SUBSURFACE INVESTIGATION USING REFRACTION MICROTREMOR

Integrated M.Tech Dissertation

by

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by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**SUBSURFACE INVESTIGATION USING REFRACTION MICROTREMOR**" in partial fulfilment of the requirements for the award of the Integrated Master of Technology in Geophysical Technology and submitted in the Department of Earth Sciences of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from May, 2018 to May, 2019 under the supervision of Dr. Anand Joshi, Professor, Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institution.

(JYOTI PRAKASH BIRUA)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

(Prof. ANAND JOSHI)

Supervisor

Date:

ABSTRACT

Refraction Microtremor method is a class of non invasive method with a passive source which uses ambient seismic noise to gather data along an array of geophones to predict the velocity model of the subsurface. This method was developed by John N. Louie in 2001 and based on the premise that simple geophones arranged in an array using passive source is able to receive very low frequency waves and that a 2D slowness-frequency (p-f) transform can separate Rayleigh waves from kinds of waves. The advantages of this method over other methods are that it is very fast and not very expensive, the tool and instruments required are readily available, it is not affected by sources of noise and can be used discreetly without an active source.
But studying ReMi data is without the use of commercial software is tough as the data is kept secret using proprietary file standards and other licences.

In this study, I present to you a computer program written in Python 3 which is able to generate a synthetic seismic traces similar to actual ReMi acquisition data and a separate program which is able to convert initial data in the form of amplitudes relative to distance and time (A(x,t)) and convert it to slowness-frequency (p-f) domain which can later be used derive subsurface velocity properties using various forward modeling and inversion methods.

CONTENTS

Seismic acquisition techniques used in shallow site investigations

Introduction:

Various methods used to find subsurface velocity patterns include seismic reflection methods, surface wave dispersion methods, refraction of body waves, etc. These methods are now also being modified to be used for determining the velocity of S - wave in low depth levels. These methods can be broadly classified as invasive and non invasive methods.
The non invasive methods comprises of methods defined by the number of recording stations. This in turn is classified into active and passive sources. Some methods can use a combination of these sources.

Invasive Methods:

As the name suggests, these methods are more involved and use much more resources. The recording devices are usually placed beneath the earth. These can further be divided into two categories: i) When the source is placed on the surface ii) When the source is placed in a borehole

Surface based source methods use sources present on the surface while the sensors are placed down along the borehole which is cased, at regular intervals. Otherwise the same sensor is used as it is pushed down using motors while recording. Velocity models are created from the arrival times of the waves.

Borehole based sources like downhole sources are usually used with multiple crossholes, that is why it is more time and resource consuming.

And also as the waves are traversing horizontally, this can have very different results compared to waves travelling vertically.

Non Invasive Methods:

The first advantage that comes to the mind is that these methods don't require any kind of borehole and generally used for shallower depth study. These are generally used to obtain Rayleigh waves dispersion curves are can later be used to find velocity models using forward modeling or inversion. Some of these methods include SASW, MASW, DASW and ReMi.
SASW is a method used phase difference of two given receivers, can be used with variety of sources like physical tools to large industrial devices which can give a variety of frequency range. Distance between the two receivers and the phase difference is used to find Rayleigh velocity.

MASW was created to improve the problems faced in SASW methods due to noise disturbances. It records data on linear array of many seismometers recording the microtremors. Time domain velocity analysis is used to separate Rayleigh waves from other waves. Recording is done in an array with 10 or more recorders is short or long separations, using an impulse source.

Active sources are generally a bad idea to generate low frequency source, which means it can only work for shallow surface. Therefore passive sources are used in case of generating low frequency waves. That is where microtremors are used instead of active sources. These can originate from natural or man made sources. Most of the methods use 2D arrays for recording microtremors but ReMi method useds 1D array. It is easier to distinguish non fundamental Rayleigh waves and other noises from the required waves.

ReMi Methods:

Refraction Microtremor method uses velocity recordings in distance time(x-t) domain and converts it slowness frequency(p-tau) domain by using slant slack transformation. Fast fourier transform or 1D fourier transform is done to transform it to slowness-frequency domain (p-f), where finally spectral ratio is computed for spectral normalization of noise and resulting image gives us the dispersion curves from which we can get the dispersion picks. These picks are then used to model the S wave velocity structure and other subsurface properties. The depth of investigation is a function of length of geophone array.

The main advantage of ReMi method is that it is very fast and not very expensive, the tool and instruments required are readily available, it is not affected by sources of noise and can be used discreetly without an active source. You only need to a series of geophones in an array on the surface, without the use of invasive sources and ground deformation. This method is only effective for a depth of 100m. Over greater depths more expensive and complex refraction systems are required.

Various methods to obtain subsurface models include Forward modeling which includes two types of methods: Propagator Matrix methods like Transfer Matrix method, Stiffness matrix method and Reflection-transmission coefficient method, and Numerical methods like Finite element, Finite difference and numerical integration.
Linear and Nonlinear inversion methods can also be used.

