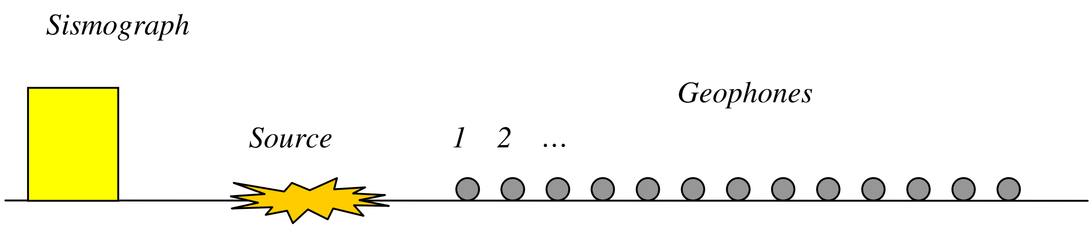
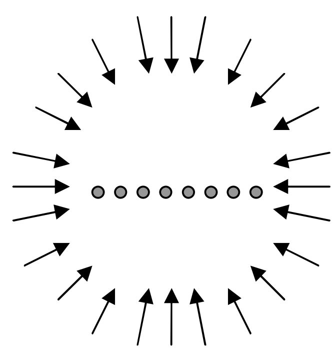
SWAN (Surface waves analysis)

Notes to the interpretation of REMI data

This document is intended to be a track to facilitate the first approach to the REMI method. This technique is similar to the MASW one and has many similarities with it. In the following pages some concepts related to surface waves and the procedures for acquisition will be considered known, and the unique aspects of the REMI technique will be highlighted.
To facilitate the user, the **SWAN** software was developed to make the algorithmic differences between the two techniques just obvious. Indeed, the technical solutions have been implemented in a manner that is transparent to the user, with the result that **SWAN** can treat the two cases virtually identical.
The only real difference between the two techniques lies in the spectrum of the seismograms acquired to be able to extract the dispersion curve, which will follow procedures in both cases slightly different. This is the issue that this paper seeks to go deeper.
You must consider that in the REMI technique useful signal has a very small width compared to that of MASW case, especially comparing it with the level of background noise. You also must consider that in the REMI case it is strongly recommended to avoid all the preliminary cleaning of the seismograms (which however can easily be done in MASW). You can find, therefore, that the signal-to-noise ratio is often very low in the REMI case. This implies that the spectrum is typically more disturbed as happens in the MASW. Therefore, removing the dispersion curve in the interpretation of the spectrum, in general, becomes a more difficult transition. The automatic extraction of the dispersion curve will be a task that the user should be able to supervise, so that he can operate with the tools that **SWAN** make available, if necessary, to achieve the desired results.
One of the advantages of REMI technique is that it cooperates very well with the MASW method. It does not require additional equipment on site or special additional theoretical knowledge. The instrumentation to be used on site with both methods is a multi-channel seismograph, seismic cables and geophones connected to it. Typically, the number of geophones is equal to 24 or 48; the limit is imposed by the maximum number of channels available to the seismograph. The geophones have typically a cutoff frequency of 4.5 Hz.

