Answers to the reviewer RNDr. Bohuslav Růžek, CSc.

objection 1: There is the first chapter called "Seismic noise deterministic analysis: single station measurements" at the page i but, substantial part of this chapter deal with seismic arrays.

answer: The most suitable title of the first Chapter would be "Seismic noise analysis: deterministic approach." Then it also fits better with the title of the second Chapter.

objection 2: Selected part of the text is arranged as ".. deterministic analysis..." and "...stochastic analysis...". As far as such a classification is not commonly used for seismic noise measurements, the author should clearly define characteristic features of both approaches and what exactly is understood by that.

answer: As far as the seismic noise analysis concerns, both approaches (deterministic and stochastic) are focused on describing the energy transport phenomena through heterogeneous media, but the deterministic one attempts to explain it formulating an initial boundary value problem involving deterministic equations of motion. The stochastic approach attempts to assess the same dynamics but seeing the energy transport phenomenon as a diffusive one. So that it can be better described by its statistical properties coupled with their scale invariance features. This is explained in page 22 as well as in introduction of paper P2.

objection 3: "two sets of questions" are mentioned at the page 6 but, 5 items follow.

answer: The first set of questions is formed by the first two items whereas the second set is formed by the last three items.

objection 4: The purpose of the figure 1 at the page 1 is unclear and, even if there is in the caption "Logical scheme..." I did not find anything logical in this figure. Moreover, this figure is quite unnecessary.

answer: The site characterization shown in figure 1 is from geological and geotechnical point of view only, i.e., the first step for assessing the site effects. This is also the logical scheme applied in the site effects studies for the city of Rome (see P3 and P4 in particular) that formed the basis of the whole Thesis. The adjective *Logical* is used within the Informatics framework and in such meaning should be understood.

objection 5: It seems that the author is using the terms ”soil shaking” and ”ground shaking” as synonyms. It is necessary to keep in mind, that most geologist understand ”soil” as highly unconsolidated sediment (i.e. ”soil” = specific kind of rock). Since the applicability of the used methods is much broader, it is better to use ”ground shaking” unless the statement is actually limited to measurements on soils.

answer: I have to confess that I have never heard such difference among the Geologist community neither in workshops nor in literature. What I have seen is the difference between *stiff soils* and *soft soils* to indicate consolidated soils (rocks, consolidated sediments, etc.) and sediments (alluvial deposits in particular holocene sediments), respectively. In this respect, ”soil shaking” and ”ground shaking” can be accepted as synonyms.

objection 6: Frequently used formulations like ”Interaction of seismic noise and near surface geology” are incorrect. Interaction is possible only provided both objects influence each other. Evidently, seismic noise has no impact on the geological structure.

answer: The term ”interaction” in the Thesis has a simple generic meaning: The wave field is affected by sources and structures. Knowing the sources, we can investigate the structures and vice versa. Just in that sense the waves ”have impact” on the structures. In this Thesis we do not solve a question whether or how the waves might change the structural properties (e.g. through the liquefaction).

objection 7: At the page 6 there is distinguished ”near-surface geology” and ”inner Earth structure”. Near-surface geology is also (a small) part of the inner Earth structure.

answer: If we want to assess surface geology or deeper Earth structures we will use different techniques and different equipment because the range of frequencies that must be investigated is different, as it is written in page 5 as well as in the introduction of paper P2. As a consequence, it is useful to distinguish between surficial and deep structures.

objection 8: There are typographical errors in the Table 1.1 at the page 7, the row regarding frequencies is incorrect. As postulated in the text at the page 8, this table should document the complexity of seismic noise wave-field. In fact only some qualitative differences between natural and anthropogenic noise are given there.

answer: There are two typographical errors in the row corresponding to frequency. The first one is in the second column and concerns the round brackets, the correct form is: f_{nh} 0.1 - f_{nh} (0.5 - 1) Hz. The second one is in the third column and concerns a wrong character, the correct form is: f_{nh} (0.5- 1 Hz) $>$ 10 Hz. Concerning the second part of the objection, the meaning of the table was to simply demonstrate the noise complexity through listing a broad range of its types, sources, wave types, and so on.

