Seismic Interferometry and Beyond

Kees Wapenaar

Cargese Workshop 2015

Contents

- Part I: Seismic interferometry by cross-correlation
- Part II: Seismic interferometry by multi-dimensional deconvolution
- Part III: Beyond seismic interferometry

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Part III is also available as E-lecture:

https://youtu.be/DrpagMsK09M

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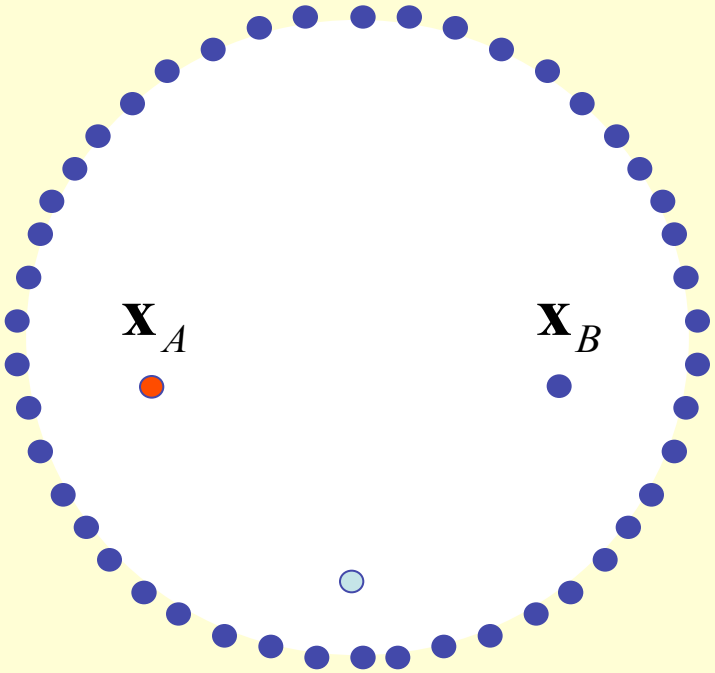
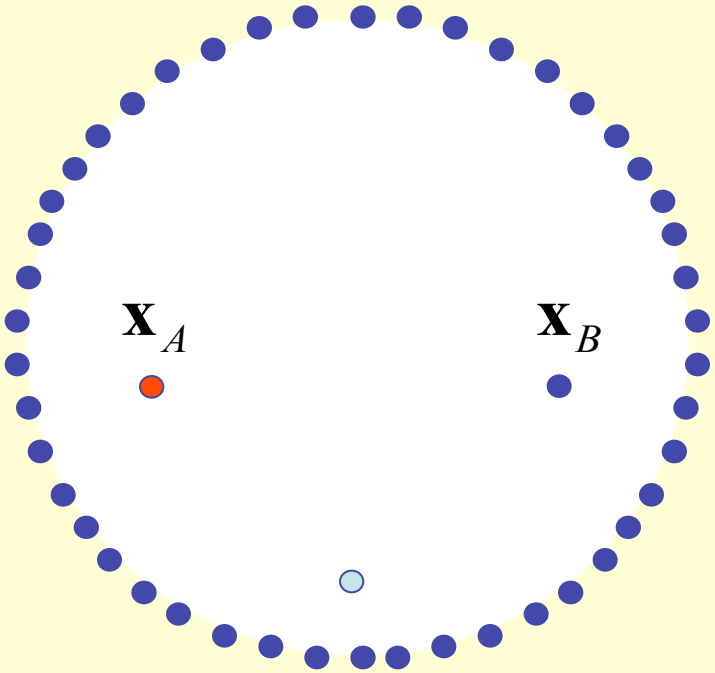


$$G_0(\mathbf{x}_B,\mathbf{x}_A,t)-G_0(\mathbf{x}_B,\mathbf{x}_A,-t)\ \approx$$

$$-\frac{2}{\rho c}\frac{\partial}{\partial t}\int_S G_0(\mathbf{x}_B,\mathbf{x},t)*G_0(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$

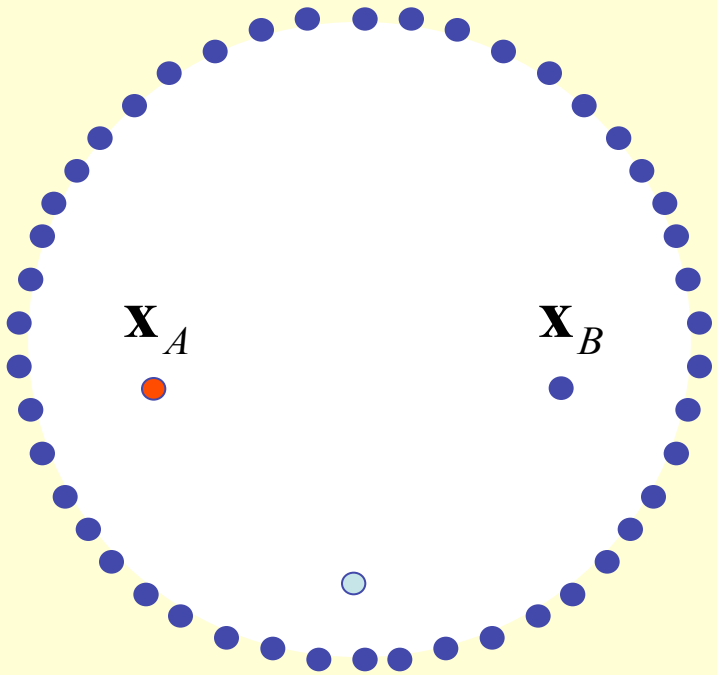


Representation proposed in the context of image-resolution analysis:

Porter, R. P., 1970, Diffraction-limited, scalar image formation with holograms of arbitrary shape: Journal of the Optical Society of America, 60, 1051–1059.

Oristaglio, M. L., 1989, An inverse scattering formula that uses all the data: Inverse Problems, **5**, 1097–1105.

$$G_0(\mathbf{x}_B,\mathbf{x}_A,t)-G_0(\mathbf{x}_B,\mathbf{x}_A,-t)\approx -\frac{2}{\rho c}\frac{\partial}{\partial t}\int_S G_0(\mathbf{x}_B,\mathbf{x},t)*G_0(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$



Representation proposed in the context of Green's function retrieval from ambient noise:

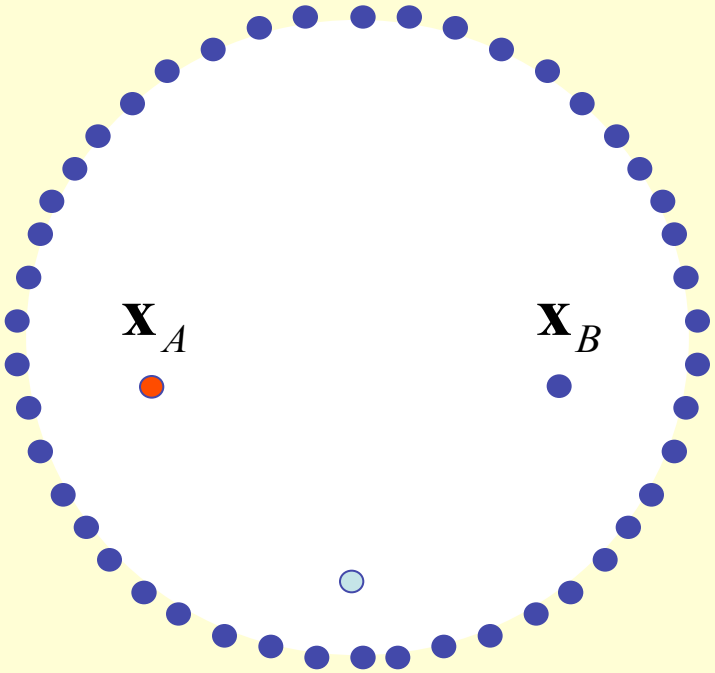
Wapenaar, K., 2003, Synthesis of an Inhomogeneous medium from its acoustic transmission response: Geophysics, 68, 1756-1759

Weaver, R. L., and O. I. Lobkis, 2004, Diffuse fields in open systems and the emergence of the Green's function L: Journal of the Acoustical Society of America, 116, 2731–2734

Wapenaar, K., 2004, Retrieving the elasto-dynamic Green's function of an arbitrary inhomogeneous medium by cross correlation: Physical Review Letters, 93, 254301

$$G_0(\mathbf{x}_B,\mathbf{x}_A,t)-G_0(\mathbf{x}_B,\mathbf{x}_A,-t)\;\approx$$

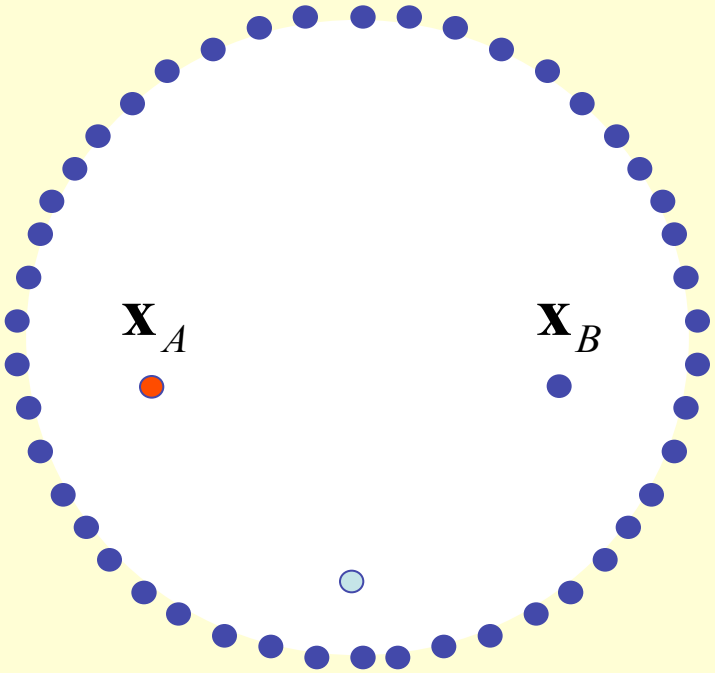
$$-\frac{2}{\rho c}\frac{\partial}{\partial t}\int_S G_0(\mathbf{x}_B,\mathbf{x},t)*G_0(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$