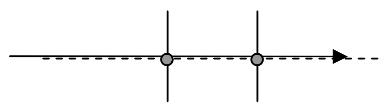


The geophones will be placed on the ground in a straight line, avoiding variations in height between each others and will be placed at a constant distance (usually between 1 to 5 meters). During a MASW acquisition the signal connected to an active source is recorded, typically generated by a hammer. The registration will be quite short, usually a few seconds (1 to 3 s), depending on the distance between the first and last geophone and the average speed characterizing the investigated medium. Typically the signal to noise ratio is very good because the signal generated from the source is more powerful than background noise, but due to the possible interference with other sources in the vicinity it is always preferable to record more acquisitions (typically 5 times is enough).
The REMI technique uses exactly the same provision of appropriate MASW geophones and is not necessary to have an active source. It is not necessary to spend additional time on site to rearrange the cables and geophones to acquire information such as REMI once MASW data have already been acquired. If you are interested only in acquisition REMI data, it is still suggestible a double acquisition or acquiring data for both methods. In this way you can resolve any ambiguities in the data processing using the REMI nevertheless provided indications of MASW data.
During REMI data acquisition, natural micro-tremors in the environment are recorded. Walking people, machinery running in the yard and other human activities can be the source of micro-tremors. Due to the low intensity of micro-tremors, signal-to-noise ratio is not high. Increasing the recording time increases the number of micro-tremors acquired automatically and the signal-to-noise ratio tends to improve. The single registration typically lasts from 1 to 5 minutes, depending on the memory capacity of the seismograph used. You must then repeat the acquisition to record a total of 10 or 20 minutes of signal.
Acquiring data in MASW mode, the position of the source is known. During acquisition of REMI data, micro-tremors come from sources not completely localizable. The technique requires that the REMI micro-tremors have a singular property: they are *isotropic*, i.e. we have true *omnidirectional* sources. Micro-tremors have to come from sources placed in each direction compared to the geophones and the energy of the signal obtained is homogeneous in each direction. For example, this assumption is satisfied if the micro-tremors come mainly from several preferential directions.

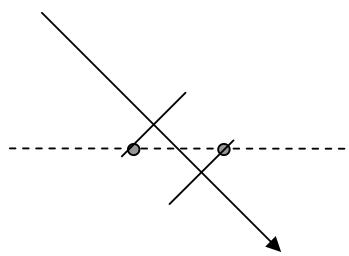


If the hypothesis of isotropy is satisfied, you can simplify the data management without the knowledge of all sources positions for all micro-tremors acquired.
Each micro-tremors in the ground moves at a given speed (from now *real speed*). According to the fact to the micro-tremor reaches the alignment of geophones, they would be, following the analysis of seismograms at a rate that will certainly be apparent higher (or equal) to the real speed. Simplifying the problem, the following reasoning becomes fairly intuitive:
let us consider a single pulse source and two geophones and assume that the source is sufficiently far from geophones in order to approximate the wave front to a plane wave front. Let us assume that the impulse propagation has an unknown speed (*real*), homogeneous in every point of the investigated medium between the geophones and the source.

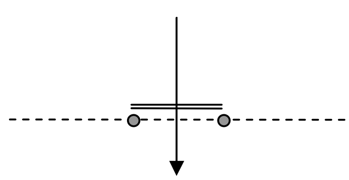
We note the instant of arrival of the first impulse to each geophone. By analysis of the ratio distance between two different geophones/ time delay of arrival, you can calculate the impulse velocity (*apparent*) of the impulse propagation.
The source, perfectly aligned with the geophones, will be associated with an apparent velocity coinciding with the actual speed of propagation.



Sources that are not in line with the geophones will measure an apparent speed greater than real. In fact, due to the inclination created between the path of the impulse and the axis of geophones, we have that the wave front of the signal actually travels a shorter distance than that between the two geophones during the delay time measured. Therefore from the ratio obtained we measure apparent speeds greater than real.