Procedures involved in ReMi Method:

This method was developed by John N. Louie in 2001 and based on the premise that simple geophones arranged in an array using passive source is able to receive very low frequency waves and that a 2D slowness-frequency (p-f) transform can separate Rayleigh waves from other kinds of waves.

Seismic Recording Equipment:

Recording can be done with a single geophone at each point rather than a cluster of geophones and using an array of 12 or more gephones. These are generally refraction based geophones, commonly available as well. No active source is required as it uses passive noise sources as input. Moving vehicles, and wind responses of trees, buildings, and constructions provide the surface waves this method analyzes.

Velocity Spectral (p-f) Analysis:

We first take a seismogram section array data for a given sequence of geophones, at least 12 of them, and get the data in the form of A(x,t), which is the amplitude based on the particle velocity at that point and changes as a function of time and distance.

This two dimensional array is then converted into A(p,tau) where amplitude is a function of slowness p (inverse of velocity) and intercept time tau.

This is done by a line integral on A(x,t) for distance x and time t,given by

$$A(p,tau) = \int_{x} A(x,t=tau+p\ x)\ dx$$

In discrete form, it can be written as

$$A(p=p_0+l\ dp,tau=k\ dt) = \sum_{j=0,nx-1} A(x=j\ dx,t=i\ dt=tau+p\ x)$$

where,

$p_0=-p_{max}$ (p_{max} is the inverse of max velocity found in the study),

dt=time interval between recordings

dp=set such that p changes from $-p_{max}$ to p_{max} in $2n_p$ ($n_p=2n_x$) steps

dx=distance between recordings

If the Amplitude A(x,tau+p x) lies between any two points then the value would be interpolated.

Now we have the A(p,tau) data which contains twice the number of traces in p compared to x. Each trace is linear sum of traces at all intercept times.

Next we would compute the 1D fourier transform for A(p-tau) data using the tau axis:

$$F_A (p,f) = \int_{tau} A(p,tau)e^{-i\ 2\ pi\ f\ tau\ dtau}$$

Which in discrete form can be written as :

$$F_A (p,f=m\ df) = \sum_{k=0,nt-1} A(p,tau=k\ dt)e^{-i\ 2\ pi\ m\ df\ k\ dt}$$

where df=1/t

We can also use Fast Fourier transform as it is more efficient. As the fourier transform was along tau axis, p axis was not affected.

Then we calculate the power spectrum S_A (p,f) which is defined as the magnitude squared of the complex Fourier transform:

$$S_A(p,f) = F_A^*(p,f)\, F_A(p,f)$$

where F_A (p,f) is multiplied to its complex conjugate

Now we fold the p axis from the middle where p = 0, so that we get the absolute value sum of both directions of p into one axis:

$$S_A(|p|,f) = [\, S_A(p,f)\,]_{p \geq 0} + [\, S_A(-p,f)\,]_{p<0}$$

Now the transformation from distance (x) and time (t) space to slowness (p) and frequency (f) space is complete.

If we have recorded more than one trace S_{An} (|p|,f), we can add them into one single array of summed power:

$$S_{total}(|p|,f) = \sum_n S_{An}(|p|,f)$$

Rayleigh Phase-Velocity Dispersion Picking:

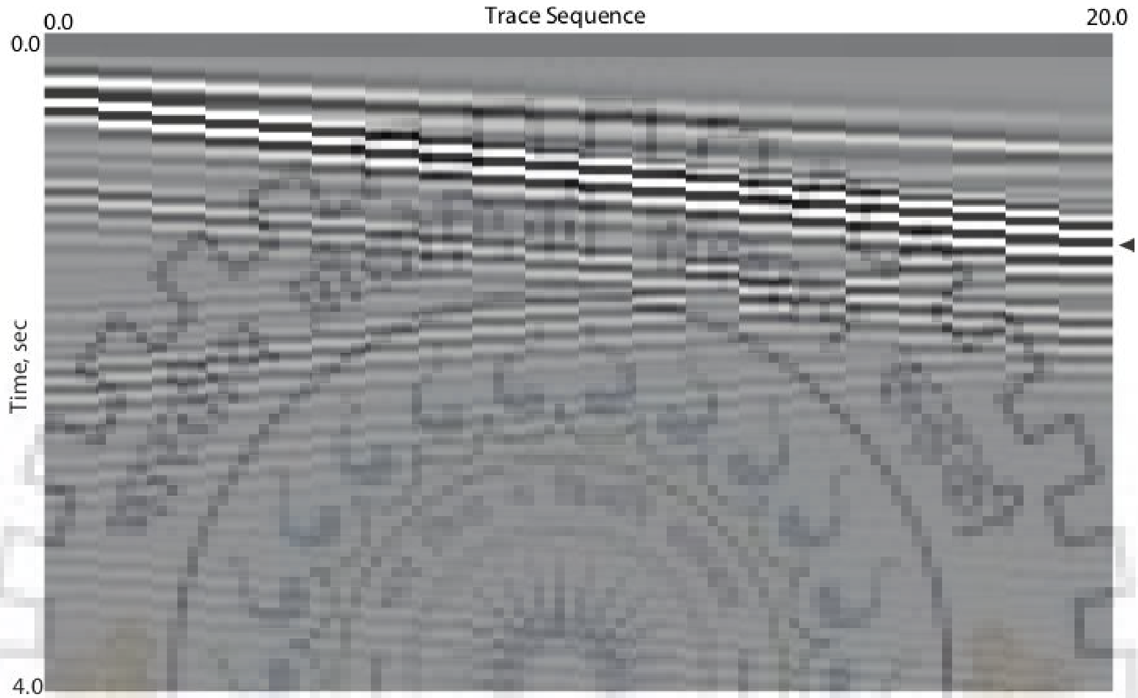
Now we move on to generate a spectral power-ratio data, to normalize the noise records. The average power varies greatly depending on the frequency over the frequency values. This method takes the S(p,f) value at each point and divides it by the average S(p,f) value to normalize the data. This is given by:

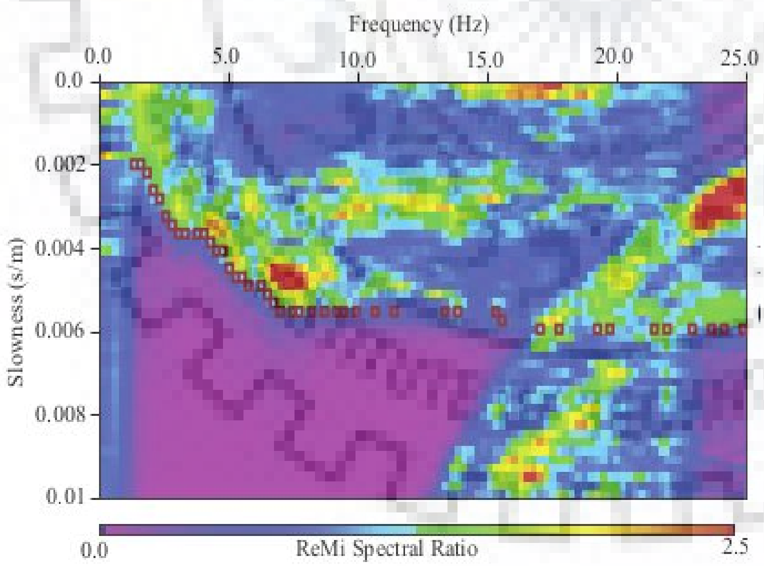
$$R(|p|,f) = S(|p|,f)\, n_p \,/\, [\, \sum_{j=0,np-1} S(|p|=l\ dp,\ f)\,]$$

where n_p is half of original number of slowness steps

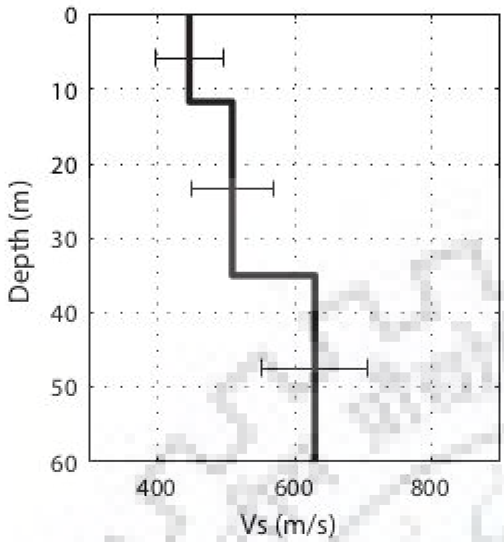
Then this image is plotted and the dispersion picks are made, which helps identify the Rayleigh waves and other wave patterns and data, using further forward modeling and inversion methods.

Synthetic example A(x,t) (from Donghong Pei,2007)



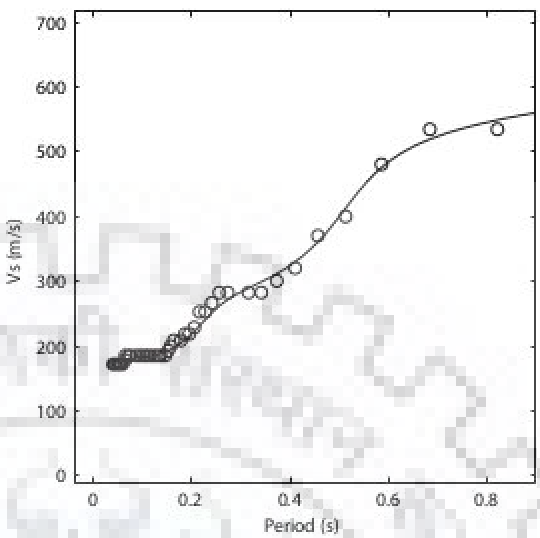


Spectral Power ratio graph with dispersion picks



Velocity model for Vs wave

(from Donghong Pei,2007)



Dispersion curve

(from Donghong Pei,2007)

Generating synthetic ReMi data:

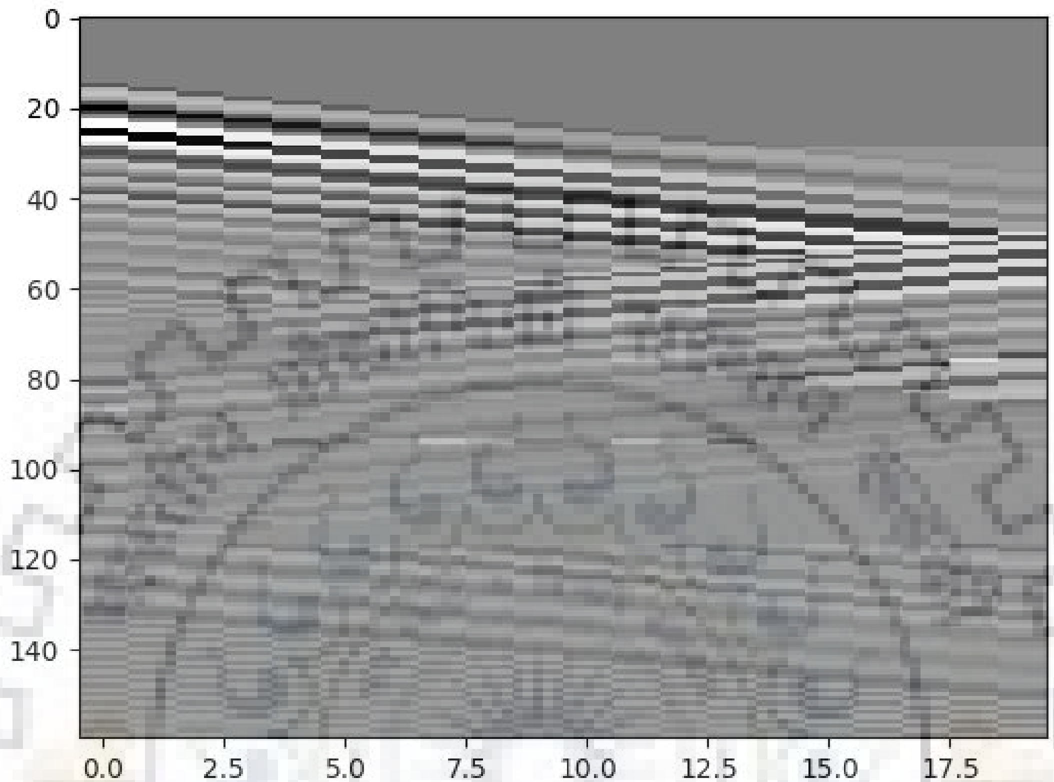
As the data is generally hidden using proprietary files, here is a replicated synthetic data which is derived from an image used by Donghong Pei, 2007. I studied the pattern of this simple Rayleigh data and prepared models for wave energy diffusion as seen in the image, and saved it as an array.
It is written in Python 3 and uses Numpy library to manipulate arrays and matplotlib to generate graphs.

The x coordinates are the separate traces at a given distance.
Y coordinates are the time interval of recordings.

```
import numpy as np
import matplotlib.pyplot as plt
import sys
np.set_printoptions(threshold=sys.maxsize)
import json

x,y=20,160

# generating empty matrix of size defined by x and t

matrix=[[0 for i in range(x)] for j in range(y)]
A_x_t=np.asarray(matrix,dtype=np.float32)

# initial data guess

A_x_t[15][0]=-0.3
A_x_t[16][0]=0.4
A_x_t[17][0]=0.5
A_x_t[18][0]=0.3
```

```
A_x_t[19][0]=-0.3
A_x_t[20][0]=-1
A_x_t[21][0]=-0.5
A_x_t[22][0]=0.1
A_x_t[23][0]=1
A_x_t[24][0]=1
A_x_t[25][0]=-1
A_x_t[26][0]=-1
A_x_t[27][0]=1
A_x_t[28][0]=0.8
# this initial value was defined for all A_x_t[i][0]

# decaying wave energy model from left to right
# this is made such that points having max and min
amplitude will converge near zero uniformly

for i in range(15,29):
    num=A_x_t[i][0]
    if(num<0):
        for j in range(0,20):
            A_x_t[i+j][0+j]=num-(j*(num/22))
    else:
        for j in range(0,20):
            A_x_t[i+j][0+j]=num-(j*(num/22))

# this section is increasing from left to right as wave
is fading from right to left
# these loops are repeated for multiple sections with
same characteristics but different intensities

for i in range(29,40):
    num=A_x_t[i][0]
    if(num<0):
```

```
        for j in range(0,20):
            A_x_t[i+j][0+j]=num-(j*((1+num)/22))
    else:
        for j in range(0,20):
            A_x_t[i+j][0+j]=num+(j*((1-num)/22))

# this is for waves colliding where the resultant
intensity is a function of both waves

for i in range(67,79):
    num=A_x_t[i][0]
    if(num<0):
        for j in range(0,20):
            if(A_x_t[i-j][0+j]!=0):
                A_x_t[i-j][0+j]=num-(j*((1+num)/30))
            else:
A_x_t[i-j][0+j]=(A_x_t[i-j][0+j]+num-(j*((1+num)/30)))/
2
    else:
        for j in range(0,20):
            if(A_x_t[i-j][0+j]!=0):
                A_x_t[i-j][0+j]=num+(j*((1-num)/30))
            else:
                A_x_t[i-j][0+j]=(A_x_t[i-j][0+j]+num-(
            j*((1+num)/30)))/2

Axt=A_x_t.tolist()

# saving file to disk to be imported later
with open('Axt.json', 'w') as json_file:
    json.dump(Axt, json_file)
```