Sum or difference of G's?

$$G_0(\mathbf{x}_B,\mathbf{x}_A,t) - G_0(\mathbf{x}_B,\mathbf{x}_A,-t) \approx$$

$$-\frac{2}{\rho c}\frac{\partial}{\partial t}\int_S G_0(\mathbf{x}_B,\mathbf{x},t) * G_0(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$



Sum or difference of G's?

$$G(\mathbf{x}_B, \mathbf{x}_A, t) = \frac{\partial}{\partial t} G_0(\mathbf{x}_B, \mathbf{x}_A, t)$$

$$G_0(\mathbf{x}_B, \mathbf{x}_A, t) - G_0(\mathbf{x}_B, \mathbf{x}_A, -t) \approx$$

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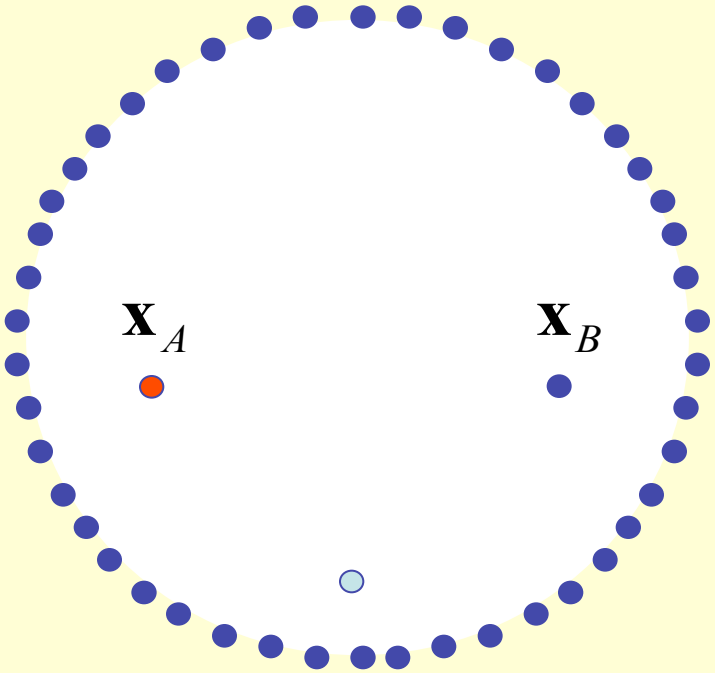
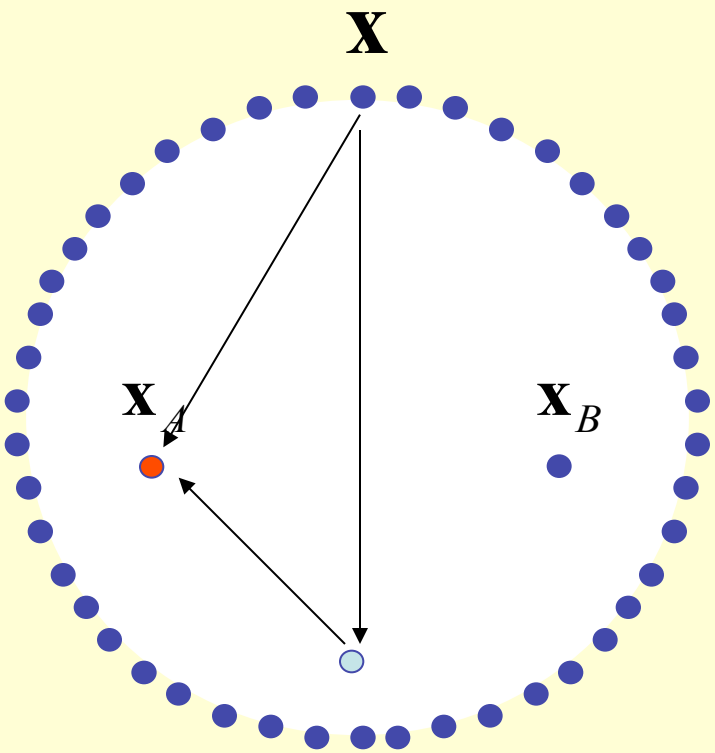


Sum or difference of G's?

$$G(\mathbf{x}_B,\mathbf{x}_A,t)=\frac{\partial}{\partial t}G_0(\mathbf{x}_B,\mathbf{x}_A,t)$$

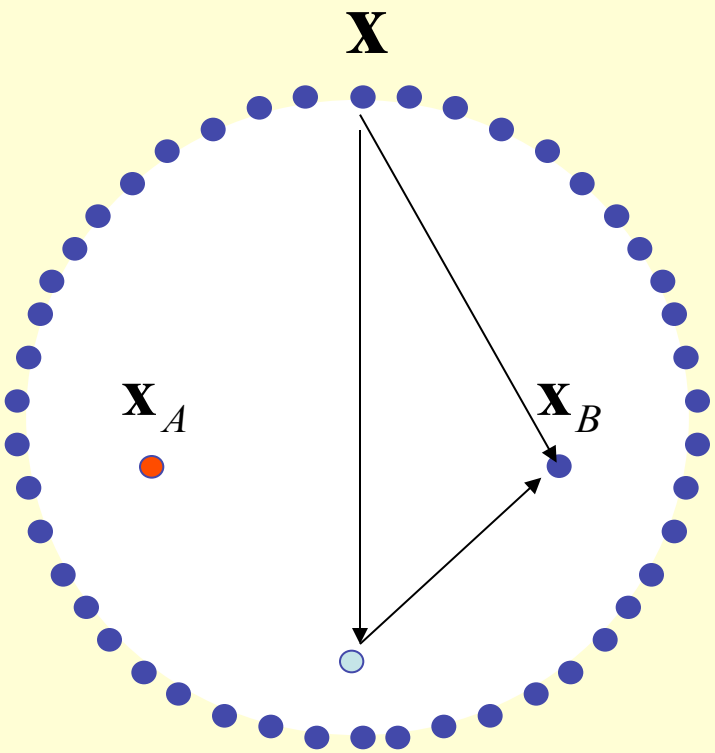
$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t)\ \approx$$

$$\frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$



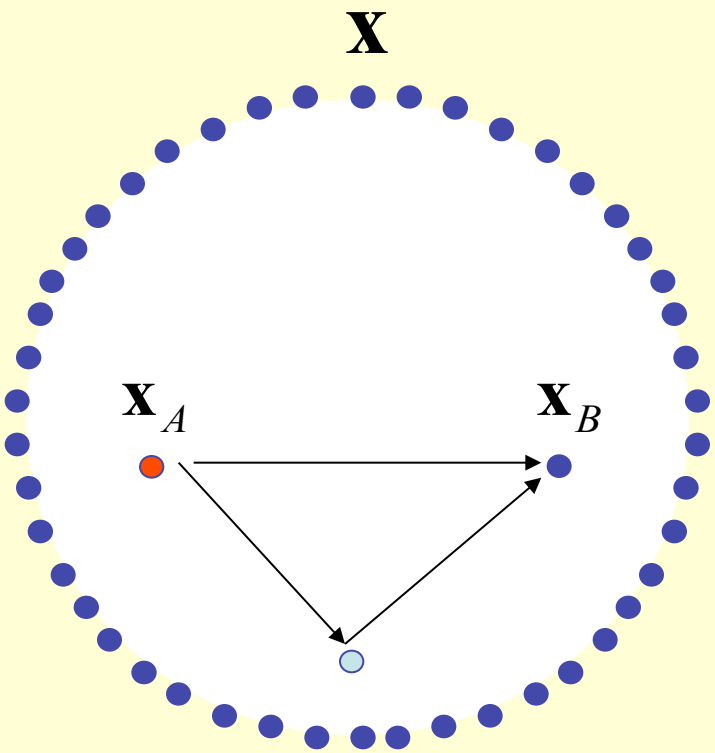
Source at $\mathbf{x}$,
Receiver at $\mathbf{x}_A$

$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t) * G(\mathbf{x}_A,\mathbf{x},-t)\,d^2\mathbf{x}$$



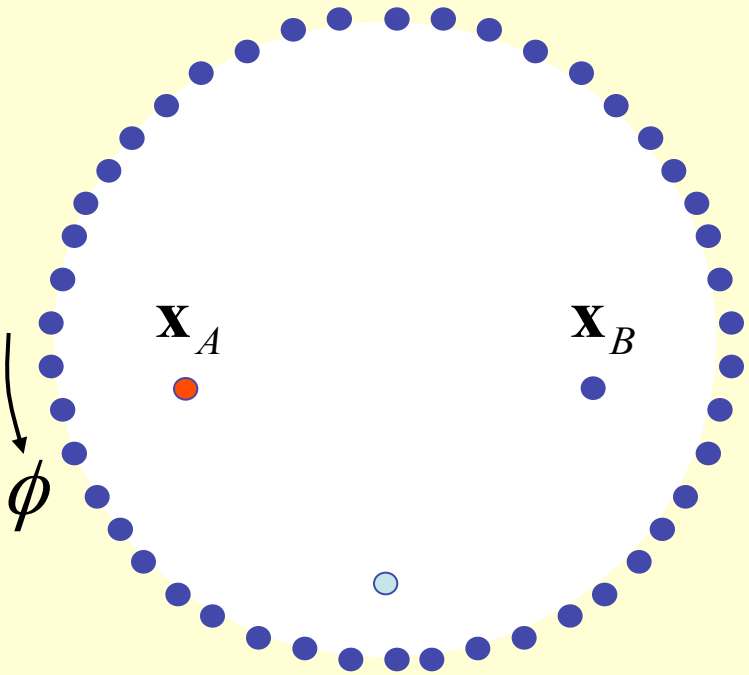
Source at $\mathbf{x}$,
Receiver at $\mathbf{x}_B$