objection 9: There is at the page 9 "...relation with the first frequency..." but, probably correct version should be "...relation with the lowest frequency..."

answer: The adjective "first" is understood as the lowest-frequency peak in the H/V spectrum that is due to the features of the near-surface geology and not due to human activity, such as characteristic frequencies of engines, pumps, pipelines, etc. It can happens that the lowest frequency could be linked with human activity; the more far we are from *free field* conditions and the higher is the probability that this latter case takes place.

objection 10: The caption regarding the figure 1.1. at the page 11 is inconvenient. It refers ambiguously to the red lines. There is no explanation what are the curves Kmax, Kmin.

answer: The red lines are correctly referenced in the caption. What was probably confusing is the formulation. A better text would be: Left column: Vs vertical velocity profiles. Right column: theoretical dispersion curves (solid red lines) computed from the Vs vertical profiles of the left column, and experimental dispersion curves (black stippled lines) with their ± 1 standard deviation (vertical bars). The missing description of the curves Kmin, Kmax is the following: they represent the limits within which the dispersion curve estimate of the Rayleigh waves from array processing is considered to be reliable. To be more specific, they define a limit beyond which spatial aliasing is very likely to occur (see page 15 later).

objection 11: The sentence at the page 12 "In order to allow a reliable ..." is quite obscure to me.

answer: To make the sentence better understandable, it should be: "In order to allow a reliable determination of the vertical Vs velocity structure, the dispersion-curve estimate of the Rayleigh waves of acceptable quality is required. Then the Vs profile can be inferred both through the inversion of the dispersion curve, or through its forward modeling."

objection 12: The abbreviation CVFK at the page 12 is not explained.

answer: The acronym CVFK stands for ConVentional Frequency-wave-number method. From deliverable Del-D18-Wp06.pdf of SESAME project (http://sesame-fp5.obs.ujf-grenoble.fr/SES_TechnicalDoc.htm).

objection 13: The equation 1.1. at the page 13 is incorrect, since the frequency ω_m is summed out according the index m and, cannot be an independent variable on the left hand side at the same time.

answer: Equation 1.1 is a coherence estimate based on the conventional frequency-wavenumber method called CVFK. Belonging this latter method to the family of F-K methods, the estimate 1.1 must depend on frequency and on wave-number. In details, the estimate 1.1 is evaluated in sliding time window and narrow frequency bands around some center frequency, i.e., ω as independent variable on the left hand side of 1.1 while the ω_m on the right hand side of 1.1 are frequencies within the chosen frequency band around ω. Each value of ω has its own frequency band where the ω_m are located. Moreover, for each value of ω we have in the (K_x, K_y) plane one coherence estimator function 1.1, its contouring for a fixed frequency ω is plotted in figure 1.2 as an example.

objection 14: I did not find any reference to figure 1.2 in the text. This figure should contain also the geometry of stations and the frequency for which it holds.

answer: The reference should have been in page 13 after expression 1.2. Figure 1.2 is just to visually underline what is explained through expressions 1.1 and 1.2. In this respect, does not matter at what frequency it has been computed and what is the adopted geometry. The role played by the array geometry is shown in figure 1.4. An improved figure caption of Fig. 1.2 can be: This is schematic figure, in which the specific value of ω and the array geometry is unimportant.

objection 15: The equations (1.5), (1.6) and (1.7) combine inconveniently the symbol R_{th}. The same symbol represents different quantities due to different number of parameters.

answer: The equations under discussion are in paragraph 1.2.3 that refers to theoretical array response function R_{th}. Expression 1.5 refers to the general R_{th} in the (K_x, K_y) plane. The same generic notation R_{th} is used in 1.6 and 1.7 where it means specifically the single and multiple plane waves, respectively.

objection 16: The caption below figure 1.3. at the page 17 contains "...vertical section of the (Kx, Ky) plane", but this is nonsense. The graph in the right part of the figure cannot result from cutting 2D plane by other vertical plane.

answer: The caption would be more clear "array transfer function as a function of K_y at $K_x = 0$". The words "vertical section" should read in that way, actually.

objection 17: The figure 1.4 at the page 19 has useless color scale, which originally defined colors in the middle column.

answer: The gray scale in Fig. 1.4 has the same meaning as the color scale in Fig. 1.3.