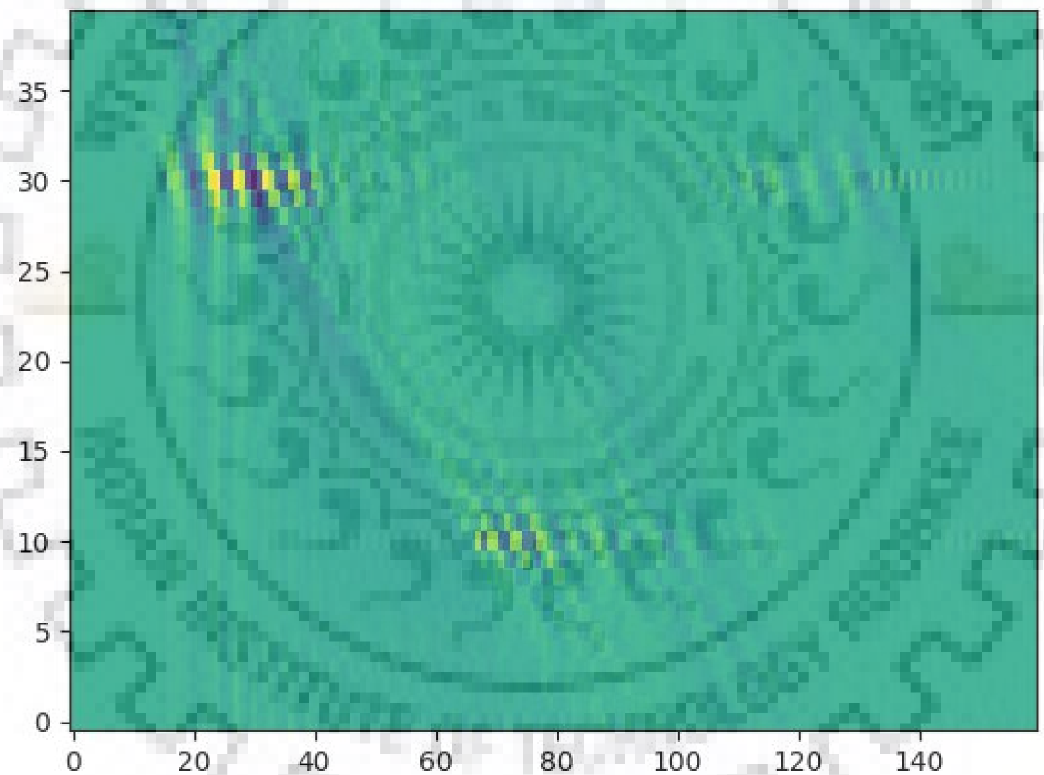
X-axis : geophone placements at interval of 10m, total length 200m, 20 data points
Y-axis : time interval of recordings for a total of 4 secs, recording interval 0.25s, 160 data points
Black shade denotes maxima and white shade denotes minima.
Grey shade is for 0 data point.

Converting A(x,t) data to Spectral Power ratio graph:

```
import numpy as np
import sys
from skimage.transform import radon
import matplotlib.pyplot as plt
np.set_printoptions(threshold=sys.maxsize)
import json


#loading the A(x,t) data file

with open('Axt.json') as json_file:
    A_x_t=json.load(json_file)
A_x_t=np.asarray(A_x_t)
A_x_t=A_x_t.transpose()


# defining constants for this particular data set

w=10     # no. of traces
l=200    # 200 mtrs (total length of array)
t=4      # 4 secs (total time of recording)
p_max=0.005 # 0.005 sec/m
dp=0.00025  # 0.00025 sec/m
dt=0.025 # 0.025 sec
dx=10    # 10 mtr
df=1/t   # 0.25 Hz
p0=(-1)*p_max
```

```
nx=int(l/dx)      # 20
nt=int(t/dt)      # 160
Np=(p_max/dp)   # 20
A_p_dim=int(2*(p_max/dp))  # 40
A_tau_dim=int(t/dt)   # 160
F_f_dim=int(t/dt)     # 160

# saving the data coordinates of A(x,t) to be used in
later functions
A_x=[i*dx for i in range(nx)]
A_t=[round(i*dt,3) for i in range(nt)]

# initializing A(p,tau) array and saving p and tau
coordinates in different arrays

A_p_tau=[[0 for i in range(A_tau_dim)] for j in
range(A_p_dim)]
A_p_tau=np.asarray(A_p_tau,dtype=np.float32)
A_p=[0 for i in range(A_p_dim)]
A_tau=[0 for i in range(A_tau_dim)]
F_f=[0 for i in range(F_f_dim)]
for i in range(F_f_dim):
    F_f[i]=i*df

# p-tau transformation
for i in range(A_p_dim):
    A_p[i]=round(p0+i*dp,5)
    for j in range(A_tau_dim):
    A_tau[j]=round(j*dt,3)
    Sum_Axt=0
    for k in range(nx):
        temp_x=k*dx
```