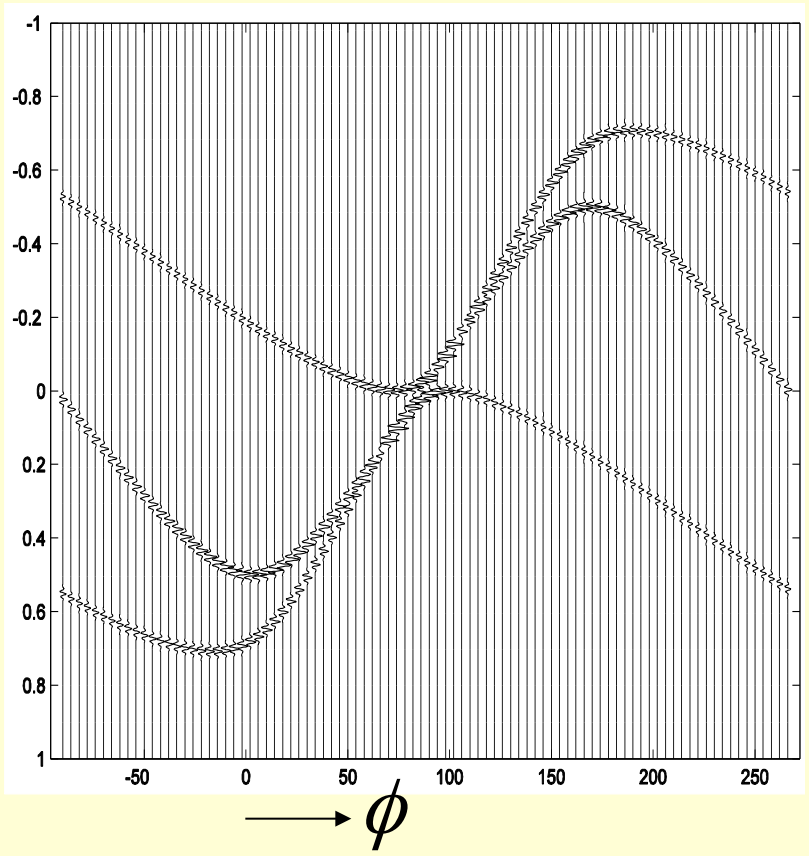
$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t) * G(\mathbf{x}_A,\mathbf{x},-t)\,d^2\mathbf{x}$$

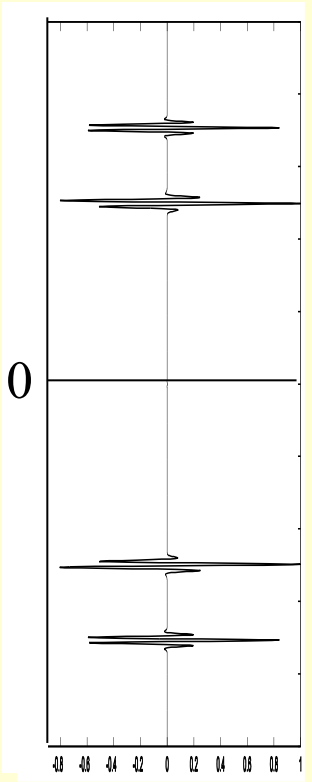


Source at $\mathbf{x}_A$,
Receiver at $\mathbf{x}_B$

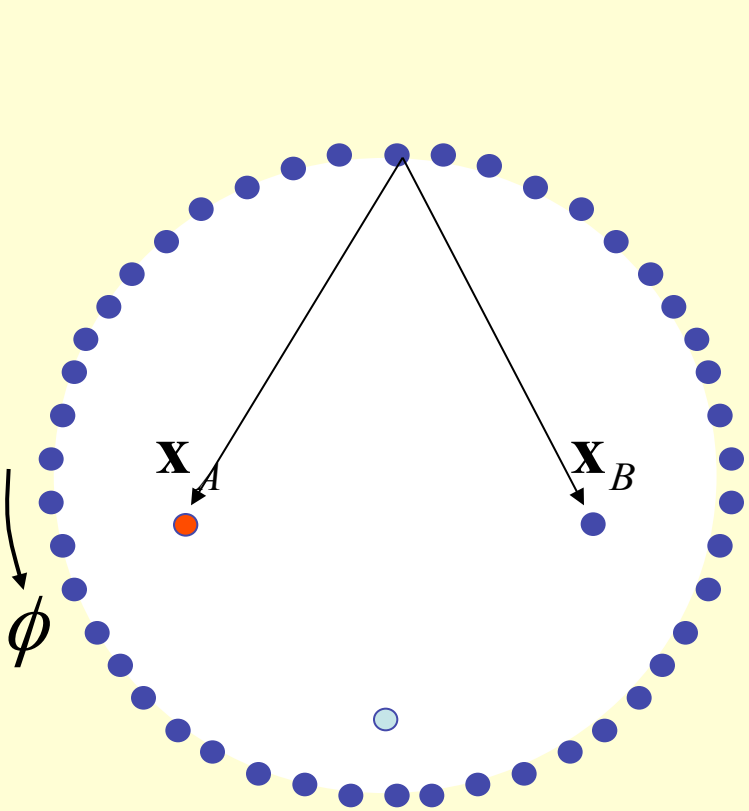
$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$