objection 18: The Chapter 2 is devoted to the discussion of statistic characteristics of seismic noise. There is insufficient justification of the merit of such studies.

answer: The purpose of Chapter 2 is to explain some basic concepts and ideas to help the reader to better understand the P1 and P2 papers. The motivation to complement the deterministic analysis by the stochastic one is explained on page 21 and page 22 of this Thesis.

objection 19: The Chapter 2.1. is some kind of extraction from the paper P1, but it is quite obscure. Even reading the paper P1 gives sense.

answer: The intention of paragraph 2.1 of Chapter 2 was to help readers to understand the short mathematical part of Paper 1 by extending slightly the derivation of formulas and describing the algorithm.

objection 20: The frequency at page 16 is denoted both as f and F.

answer: After expression 1.6 in page 16, $A(F)$ should read as $A(f)$.

objection 21: It is rather problematic to introduce the Brownian motion into modelling the seismic noise. The premise $\sigma(t) \sim \sqrt(t)$ is not acceptable for seismic noise. If yes, for $t \to \infty$ we would obtain indefinite variance, what is clearly not the case.

answer: The standard deviation of a diffusive process tends to infinity as the time tends to infinity. This is well known. The physical meaning of such a situation is that a system, in a diffusive regime, moves from one point and goes away from it indefinitely up to infinity, provided no boundaries are present. In a physically realistic case, i.e. in the presence of the boundaries, the dynamical regime becomes "sub-diffusive" and the scaling between space and time changess, thus removing the inconsistency.

objection 22: Equations at pages 27-28 are difficult to understand, the symbols t', c, δt and the expression $[t/\delta t]$ are not explained.

answer: I did not go in details in this paragraphs, because what is in the Chapter can be found in every book of stochastic precesses (references are included in the text as well as in figure 2.2). The purpose was to introduce reader into paper P2. The symbol δt represents the time-step of the random walk, i.e, a discrete (in time) Brownian motion. The symbol t represents the generic time at which the generic step of the random walk is done, we have $t = n\delta t$. The symbol c is a constant while the brackets [] denote the largest integer number which is smaller than the argument within the brackets.

objection 23: It is not clear, for which variable Eq. 2.11 at the page 30 is averaged.

answer: It is averaged for all times t' within the time lag τ, i.e., t and $t + \tau$ being the time τ a variable itself. I mean, τ is a variable and represents the time scales taken in consideration in analyzing the scale invariance of the statistical features of the time series under study.

I would also like to answer to the *Concluding comments.* The first of such comments refers to the graphical quality of the figures. I can only apologize and hope that the low quality of the graphics did not affect scientific information included in the figures.

Concerning the observation that "The text is from time to time illogical", I hope that i explained the objections through the above answers.

Answers to the reviewer RNDr. Jan Burjánek, Ph.D.

Chapter 1

objection 1: Page 2: I do not fully understand the flowchart (Figure 1).

answer: This is the same answer as that to the other reviewer. The site characterization shown in Figure 1 is from geological and geotechnical point of view only, i.e., the first step for assessing the site effects. This is also the logical scheme applied in the site effects studies for the city of Rome (see P3 and P4 in particular), that formed the basis of the whole Thesis.

objection 2: Title 'Seismic noise deterministic analysis: single station measurements' is not appropriate, as most of the chapter is devoted to array measurements.

answer: This is the same answer as that to the other reviewer. The most suitable title of the first Chapter would be "Seismic noise analysis: deterministic approach." Then it fits better with the title of the second Chapter.

objection 3: Subsection 1.1.1: The relation between H/V spectral ratio and the content of the microtremors is not discussed properly. Particularly, the influence of surface waves should be discussed (e.g., with respect to impedance contrasts at depth, source distribution, etc.). This is important, since it is shown later, that surface waves dominate the wavefield.

answer: The paragraph 1.1.1 deals with H/V spectral ratio and body waves. Surface waves are involved in the array measurements, not in single station measurements. However, the purpose of Chapter 1 is to explain only basic concepts and ideas to help the reader in better understanding what has been done in papers P3 and P4.

objection 4: Page 9: The link between H/V and structure is limited just to the fundamental frequency. What controls the shape of H/V curve?

