >
> > -----Mensaje original-----
> > De: David M. Boore
> > [mailto:boore@usgs.gov]
> > Enviado el: Vie 11/10/2002 04:41
> > p.m.
> > Para: Hortencia Flores
> > CC: Michael W Asten; Michael Asten
> > Asunto: coords of Coyote Ck stations
> >
> > Hortencia--
> >
> > Michael Asten, from Australia, wants
> > to analyze some of the data
> > collected
> > by you this summer. Jack gave us
> > some time series files, but we do
> > not have
> > the coordinates of the stations.
> > Could you send the coordinates?
> > According
> > to the map that I have, the station
> > names are as follows:
> >
> > small triangle at borehole site:
> > CLRM
> > CLR1
> > CLR2
> > CLR3
> >
> > small triangle at park:
> > PRKC
> > PRKL1
> > PRKL2
> > PRKL3
> >
> > large triangle at park:

> > PRKC
> > PRK1
> > PRK2
> > (PRK3 seems to coincide with CLR1)
> >
> > Thanks.
> >
> > --Dave Boore
++
Subject: Re: Fw: Coyote Creek 3C data
Date: Sat, 16 Nov 2002 10:02:00 +1100
From: Michael Asten <michaelasten@flagstaff-geoconsultants.com.au>
Organization: Flagstaff GeoConsultants
To: Russell Sell <rwsell@usgs.gov>
CC: Michael W Asten <Michael.Asten@sci.monash.edu.au>, "David M. Boore" <boore@usgs.gov>
References:
1
Russell Sell wrote:

> Hi Michael,
>
> I believe all your assumptions are correct. Channels 1, 2, and 3
> recorded the Z, NS, and EW components of the Guralp CMG-40T broadband
> sensor and channel 4 recorded the Z component L-4 one hertz sensor.
>
> The DASes SN 7726, 7732, 7879, and 7883 stayed at the same locations
> and only DASes 7728, 7875, and 7877 were relocated (during the time period
> 20:40 to 21:35) to create the CLR array.
>
> Wasn't Hortencia efficient creating three 4-element arrays with only
> 7 sets of instruments?

Certainly yes. Im in process of writing up now, and ther is a lot of useful
info here. Ill copy my recent memo for David, to you.
REgards,
Michael Asten

>
>
> Cheers,
> Russ Sell
>
> >Russell--
> >

> >I sent Michael the data you gave me recently, but I cannot answer his
> >questions regarding components and stations at which the data were
> >collected. Can you please respond to Michael email and tell him how to
> >interpret the file names? Thanks.
> >
> >--Dave Boore
> >
> >
> >----- Original Message -----
> >From: "Michael W Asten" <masten@mail.earth.monash.edu.au>
> >To: "David M. Boore" <boore@usgs.gov>
> >Sent: Wednesday, November 13, 2002 2:36 PM
> >Subject: Coyote Creek 3C data
> >
> >
> >> The two files came thru ok (just; got a rude message from the server
> >> about
> >> exceeding 15Mb limit on the inbox).
> >>
> >> I need some extra info on what the files represent.
> >> 1) original files obtained from you on CD (as documented by Hortencia)
> >> contain
> >> files of form
> >> 2002.228.hh.mm.00.7728.n.asc
> >> where hh.mm is 19.30 for PKL array, 20.00 for PRK(big)+PKL(small)
> >> array
> >> 20:30 for PRK, 21.00 for PRK, 21.30 for PRK,
> >> 21.40 for CLR (small borehole) array.
> >> You gave me channels n=1 and n=4, which I assume are the same vertical
> >> component but from different tranducers (1=accelerometer; 4=L4C
> >> geophone). Right?.
> >>   In my analysis
> >> so far I have used only channel n=1 data and assumed it is the vertical
> >> component.
> >>
> >> 2) The new files sent by email contain files of form
> >> 2002.228.hh.mm.00.7728.n.asc
> >> where hh.mm is 20.15 and 22.00, and n=1,2,3 and 4.
> >> the new times are different from the original set, so must represent new
> >> data
> >> sets in vertical component.
> >>
> >> I am guessing that: 20.15 , which has 7 geophone numbers, is the same
> >> configuration as 20.00, ie it is the composite PRK(big)+PKL(small)
> >> 7-station
> >> array.

> >>
> >> Files 22.00 have the same 7 geophone numbers, and n=1,2,3 and 4 for each
> >> geophone number.
> >> However the time 22.00 is after the CLR (borehole) array was recorded.
> >> Hortencia said in her recent email that the CLR array was installed and
> >> used
> >> after the PK array. Am I correct in deducing that the PRK(big) array
> >> was
> >> recorded simultaneously with the CLR array at time 22.00?
> >> If we assume that geophone numbers 28,75,77,83 represent the CLR array
> >> (as for
> >> time 21.40) the remaining geophones may represent the PRK (big) array
> >> The
> >> remaining geophone numbers 26,32,79 represent
> >> stations PRK2,PRKC, PRK1 in the earlier PRK file at time 20.30. and I
> >> assume
> >> the same geophone numbers at the same stAtion names will apply for time
> >> 22.00.
> >> Pls confirm.
> >>
> >>
> >> Regards,
> >> Michael Asten

> >> "David M. Boore" wrote:
> >>
> >> > Michael--
> >> >
> >> > I went on leave last week, and I will be out of town for most of Nov.
> >22 -
> >> > Dec 1.
> >> >
> >> > This email will be followed by the two emails with the data.
> >> >
> >> > --Dave
>
> **
> Russell W. Sell
> USGS Earthquake Hazards Team   phone: 650-329-5692
> 345 Middlefield Rd., MS 977   fax: 650-329-5143
> Menlo Park, CA 94025
>
> Earthquake info on the internet: http://earthquake.usgs.gov/
>
> **

+++
Subject:
Re: Fw: Coyote Creek report
Date: Fri, 15 Nov 2002 16:32:08 -0800
From: "David M Boore" <boore@usgs.gov>
To: "Michael Asten" <michaelasten@flagstaff-geoconsultants.com.au>
CC:
"Dave Boore" <boore@usgs.gov>
References:
1 , 2

Michael--

Please direct any instrument questions to Russell Sell--- he's the man.

Check this link for a map of the area (http://www.walksanjose.org/olinder_neighborhood.htm). The borehole is across E. William Street from WIlliam Street Park; the property on which the borehole is located is bounded by Coyote Creek (shown in green on the map).

Note that Carl Wentworth included a lat/long for the borehole (1927 datum) in a recent email sent to the people in the group to whom I sent the spreadsheet--- you should have received it. You can probably generate a better map, using the coordinates of the borehole.

I'm very please to hear that the material beneath the borehole and the Park may be very similar. Few measurements were made in both places, and it is important to establish the degree of later variabilty.

Looking at Jom Gibbs' downhole data, I see that they are very noisy--- for the same reason that the CLR data are noisy? In fact, they are so noisy that I am not sure I trust the downhole velocity model. I have yet to compare it with the suspension log model.

--Dave