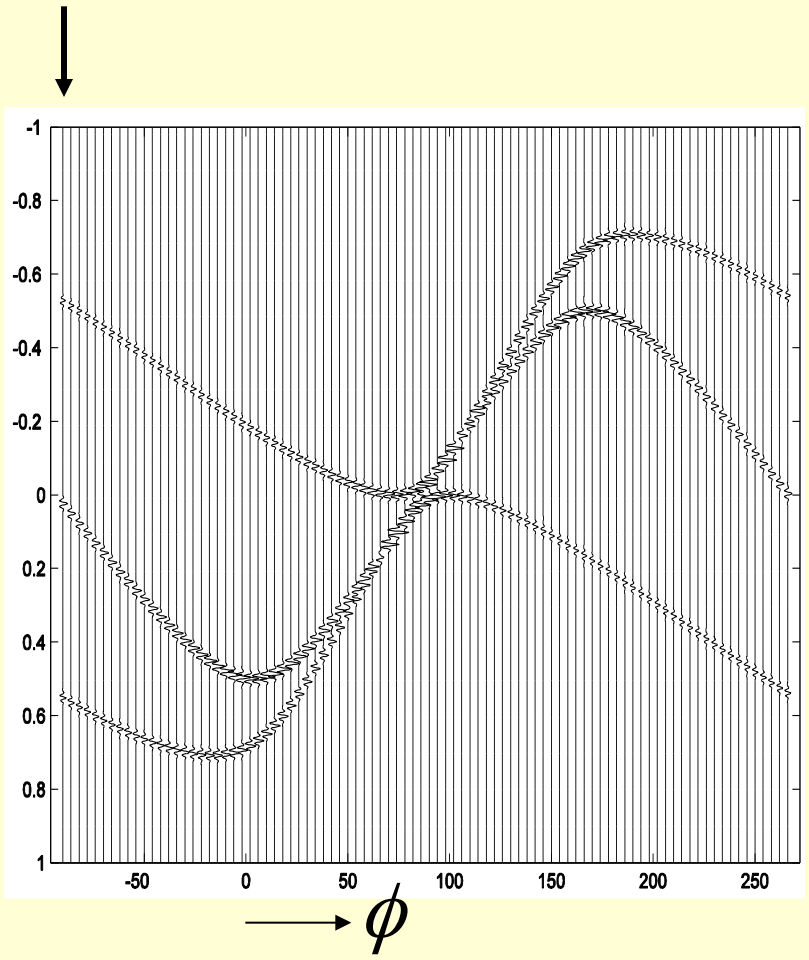


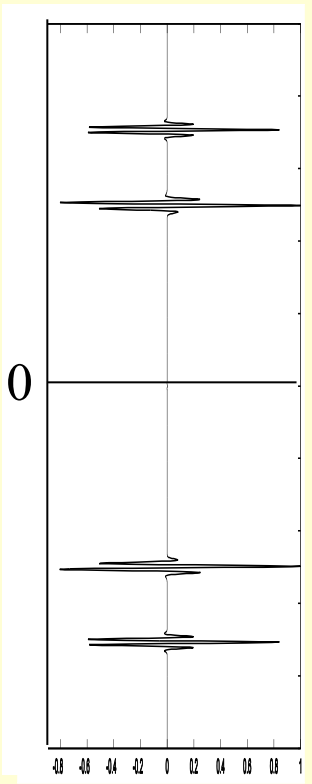




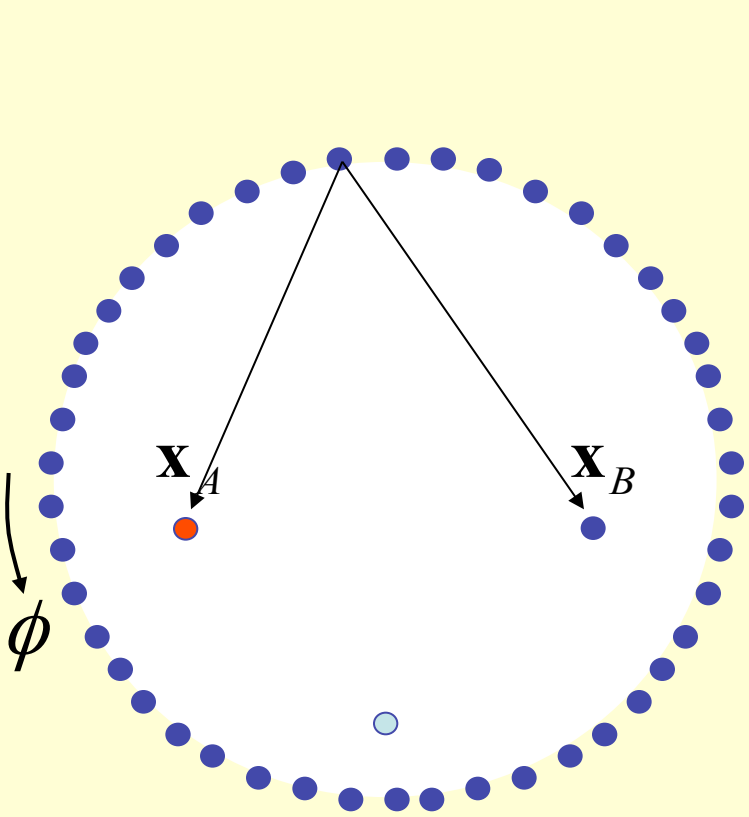
$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$

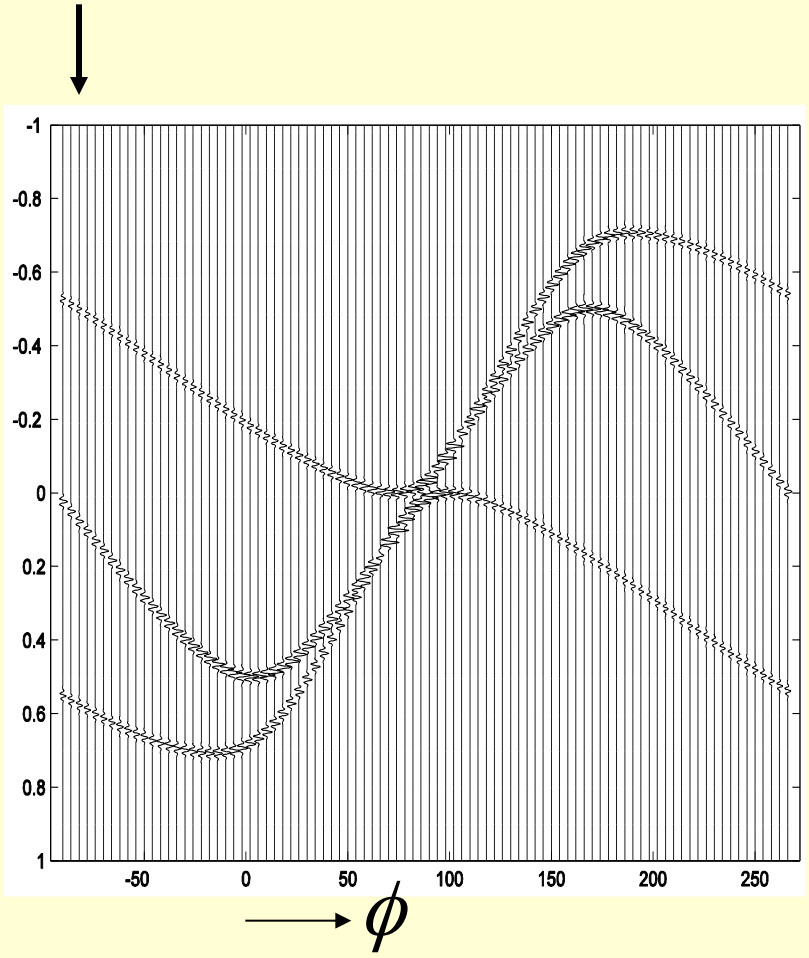


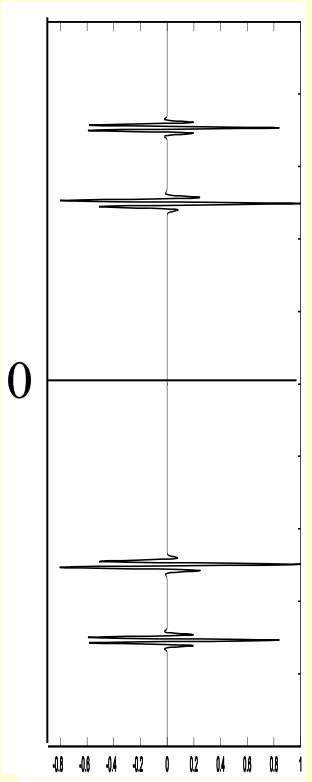




$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$







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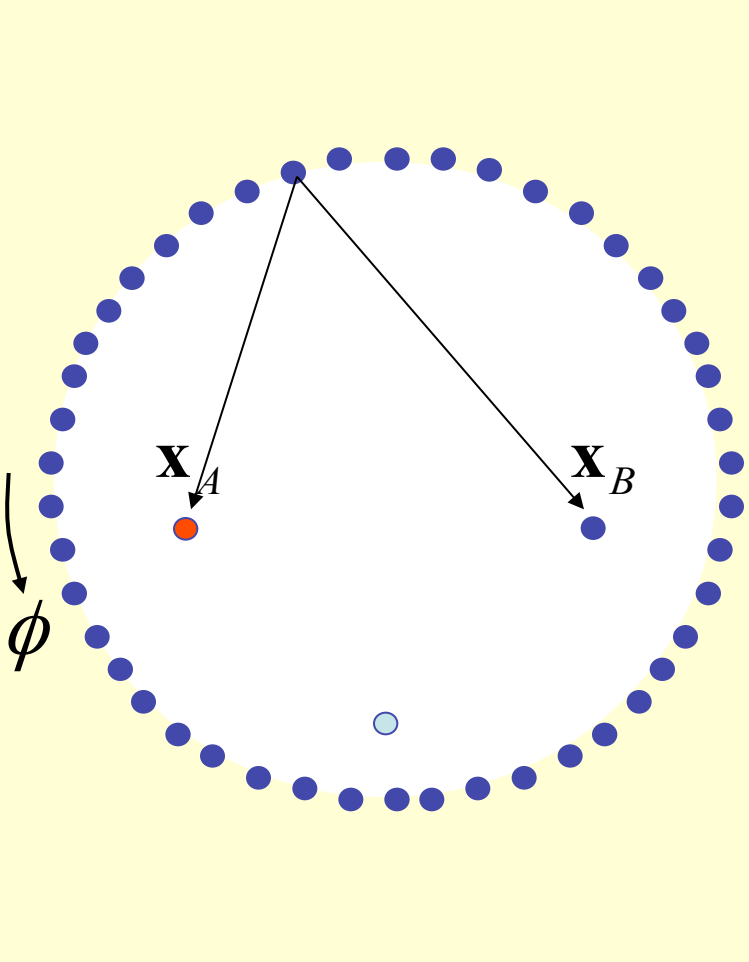