answer: The H/V spectral ratio is limited to the fundamental frequency only, actually. Now-a-day no one theory is available for explaining peaks beyond the fundamental one. Concerning the second part of the objection, it is widely recognized that the width of the fundamental peak is mainly controlled by the impedance contrast between the layer and the half space: the higher is the impedance contrast and the narrower and well defined will be the shape of the fundamental peak.

objection 5: Page 9: The quarter wavelength estimation of fundamental frequency using a layer over half-space (0.25*Vs/h) is oversimplified. Real structures usually contain velocity gradients.

answer: In spite of its simplicity, such estimate is useful for explaining the fundamental peak in the H/V spectrum by means of an equivalent homogenous layer. This is the case of Tiber valley (see paper P3). The equivalent homogeneous layer is a sufficient approximation because we are interested in the dynamical behavior of the near-surface geology not in its actual stratigraphy.

objection 6: Page 12: Work of Capon (1969) is related to frequency-wavenumber (f-k) technique, not to spatial autocorrelation method (SPAC) as mentioned in text.

answer: Yes, the reference to Capon is misplaced.

objection 7: Section 1.2.1: Conventional semblance f-k method is mentioned to be adopted in the thesis. However high-resolution f-k method (Capon, 1969) is used in works P3, P4.

answer: There is a set of f-k methods and all of them are based on the f-k Capon original method. On the other hand in Section 1.2.1 at page 12 bottom is written: "In the present Thesis has been adopted a particular F-K method called CVFK (ConVentional Frequency-wave-number method, Ed.)".

objection 8: Page 14: A plane wave-front is also a key assumption in processing of ambient vibration surveys.

answer: The planar waveform is an important assumption, but in page 14 the point under discussion is the different frequency range involved in earthquakes and in seismic noise. The frequency range is different due to the degree of randomness of the two different wave-fields.

objection 9: Page 14: An enhancement of the resolution/aliasing capabilities can be achieved also by different power spectrum estimators, no?

answer: An enhancement can be achieved provided a suitable array size and geometry have been chosen. In page 15 top is the conclusion of the discussion: ".... there is little one can do with respect to the resolution/aliasing issue for dispersion curves, except choosing an appropriate array size and array geometry." Once one has fixed that, the further step could be the choice of the more suited power spectrum estimator function for that array size and geometry. In papers P3 and P4 a conventional CVFK estimator has been used (see for example

SESAME deliverable Del-D18-Wp06.pdf at http://sesame-fp5.obs.ujf-grenoble.fr/SES_TechnicalDoc.htm).

objection 10: Section 1.2.2: Although the retrieval of resolution limits is described thoroughly, and several criteria are mentioned, the scatter of estimates which appear in literature is not explained (e.g., with respect to f-k power spectrum estimator). The relation with penetration depth is also not well explained, several contradictory statements are present, e.g., P3 (page 13): " ... depth of investigations is 2-6 times of radius of the array ..."; page 10 of the thesis: 1/3 of wavelength related to fundamental resonance mode; page 15 of the thesis: one half of maximum resolvable wavelength. This should be clarified.

answer: I interpret the "scatter of estimates" as the error of the estimate 1.1 page 13. Such error is represented by the standard deviation (vertical bars) in figure 1.1. Concerning the penetration depth, from relations 1.3 it arises that such depth is 1/3 of the wavelength λ_{max} and it is equal to the maximum diameter, D_{max}, of the array. This holds for all frequencies including the fundamental resonance mode. That is why at page 15 of the thesis is written: "1/3 of wavelength related to fundamental resonance mode". As it is written in the Thesis, λ_{max} from 1.3 must be divided by 2 for surface waves. As a consequence, the maximum penetration depth is equal to 3 times the maximum radius of the circular array. This estimate has to be seen as an average. This is because relation 1.3 is an empirical, not theoretical one. The actual penetration depth depends on the site efficiency in generating surface waves. That is why on the basis of the SESAME project experience, the range of penetration depth, expressed in terms of the radius of the array, is 2-6 times the radius.

objection 11: Paper P3, Figure 15: Resolution limit Kmax/2 seems too conservative from my experience. Strong aliasing is maybe caused by inappropriate limits for the grid-search in wavenumber plane. An extension of the search limits can improve the result.