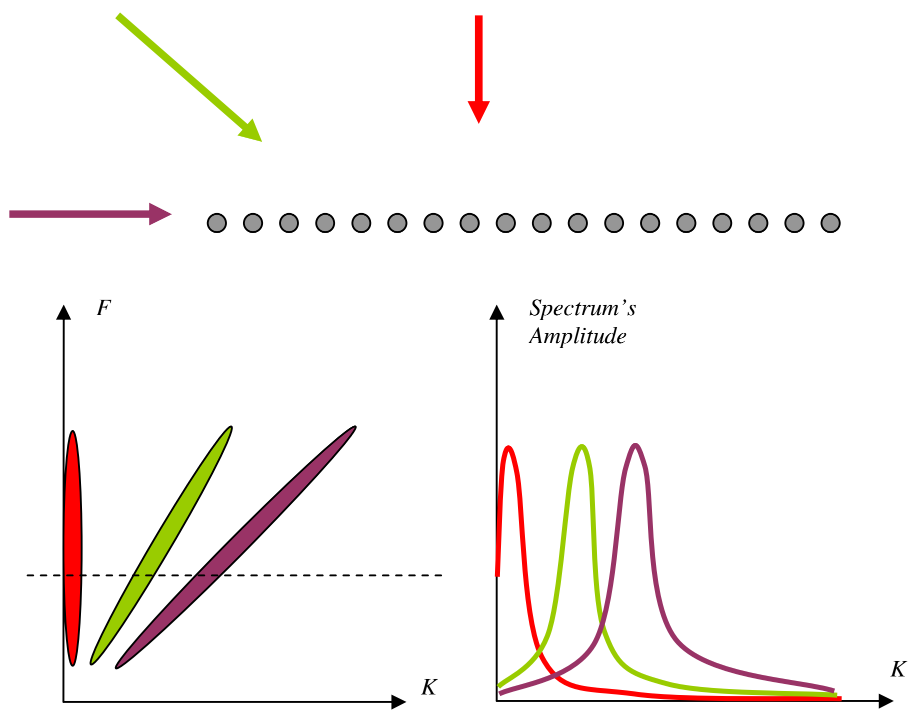
As the angle between the path of the wave and the geophones axis increases, also increases the apparent speed calculated. The limit situation is when the direction of propagation is perpendicular to the axis: in this case the apparent velocity measured will be very high (infinite). This is because the time lag observed between the two geophones will be virtually nil.



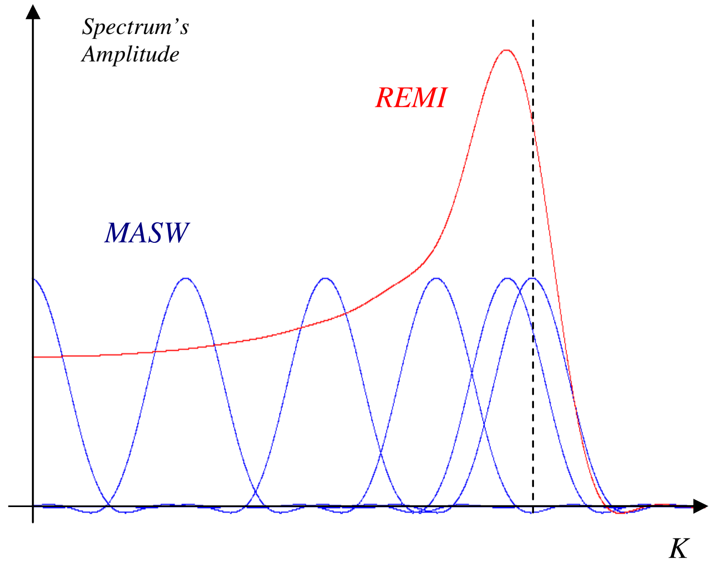
You can also assign a sign to the apparent speed. To do this it is enough to rename two geophones, such as "A" and "B". You can then introduce the convention that an apparent velocity is positive if the pulse is first detected at the geophone "A"; vice versa we will have a negative apparent speed if the pulse is first detected at the geophone "B". Obviously the real speed is always positive and independent of the geophones because is a distinctive feature of the terrain.
So the "apparent velocity" in absolute value is always higher (or equal) to the "real speed." It seems that the apparent velocity does not have the upper limit in its absolute value, which can also be infinite. The sign and its absolute value differs from "real" only by the direction from which the impulse comes.
Due to the phenomenon of "dispersion" each frequency in the spectrum spreads at different (real) velocities. The spectral analysis should be repeated for each frequency of interest in obtaining a list

of values of velocity for the given frequency analysis: in this way we obtain the samples of the dispersion curve (in the domino-speed frequency).