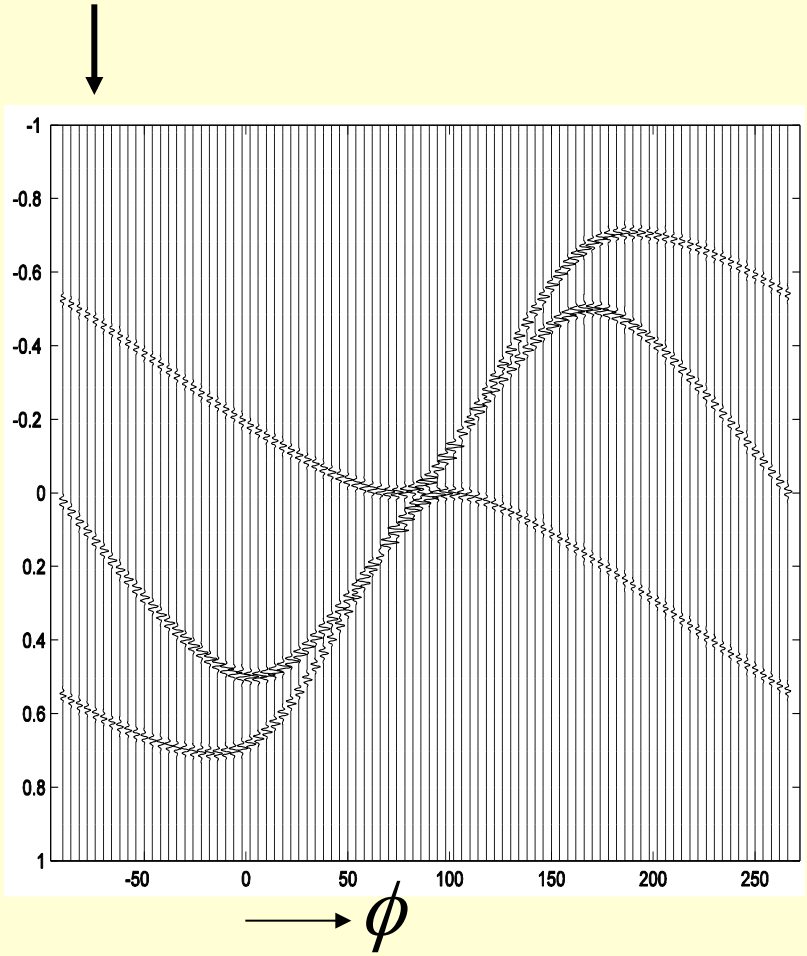

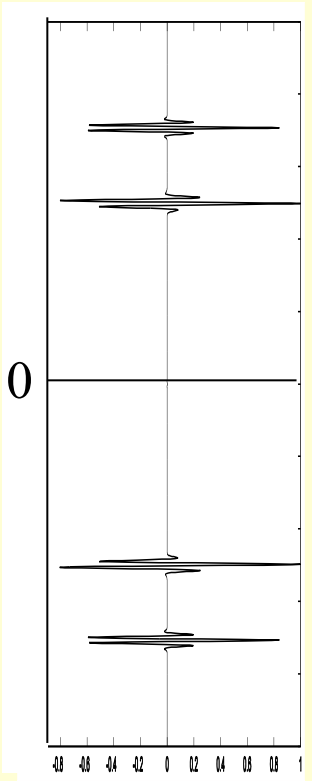

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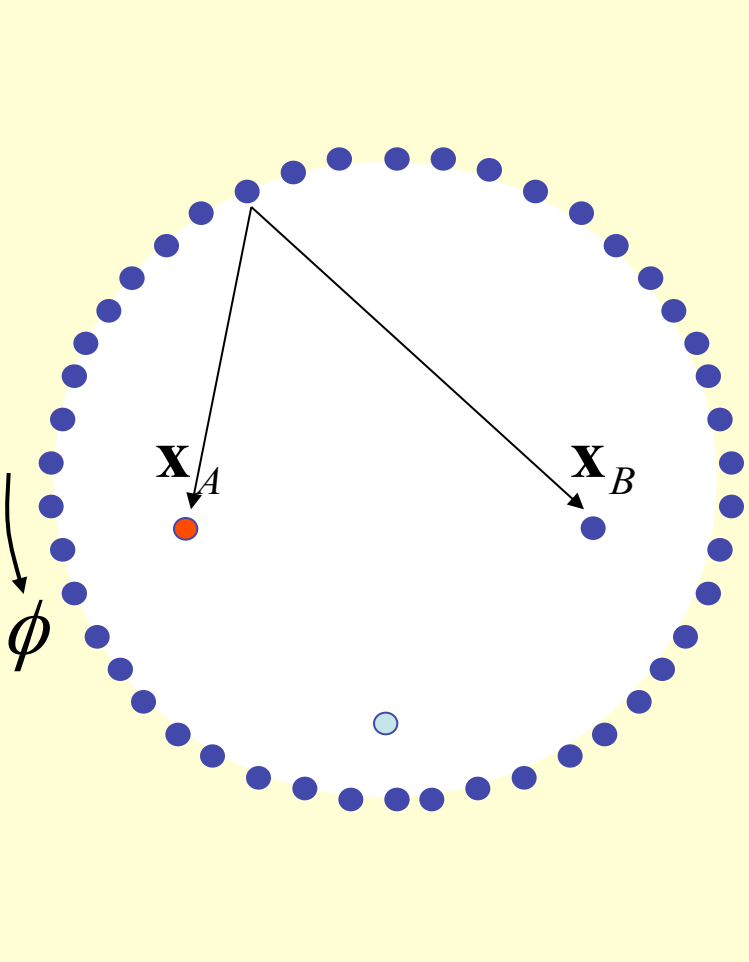

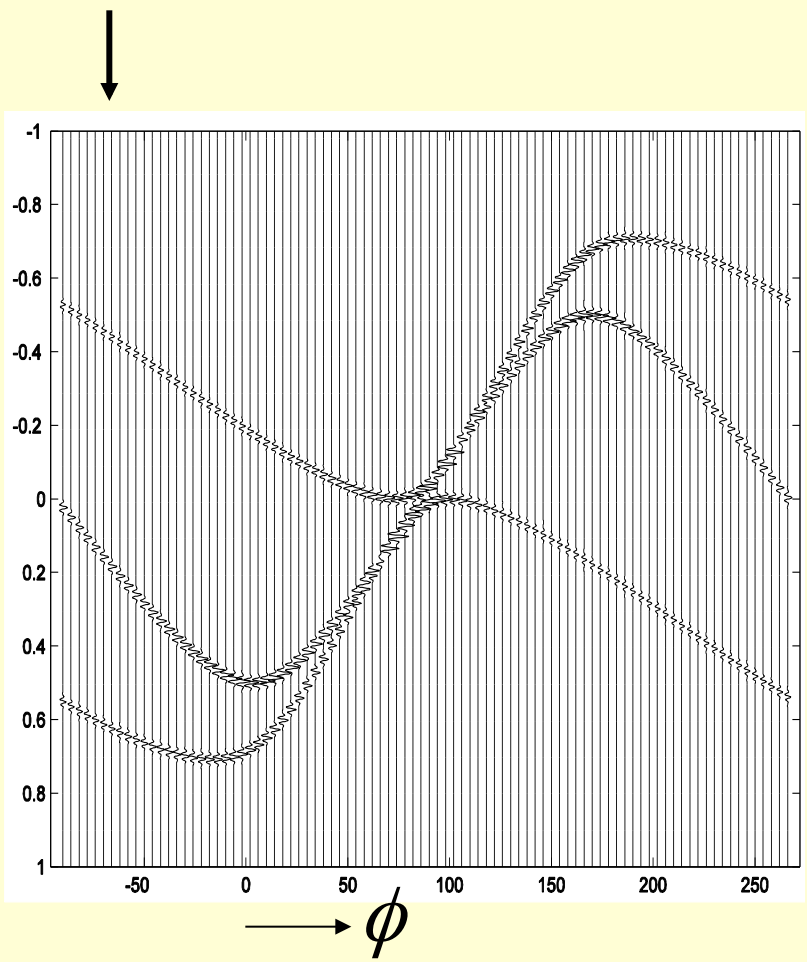

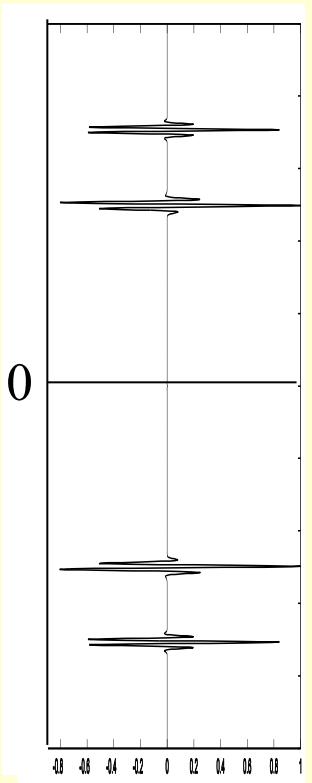

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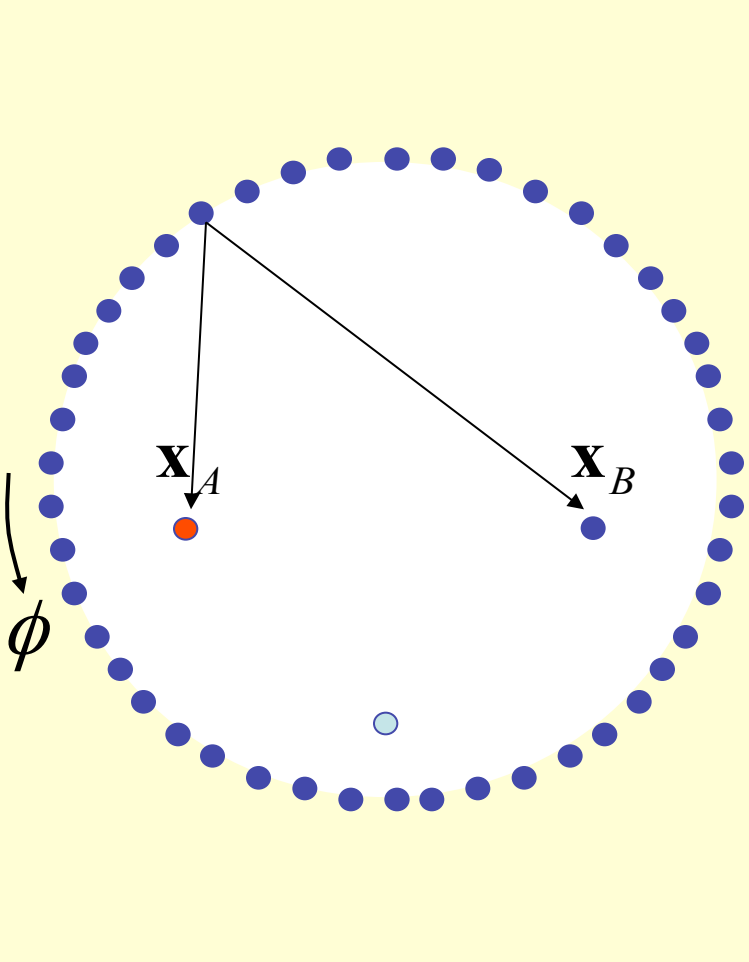