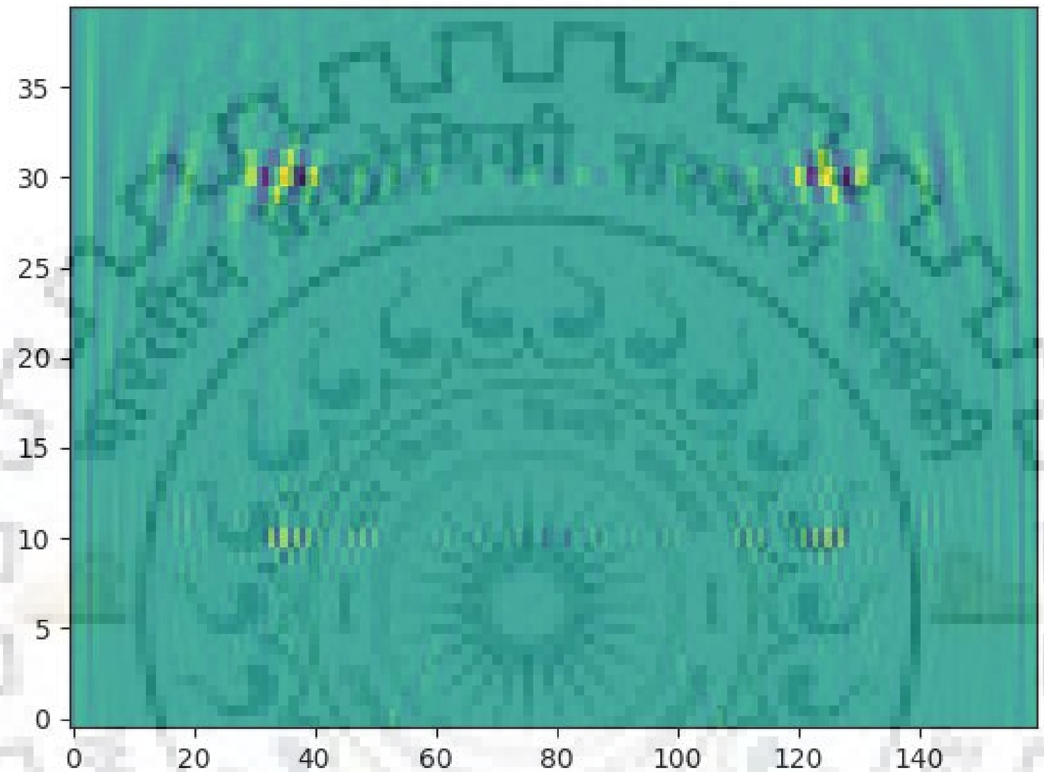
```
            temp_t=round(A_tau[j]+A_p[i]*temp_x,3)
            if temp_t in A_t:
                index_x=A_x.index(temp_x)
                index_t=A_t.index(temp_t)
                Sum_Axt=Sum_Axt+A_x_t[index_x][index_t]
            else:
                index_x=A_x.index(temp_x)
    Sum_Axt=Sum_Axt+np.interp(temp_t,A_t,A_x_t[index_x])
        A_p_tau[i][j]=Sum_Axt
```



X-axis shows the intercept time from 0 to 4s.
Y-axis shows the slowness points from -0.005s/m to 0.005s/m.
Faintly visible lines are the Rayleigh waves, the image here is inverted by 90°.