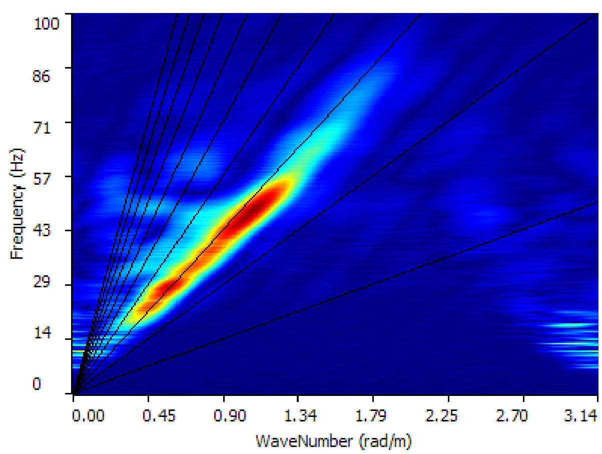
In REMI theory, micro-tremors acquired will be not treated individually, because it would not be a trivial task to isolate the weak contribution in the seismograms. Micro-tremors are then treated as a whole. In the seismograms is not simply to discriminate between the individual apparent velocity observed. This distinction can be made more easily by analyzing the data in the spectral domain.
In the FK spectrum, with the variation of the angle between the direction of the impulse propagation and the geophones axis, or the increase of apparent speed, there is a rotation of the spectrum linked to the value of that angle.
In the FK spectrum the change of the angle between the direction of impulse propagation and the geophones axis, or the increase of apparent speed, appears with a trivial rotation of the spectrum itself of a quantity related to the value of that angle.
In figure are shown schematically three situations: the case with the source in line with the axis of the geophones, the case with an angle of about 45 °, and the case with perpendicularity between the axes.
The geometry of acquisition and a diagram of the FK spectrum with indication of where you should see the energy on the single micro-tremor are shown, and finally displaying a section of the spectrum at a given frequency (see dashed line on spectrum).



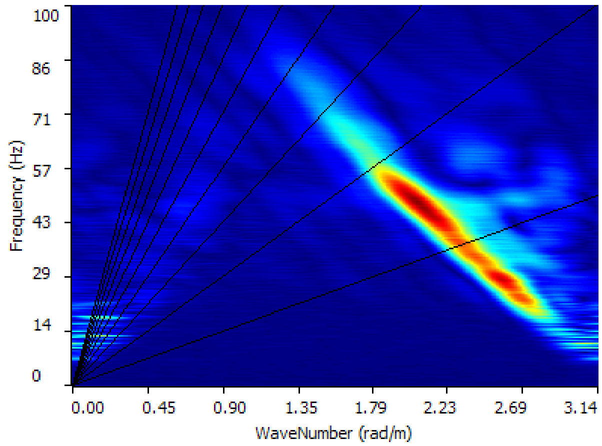
In typical FK spectrum (REMI) you will see the overlap of the effects of various micro-tremors. This overlap is shown in the figure, where you can see the composition of a simulated section (at a given frequency) FK spectrum since the effects of individual microt-remors. The dashed vertical line is an indication of the actual speed at this frequency. As it can be seen, there are overlapping effects associated with apparent speeds of greater value (or associated with a wave number lower K).