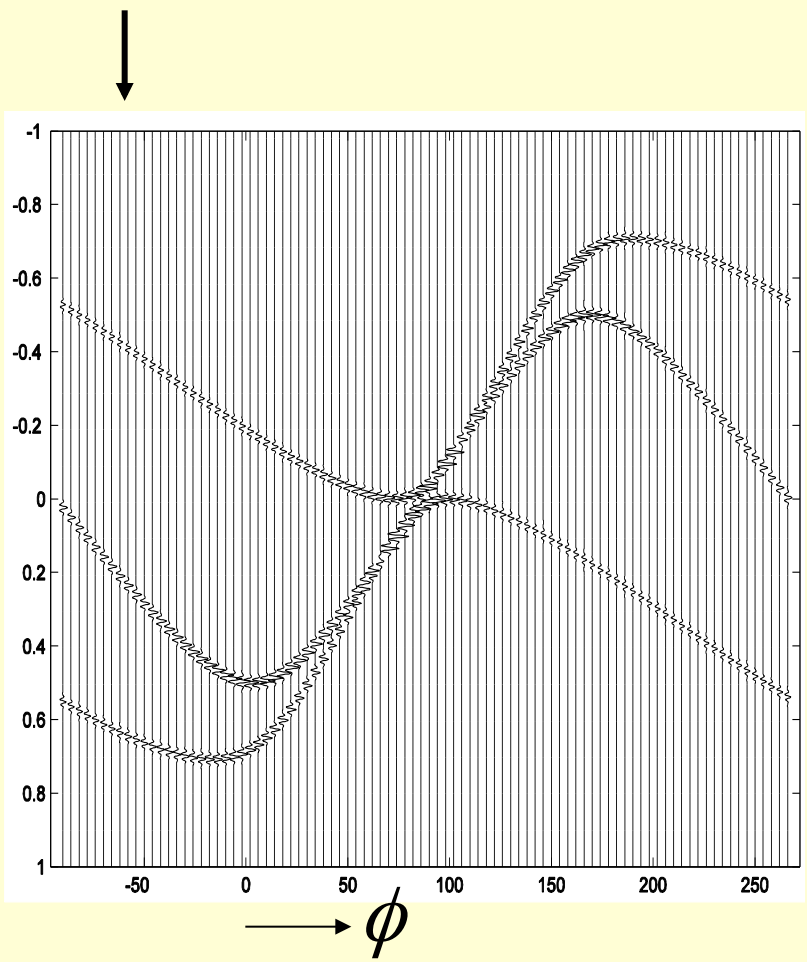

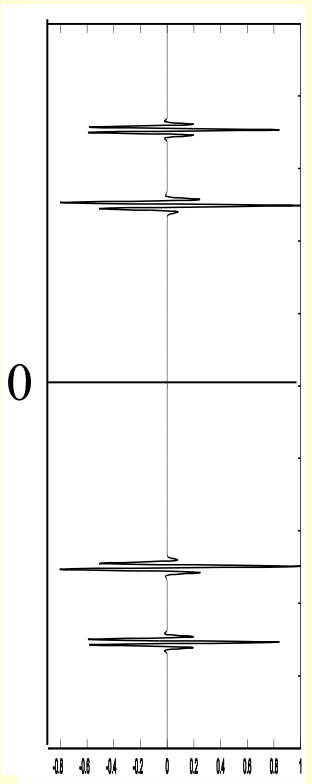

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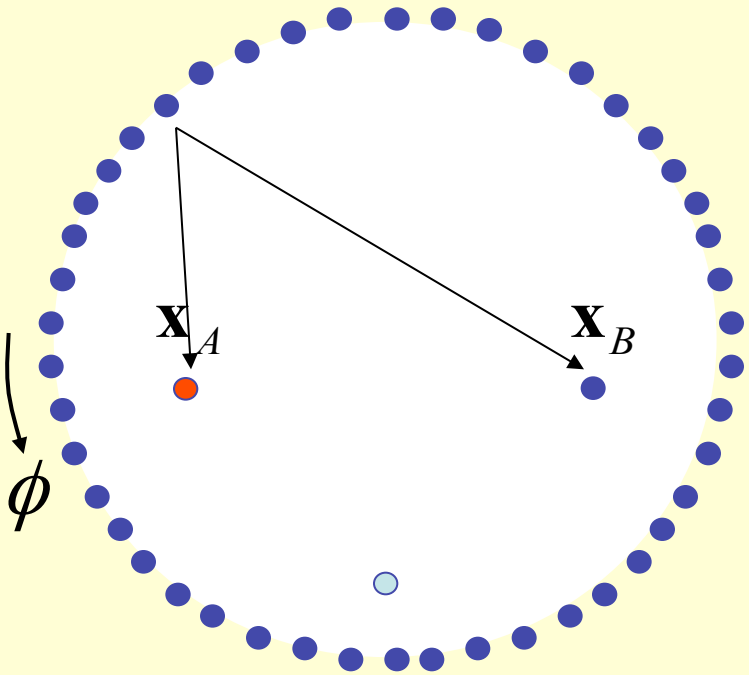

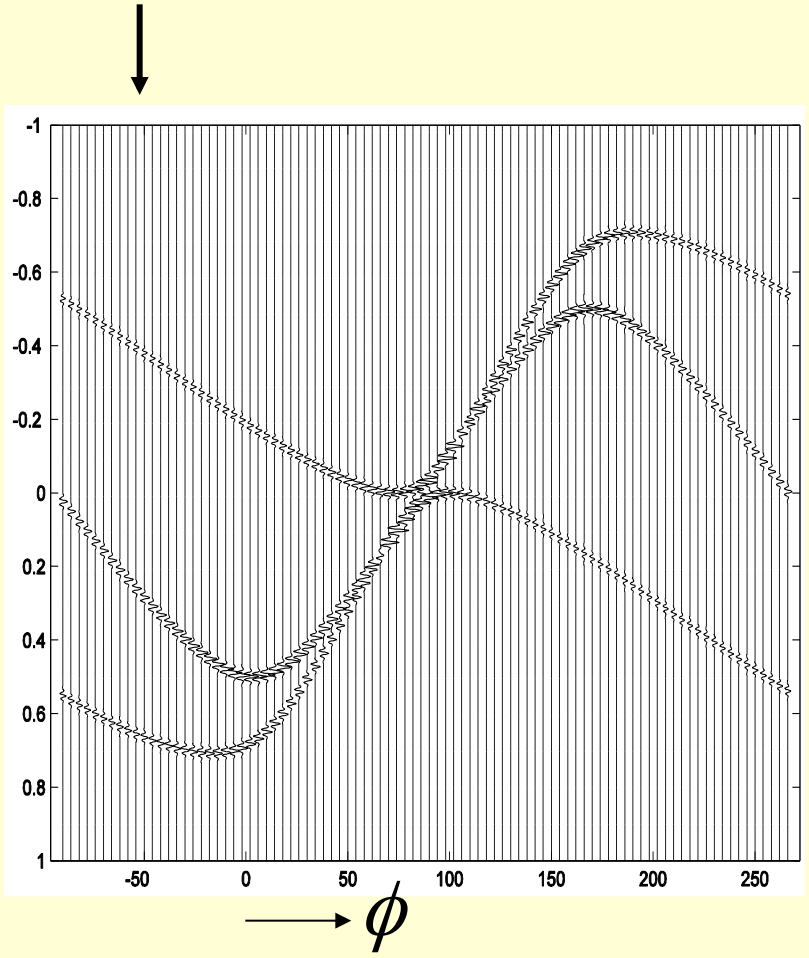

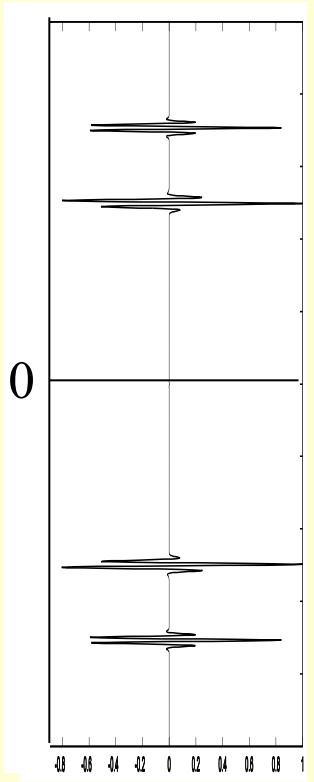

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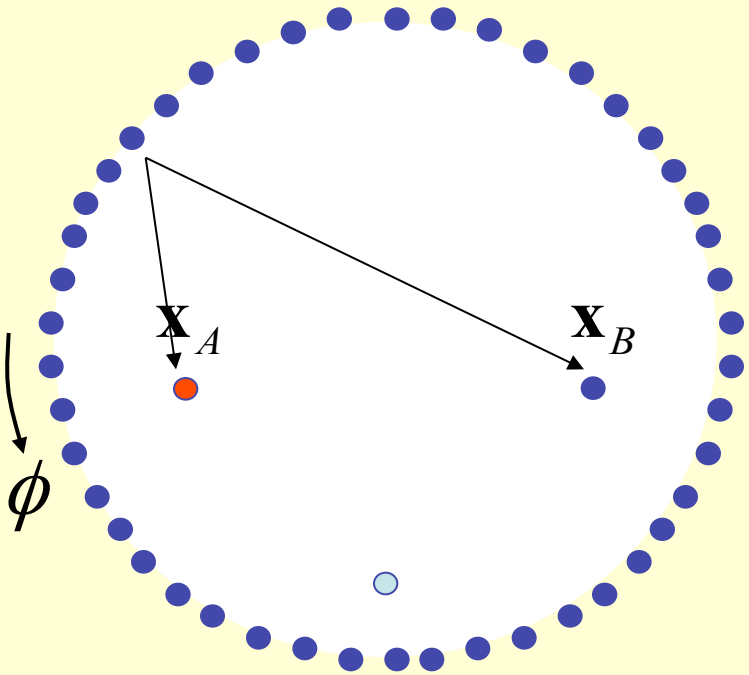