answer: I agree with the reviewer's observation, understanding this latter as a general one. But this must be checked for each site under study. For example, in figure 15 of paper P3 is clearly seen that beyond the limit $K_{max}/2$ no agreement between estimated dispersion curve and theoretical one takes place at all. On the other hand, such limit is suggested by SESAME project after three years of studies concerning noise records.

objection 12: Paper P3: What is more representative of S wave velocity structure for the numerical ground motion simulations: "locally smooth" profile retrieved from ambient noise (based on surface wave propagation in quasi 1D media), a point borehole measurement (adopting laboratory tests), or even down-hole survey? What is the strategy for the future?

answer: According to SESAME conclusions, seismic noise analysis should be complemented with information from other techniques such those mentioned by the reviewer. For example, in papers P3 and P4 the target was to extrapolate the velocity values found in a point, Valco S. Paolo, to all the Tiber valley where the velocity profiles are not available. This because borehole measurements and/or down-hole survey represent accurate analysis but in a point of the site under study only. So, array noise analysis in Valco S. Paolo has been used to tune the array noise technique and use it in other points of the site under study, saving in this way efforts and money for digging new boreholes and making new laboratory analysis. As far as studies concerning the site effects in the city of Rome, a realistic strategy for the future could include to design, plan and realize experiments first for characterizing the soil shaking outside the Tiber valley; second for studying the role played by the tributary lateral valleys on the soil shaking; third for assessing the topographical effects of the so called "seven hills", if any.

Chapter 2

objection 1: The effect of noise sources is not discussed at all. Is it negligible in the presented estimates?

answer: From stochastic point of view the effects of noise sources is just to energize the near-surface geological structures. Our target is to assess how such energy is transported through the medium. Indeed, we have found (paper P2) that such transport can be represented by a super-diffusive process as a fractional Brownian motion. Its scaling exponent (fractal dimension) depends on the nature of the near-surface geology. This link is fully disjoint from the noise sources provided the source is not so energetic that the structure behavior is hidden.

objection 2: It would be interesting to demonstrate estimated parameters (e.g., β) directly on power spectrum of the microtremors. If I understand well, power spectrum of total displacement should follow a power law. Is it in agreement with findings of Chapter 1 (e.g., relation to H/V peaks)?

answer: In principle the parameter β can be estimated directly from the power spectrum of the time series representing the noise record. In practice the analysis may be strongly biased by deterministic components in the original signal as well as by the asymmetric distribution of the absolute values of the square of amplitudes around the expected value. As a consequence if we fit a power law to the data by visual correlation we will bias towards higher exponents β. Analyses based on power spectra are often biased and therefore not very reliable. That is why in paper P2 such analysis has been based on the variogram. Concerning the second part of the objection: the power law has no relation with findings of Chapter 1, in particular with H/V peaks. The analysis in Chapter 1 is related to the wave character of the noise field, i.e., its deterministic linear part, called ballistic component. The power law is a marker of a non linear behavior, and according to the numerical value of its fractal dimension such dynamics can be represented as a diffusive process, sub diffusive one, super diffusive or even chaotic one.

objection 3: A five minute window of microtremors recordings analyzed in work P2 is too short to make any conclusion about structure (it may reflect, e.g., source distribution).

answer: The target of paper P2 is not to achieve information about the geological structures from noise records. In order to determine the nature of the dynamics of the energy transport through inelastic media, a power low over two decades minimum is needed. In other words, a straight line in a log-log scale over two decades is enough to conclude that we deal with a power low (see figure 4 in paper P2). As a conclusion, duration of records must be enough to stabilize a power low over two decades, at least. In the sites analyzed in paper P2 five minutes of microtremors recordings have been enough.

objection 4: Is it possible to explain higher coherence of ground motion in sediments by presence of surface waves propagating coherently in a horizontal plane?

answer: Even though the surface waves are more coherent than the body waves, they are not monochromatic. What can explain the high level of coherence in some particular frequencies are most likely resonance effects in the near-surface structures.