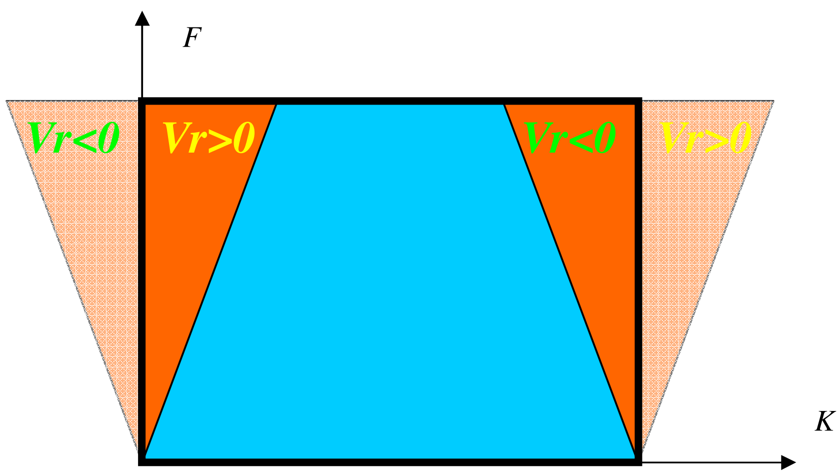
Shown in the figure is a real example of FK spectrum for MASW data.
In this case we see that energy is distributed mainly on a line approximately passing through the origin (area with red colour tending to). The slope of the line is such as to indicate a apparently positive propagation speed.



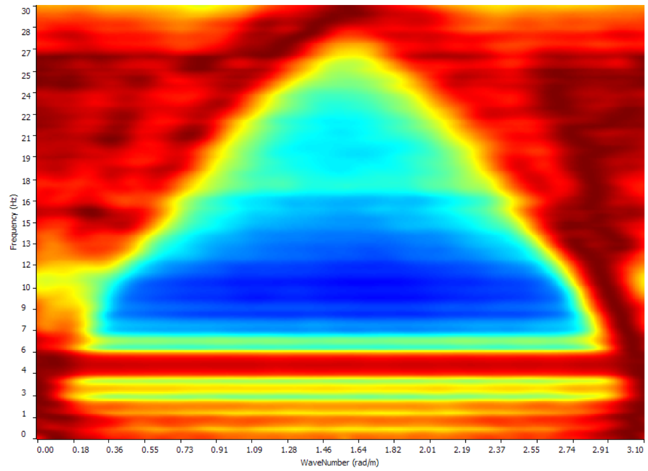
If the source was at the other end of the geophones line, spectrum obtained was similar to that shown in the figure. In this case the line on which the energy is indicative of a apparently negative propagation speed.



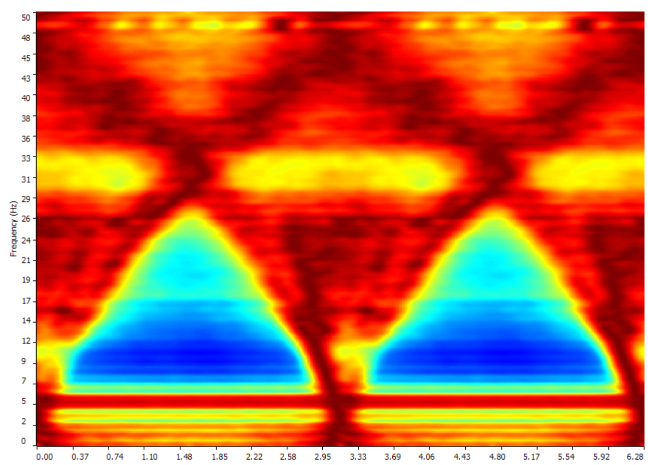
To facilitate the interpretation of this spectrum we should take into account the cyclicality of the spectrum as a result of the properties of the Fourier transform.
The spectrum FK (MASW or REMI) has the property of being periodic along the K axis. One way to get a correct view of the information contained therein, is thinking of creating a barrel roll so as to bring the left side of the spectrum with his right hand.
In figure is shown schematically where tremors are apparent speed with positive and negative, at the same time is also graphically shown the frequency spectrum.