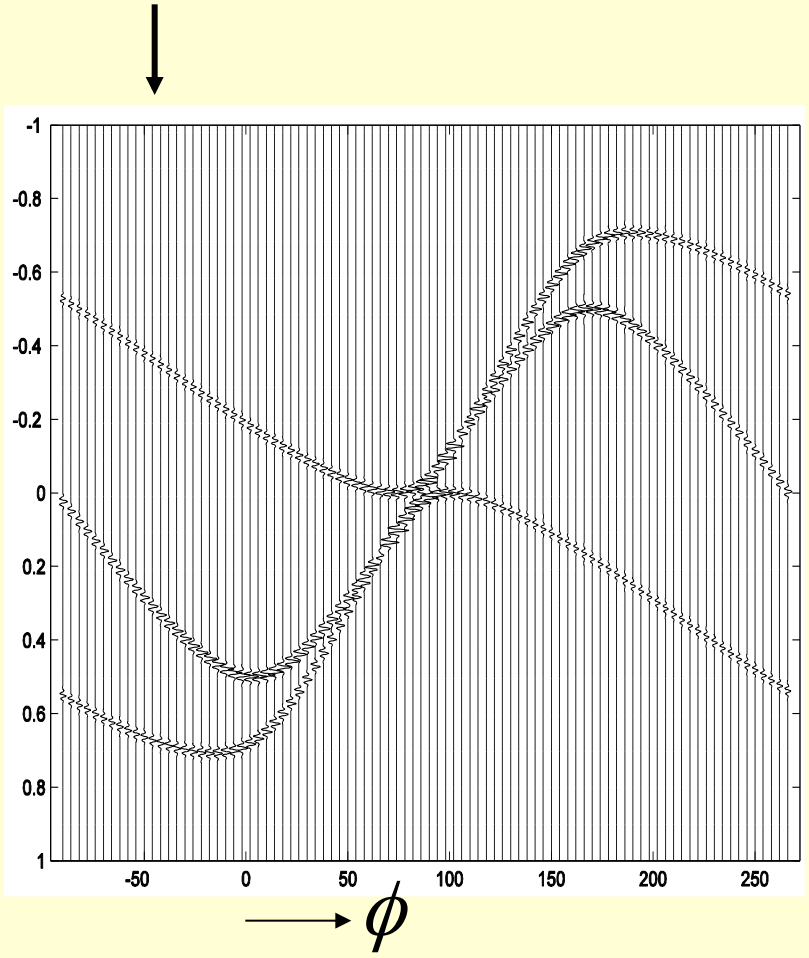

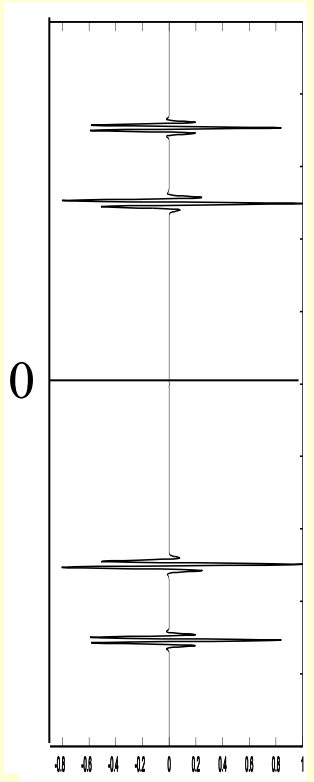

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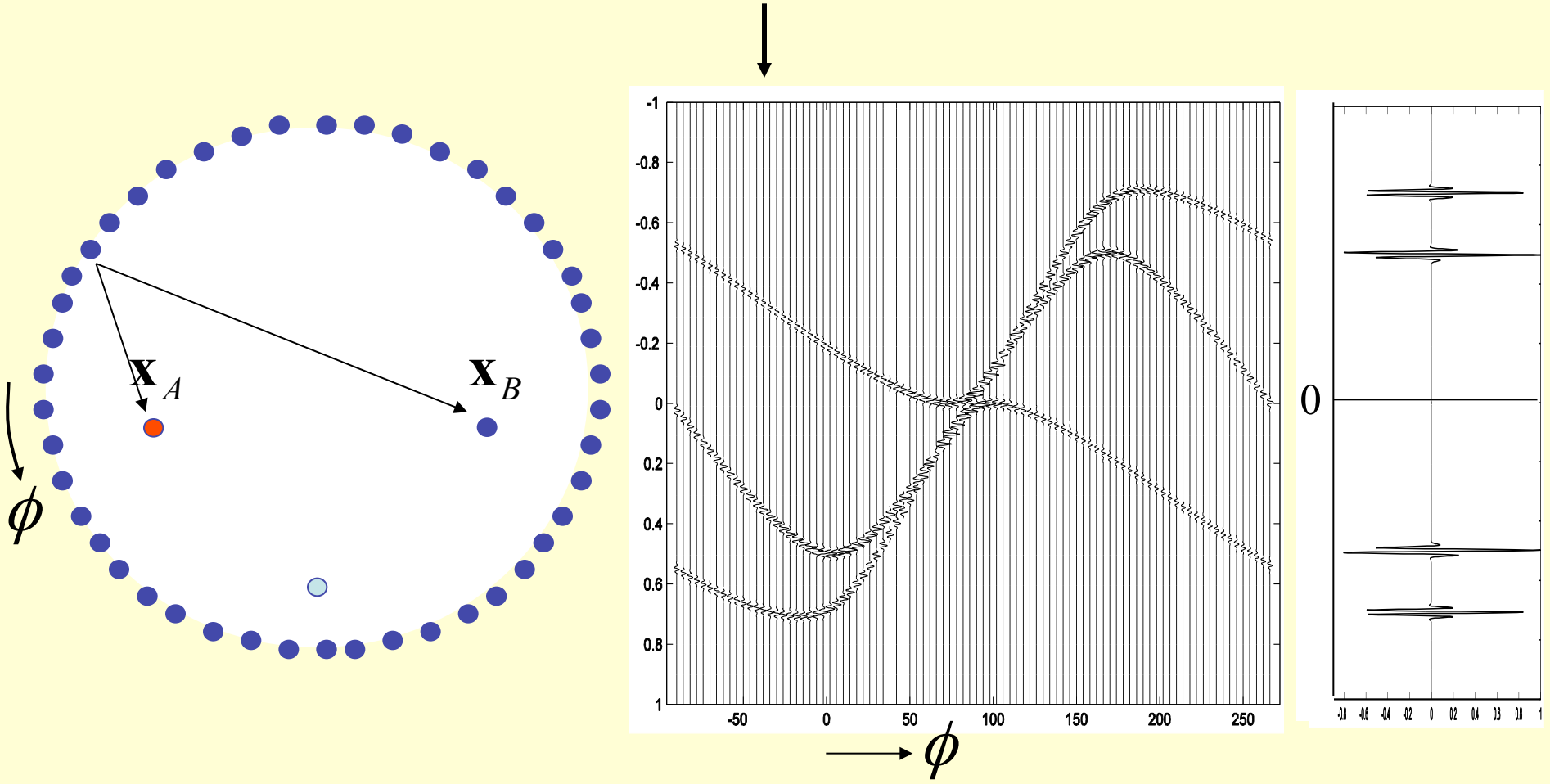

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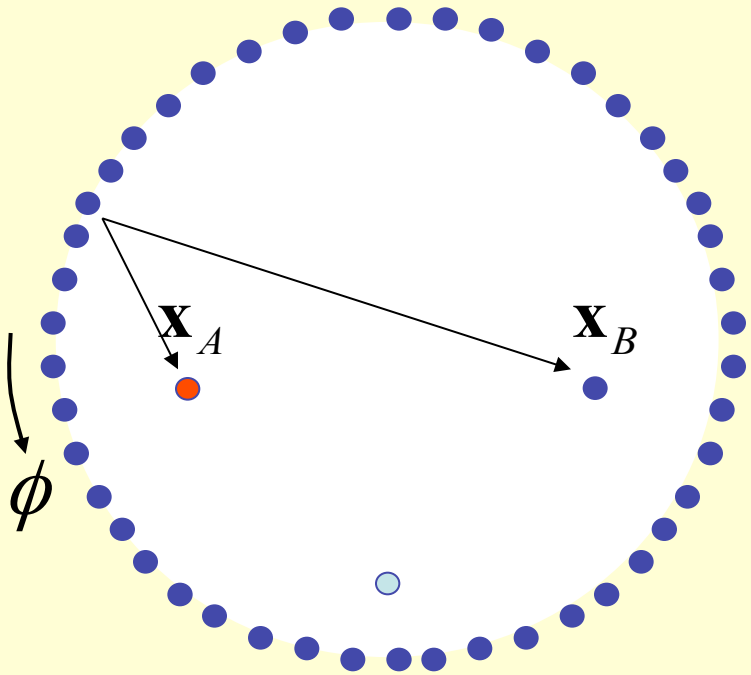