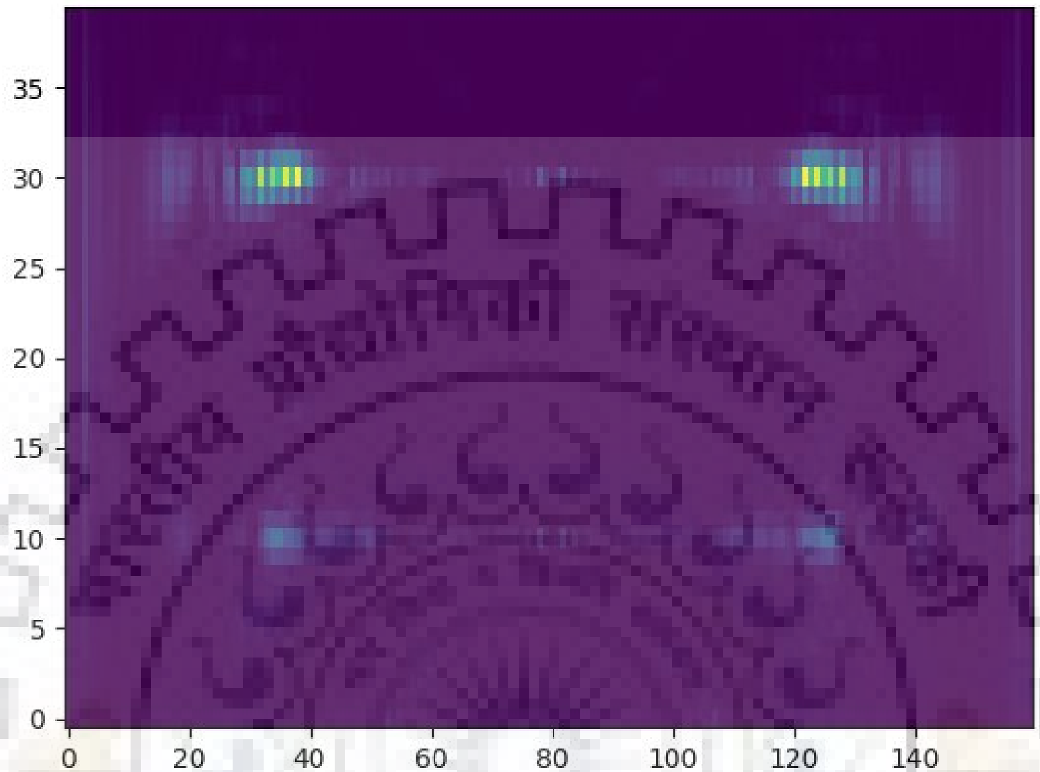
Fast fourier transform in tau direction

```
F_a_p_f=np.fft.fft(A_p_tau)
```



X-axis shows the frequency from 0 to 40Hz at 0.25 intervals.
Y-axis shows the slowness points from -0.005s/m to 0.005s/m.

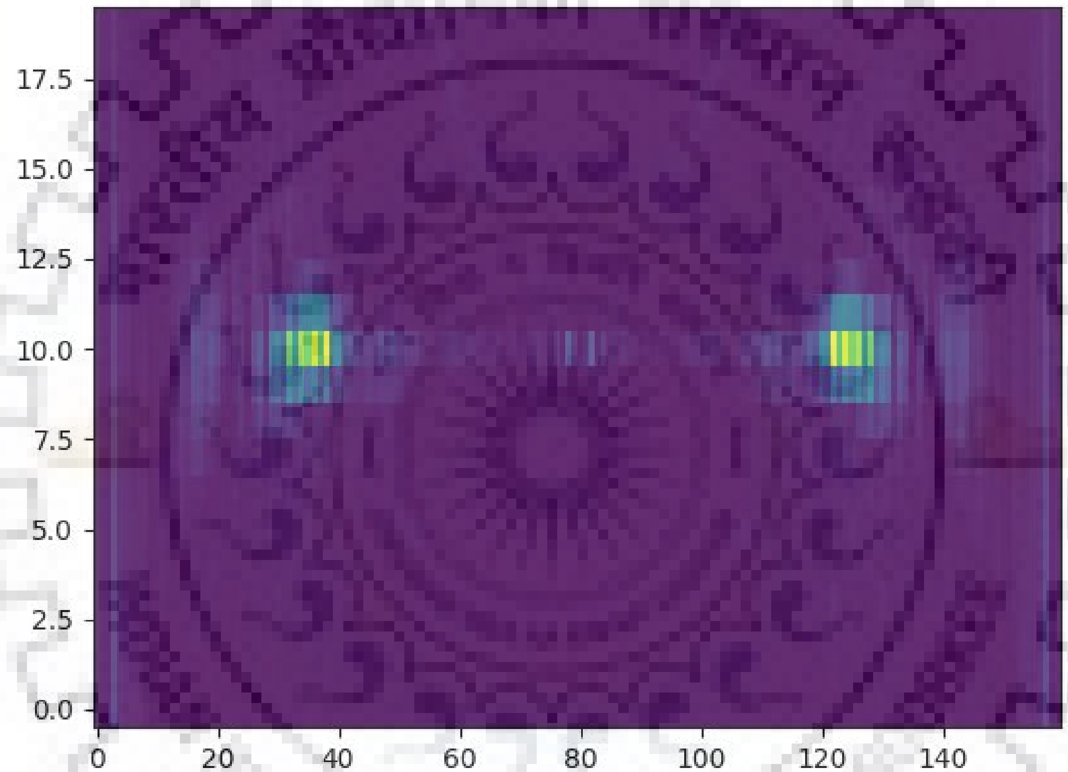
```
Conj_F_a_p_f=np.matrix.conjugate(F_a_p_f)

S_a_p_f=np.multiply(Conj_F_a_p_f,F_a_p_f)
```



X-axis shows the frequency from 0 to 40Hz at 0.25 intervals.
Y-axis shows the slowness points from -0.005s/m to 0.005s/m.