Chapter 3

objection 1: Spectral ratios presented in Figure 3.8 are calculated just for S wave-group or complete seismograms?

answer: The spectral ratios are computed using the complete seismograms.

objection 2: It would be interesting to see a comparison between presented spectral ratios and H/V spectral ratios made on both noise and earthquake recordings (Figure 3.8). Moreover, presenting ratios GRB/BRH would be useful for understanding the bedrock conditions.

answer: H/V made using noise are in both figures 15 of papers P3 and P4. Comparing these latter spectral ratios with those in figure 3.8 of the Thesis, we see that the frequency of the first peak is the same, i.e., around 1 Hz. Concerning the GRB/BRH spectral ratio, it is a useful observation that I will take into account for future studies involving particularly just the borehole.

objection 3: Still a peak around 1 Hz is present in recordings made at GRB (Figures 3.7,3.10). This may suggest that the amplification at this frequency range is not completely controlled by the basin sediments at VSC, but rather by some common deeper structure. The velocity profiles are not constrained well bellow the gravel layer. Characterization of velocity structure outside basin should be discussed.

answer: In figure 3.7 the Fourier amplitude spectra of single components only are plotted. As a consequence we cannot speak about site amplification because no reference site is included. Such peak in a single component could reflect some source characteristic, and/or could be due to crustal propagation as well as being linked to some site characteristic. More studies are needed for interpreting such peaks. As for second part of the objection, we work on future designing permanent arrays for assessing strong ground motion outside the Tiber valley.

objection 4: Paper P3/P4: Does exist any historical record about non-linear site effects in Rome, reporting, e.g,. ground failure, sand boils, liquefaction, etc?

answer: No one record about non-liner site effects exists for the city of Rome. On the other hand, to have such non-liner effects a peak ground acceleration around 0.4 g is needed and the duration must be long enough so that several cycles of compression-decompression can take place. In addition, soft soils drenched with water and low quality geotechnical properties must be present. As a consequence, such non-linear effects are very uncommon in Italy, they have never been observed in the city of Rome.

Chapter 4

objection 1: Although the main results of this chapter are not supported by a paper in the appendix of the thesis, the chapter is relatively brief. Results would deserve more discussion from my point of view.

answer: Final, detailed study will be published in a forthcoming paper. From this preliminary simulation we learned how to plan next simulation. Some additional plots and movies will be shown during the defense.

objection 2: Why is the gravel layer representative for the bedrock? The gravel layer is relatively thin in profiles presented in P3, and P4. The bedrock seems rather composed from consolidated sediments (e.g., compacted clays).

answer: In the profiles shown in P3 below the gravel layer there is another layer of high consistency blue clay called "marne vaticane" (UMV). The laboratory tests on UMV undisturbed samples, picked up from the borehole, show an inversion in the velocity profile having these latter Vs=480 m/s whereas the gravel layer has Vs=713 m/s. To assume Vs=480 m/s for the bedrock is unrealistic according to data present in literature concerning the geotechnical features of the near-surface lithology of the city of Rome. On the other hand, there is big discrepancy between in situ down-hole and laboratory tests results (see figure 13 of P3) showing the unreliability of the Vs measure concerning the UMV layer. This could be due to the deterioration in the state of the undisturbed sample. That is why we assumed a Vs value for the bedrock equal to the gravel one. It is clear that new investigations must be planned in order to better constrain the Vs value of UMV layer and below it.

objection 3: The movie presenting snapshots of ground motion induced by l'Aquila earthquake is dominated by waves of large wavelengths (larger then width of valley itself) passing across the valley. I could not recognize any trapped or edge generated surface waves. Are these phenomena not present for simulated frequency band, or is not visible in present graphical representation?

answer: During the defense an improved version of the movie will be shown. Reverberation of energy inside the valley can be seen from 20 to 40 seconds, i.e., with the body waves. Trapped and/or edge generated surface waves effects are not present probably because the simulated frequency range, up to 1.5 Hz, is to low.

objection 4: How are the resulting ground motions affected by a strong interface in depth 0.7 Km?

answer: The impedance contrast at depth 0.7 Km is slightly less than 2, it is not so strong. However, we introduced such interface because from some boreholes dig downtown in the past at that depth., i.e., below the volcanic layer, an interface of flysch has been found. The thickness of the flysch layer is unknown.