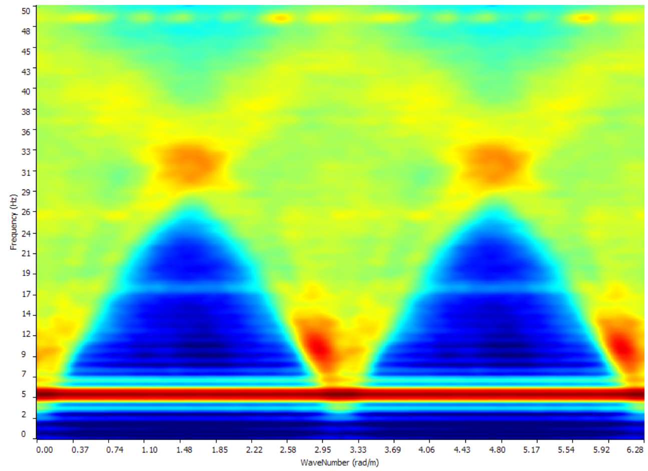


In figure, finally showed a spectrum FK on the REMI method. It is noted that the area coloured in red, indicating the presence of energy, can be reduced to speed apparent positive and negative. You notice any apparent speed also very high in absolute value. There is also a lack of energy (area coloured in blue) at speeds below a certain threshold, confirming the expectations. This threshold is, as shown above, linked to the actual speed of propagation in the soil in the wave analysis.
You can see a fairly homogeneous noise at low frequencies. This information is not attributable to any waves in propagation, but only to noise associated to physical limits of operativity of geophones used.

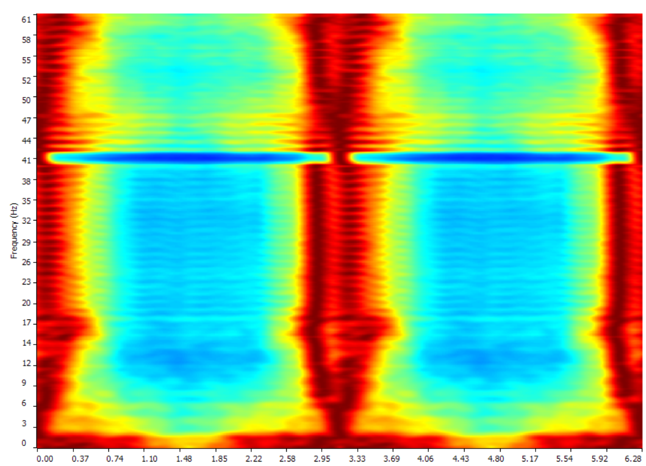


SWAN makes visible the spectrum on the REMI method normalizing it for every frequency to increase the graphic contrast with the background noise even at frequencies where micro-tremors are weak.
SWAN also juxtaposes the first image of the spectrum to a second identical image, justifying this with the periodicity of the frequencies previously mentioned. This option allows you to observe the central part of the image that was more easily obtained to analyze the symmetry of the spectrum. This in order to assess the quality, especially in the validation of property of isotropy of sources.
In figure is shown the image obtained by placing two copies of the same REMI spectrum flanked. Below is a figure that shows the same result without normalization of the amplitude for every frequencies, but using a logarithmic scale representation of the amplitudes of the spectrum.