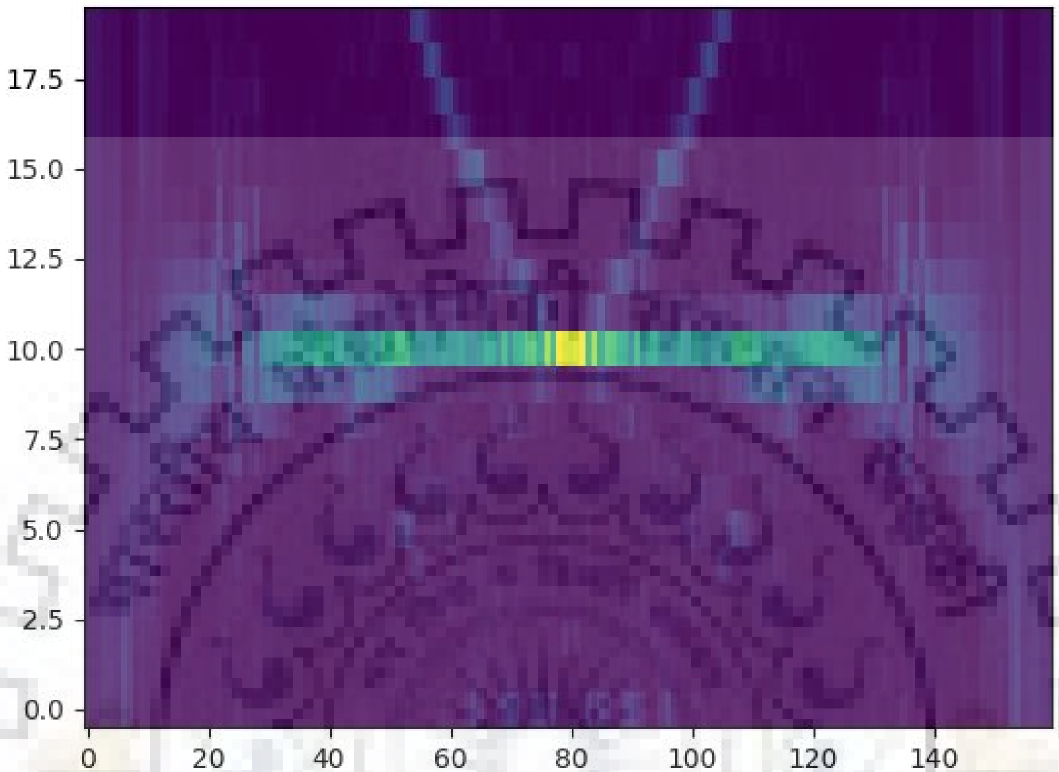
```
# Summing energy in forward and reverse direction into one p axis,folded about p=0

P0=int(A_p_dim/2)
S_a_P_f=[[0 for i in range(A_tau_dim)] for j in range(int(A_p_dim)/2)]
```

```
for i in range(int(A_p_dim/2)):
    for j in range(A_tau_dim):

S_a_P_f[i][j]=abs(S_a_p_f[P0+i][j])+abs(S_a_p_f[P0-i][j
])
```



X-axis shows the frequency from 0 to 40Hz at 0.25 intervals.
Y-axis shows the slowness points from 0 to 0.005s/m, total of 20 points.
Length of Y axis is halved as we folded the points at p=0

```
# Spectral Power Ratio

R_p_f=np.empty_like(S_a_P_f)

for i in range(int((A_p_dim)/2)):
    for j in range(A_tau_dim):
        numerator=S_a_P_f[i][j]*Np
        Summ=0
        for k in range(int(Np)):
            Summ=Summ+S_a_P_f[k][j]
        R_p_f[i][j]= numerator/Summ

# Plotting the Spectral ratio graph

plt.imshow(R_p_f,aspect='auto')
plt.gca().invert_yaxis()
plt.show()
```



X-axis shows the frequency from 0 to 40Hz at 0.25 intervals.
Y-axis shows the slowness points from 0 to 0.005s/m, total of 20 points.
Shows the variations in spectral ratio

Conclusion:

After this exercise we could generate a synthetic data array for geophone response in a ReMi setup in the form of A(x,t). We were able to transform this data using slant slack transform and later using other processes to finally obtain a Spectral Power Ratio graph, which when projected as an image can be used to visualize subsurface waves and get dispersion picks. If good quality data is used and multiple records are obtained for a ReMi setup, we can get much better dispersion picks from the data, as the noise would be normalized.

This data can be further manipulated to obtain subsurface S wave velocity profile and dispersion curves using forward modeling and inversion methods.

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Raines, M.G.; Gunn, D.A.; Morgan, D.J.R.; Williams, G.; Williams, J.D.O.; Caunt, S.. 2011 Refraction microtremor (ReMi) to determine the shear-wave velocity structure of the near surface and its application to aid detection of a backfilled mineshaft. *Quarterly Journal of Engineering Geology and Hydrogeology*, 44 (2). p211-220.