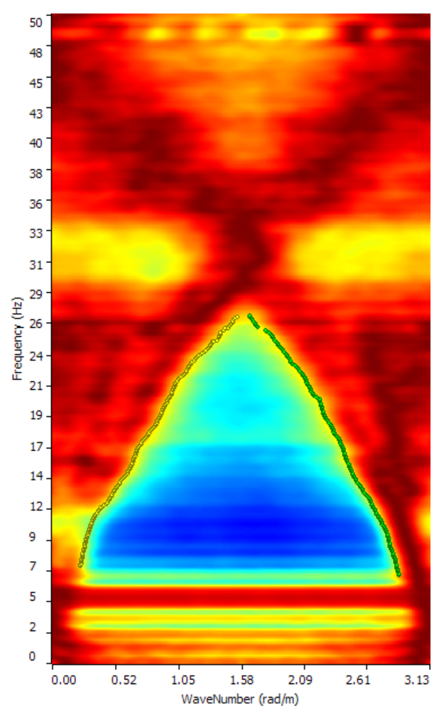
By observing the symmetry of the spectrum in the central area, or at the junction between the two copies of the spectrum, there can be an indication of how satisfied the hypothesis of isotropic sources is. In this case, neglecting a slight asymmetry quite evident around the frequency of 10 Hz, the spectrum is symmetrical enough to be able to proceed with processing.
In figure a FK REMI spectrum is shown, where you can find a strong asymmetry due to the not isotropic sources. In this case the analysis will be very difficult or even impossible as a result of the non validity of initial assumptions.
In particular, one can intuit the presence of a dominant source respect to the other. This source is likely to reach many micro-tremors perpendicular direction relative to the geophones: the dominant energy contribution is related to extremely high apparent velocity. At the same time is almost completely absent the contribution due to micro-tremors coming from direction oblique or parallel to the geophones axis. And it is quite clear that the signal in this case is also disturbed by a noise that makes the horizontal stripes to the spectrum over the frequency range observed.

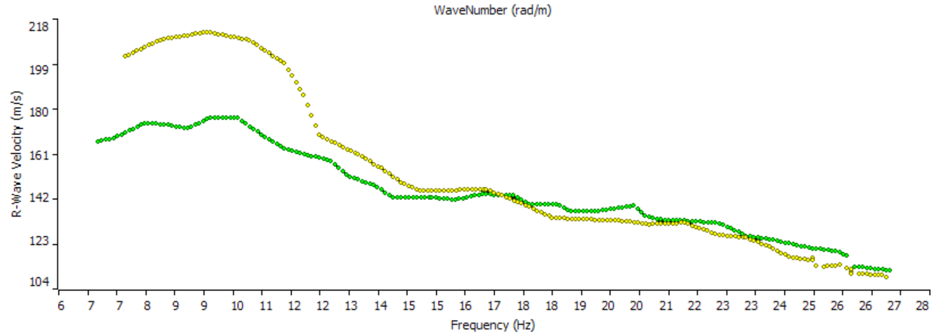


During the interpretation of spectrum task, the objective is to estimate the actual speed of propagation of the seismic wave at different frequencies. The experimental dispersion curve is nothing but all of these obtained speeds in the frequency range of interest.
The MASW method, due to the acquisition geometry, the apparent speed coincides with the actual speed of propagation. Then, extracting the dispersion curve consists simply in extracting the value of K, for each frequency, for which you have the maximum amplitude in the FK spectrum. From the value of K thus found, you can calculate the speed of propagation of waves at that frequency.

By observing how it is constructed a section of the REMI spectrum through the overlap of the effects on micro-tremors coming from receivers, it follows that in the REMI method, you should not chase the highest section of the FK spectrum (as with the method MASW) otherwise you should identify a value of K less than the correct one, that would lead to an overestimation of the actual speed of propagation. The maximum amplitude in the REMI spectrum is a very useful information as it is used as reference to identify the correct value of K, which is linked to the actual speed of propagation. In general, you can choose the value of K for which there is a wide section of the FK spectrum of approximately 80% of its maximum value (as previously confirmed by the position of maximum spectrum REMI and position on the actual speed of propagation).
Using the colour scale proposed by SWAN, the concept just described is reflected in the search for the dispersion curve of the spectrum following the REMI area approximately coloured in yellow near the transition between the full of energy area (coloured in red) and the area where there is only background noise (coloured in blue).

The figures below show how you can extract the dispersion curve from a REMI spectrum.
Unlike the MASW case, in REMI we can extract two dispersion curves: the first one is to associate to micro-tremors propagating with apparent positive speed and the second one relative to micro-tremors that spread with apparent negative speed. In theory the two dispersion curves obtained should be coincident, but as a result of possible asymmetries in the source during acquisition we have often a slight asymmetry in the spectrum that leads finally to small inequalities in the two curves.





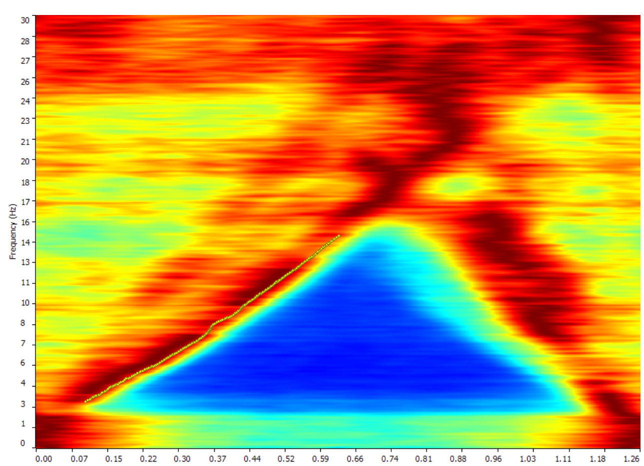
Once the dispersion curve is extracted, the processing of data through **SWAN** of MASW and REMI data coincides, i.e. we will search for the more plausible stratigraphic model, namely that which approximates satisfactorily the experimental dispersion curve found. In this case, the stratigraphic model should be such as to interpolate simultaneously the two curves. Probably, in the case shown in figure, it will give more importance, at low frequencies, to the green curve (extracted by analyzing the speed of apparent negative) that is associated with lower apparent velocity (therefore, is probably a better indication of actual speed of propagation). The yellow curve, linked to the apparent positive velocity, is suffering from a mild disorder linked to imperfect isotropic sources.

Often the intersection between the two dispersion curves extracted with the analysis of apparent positive and negative minimum speeds, indicates a spectrum in which it is not easy to proceed with the analysis. In most cases this happens at fairly high frequencies, related to the wavelength of the signal comparable to the spacing between the receivers. The curve, even if it is pulled beyond the crossroads of the frequency curves, contains information not very accurate. So you can omit the analysis above these frequencies without mistakes. In practice, we renounce in advance a comprehensive analysis of the shallower stratigraphy, concentrating on information relating to the deeper layers.

The previous observation poses a limit to maximum analyzable frequency in the spectrum. As regards the minimum frequency to be analyzed during the analysis, very often this is determined roughly by frequency of the used geophones.

In situations where it is more obvious an asymmetry between the directions of arrival of micro-tremors, if you decide to continue with the development, you probably will pull out only one of the two dispersion curves. It is important to remember that you will always keep the dispersion curve (or parts of it) which shows lower apparent speed values. It will be important in these cases, the sensitivity and experience of the operator who performs the interpretation too.

Sometimes, if you already suspect during data acquisition that the hypothesis of isotropic sources is not satisfied, you can, where fairly lucky, risk acquisition of REMI data. This is easily possible if you can identify the directions from which the most intense micro-tremors come. In this case we have the put the geophones on the ground trying to seek the source of plausibly more intense micro-tremors. This choice is useful to ensure the detection of minimum apparent speed. In fact, as previously highlighted, the apparent speed is minimal (equal to the real) just when the axis of the geophones coincides with the direction of propagation.



In this case the construction of the REMI spectrum's section does no longer strictly follow the principle described above, since the contributions from different directions do not add more with the same weights. Consequently we have, with this configuration, that the maximum value of the REMI spectrum is very close to the real value of the real speed. Therefore we will have that the

empirical method for the extraction of the dispersion curve described above, which suggested to identify the intersecting curve 80% of the full section (for every frequency), is no longer correct. This method should be changed raising this percentage to 90-95% during the treatment of more intense micro-tremors. This percentage, instead, will be greatly reduced during the analysis of the dispersion curve associated with apparent opposite velocities, where the signal is likely to be very weak. See example below.
It remains always strongly recommended acquiring MASW data every time you acquire REMI data. These are always useful and important additional economic information to assist the operator during the interpretation of data REMI.