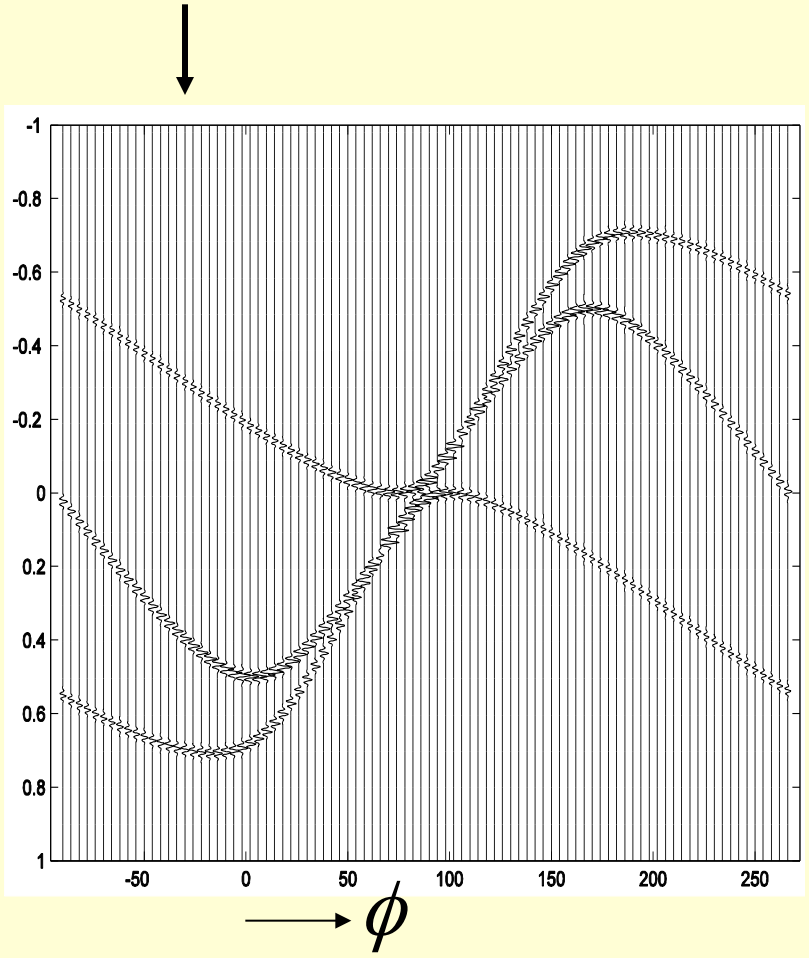

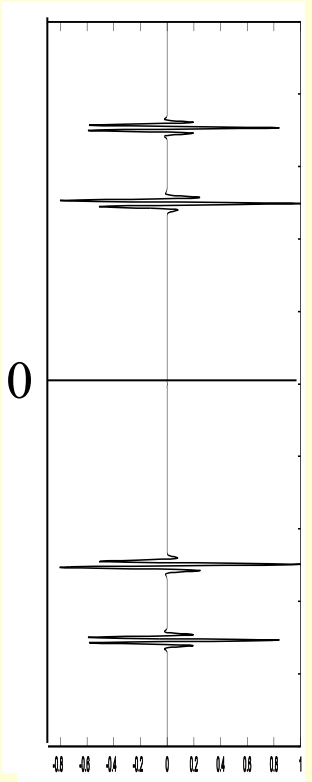

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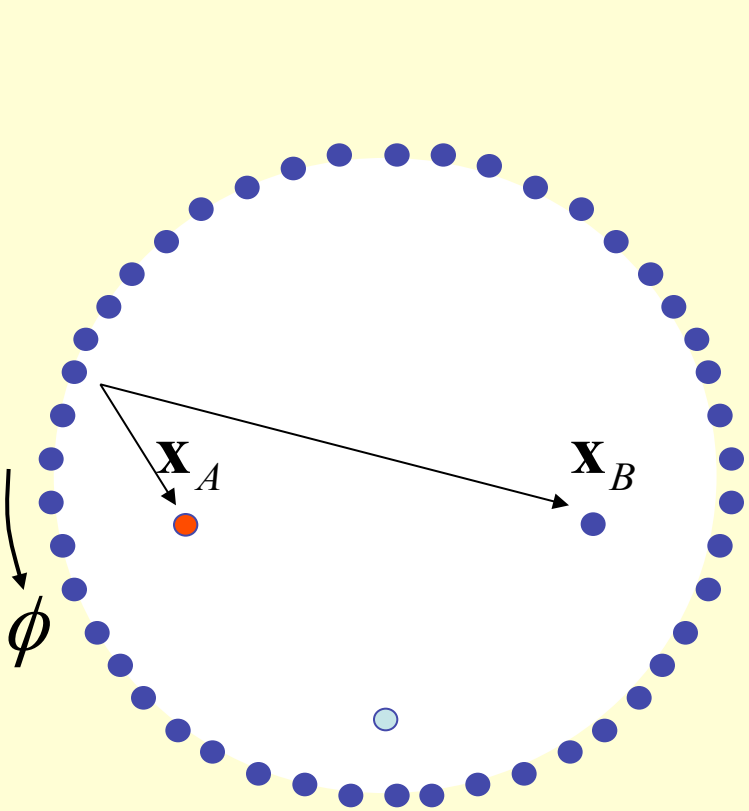

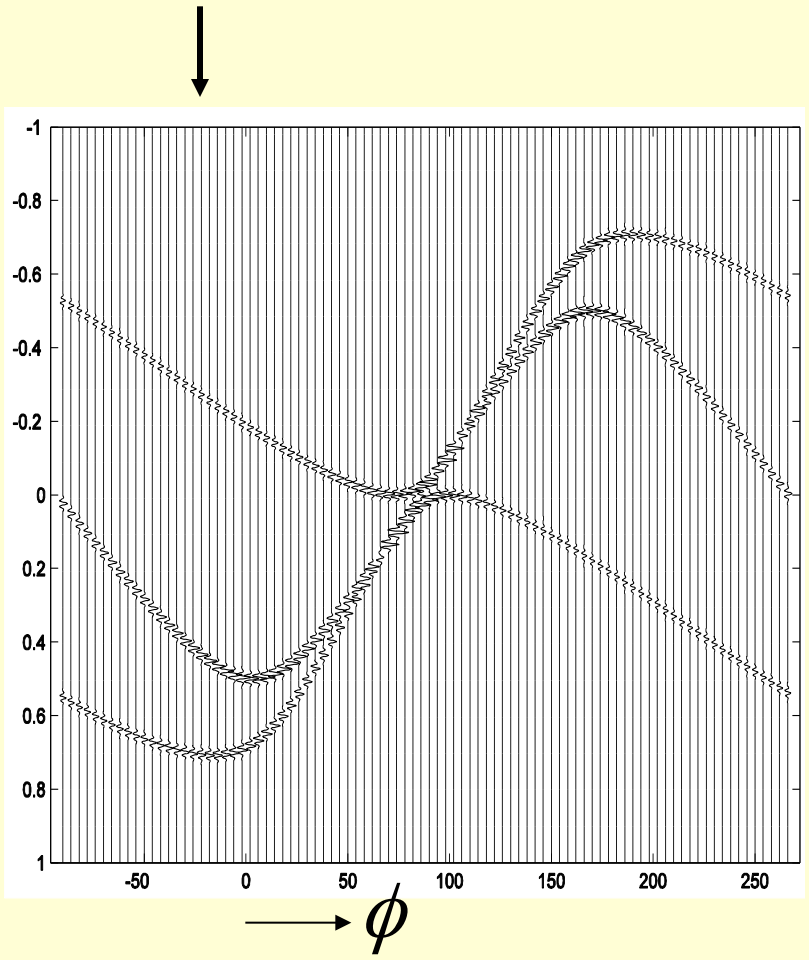

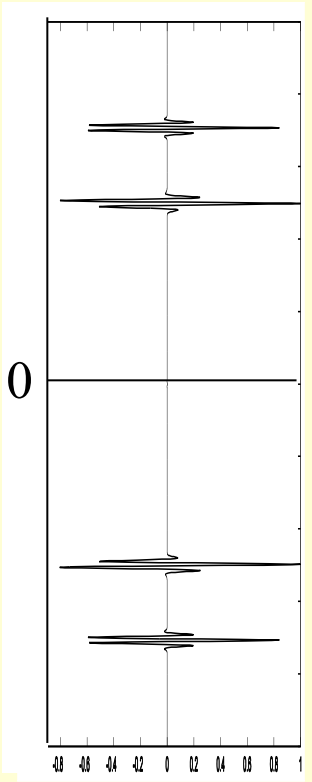

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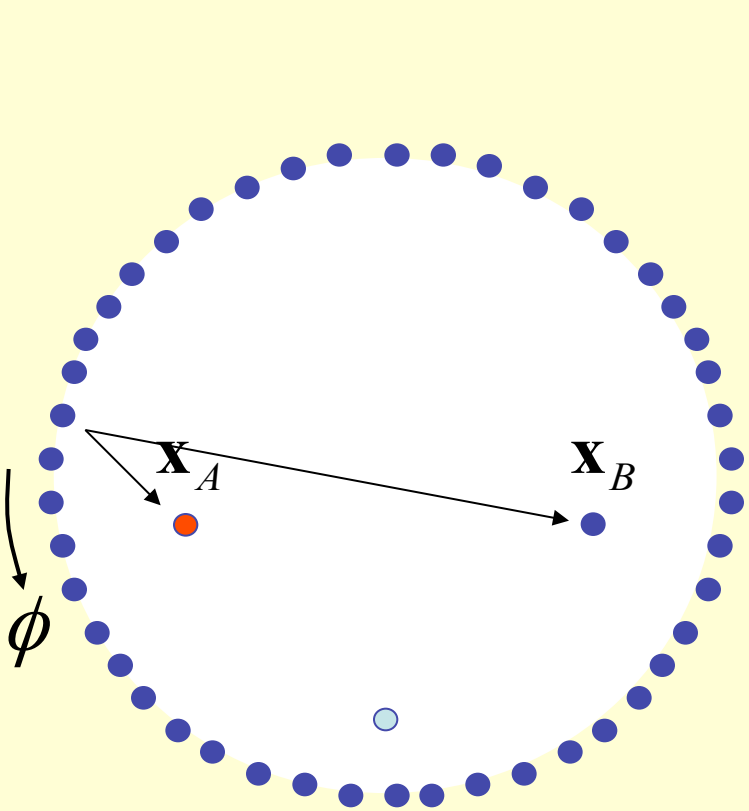

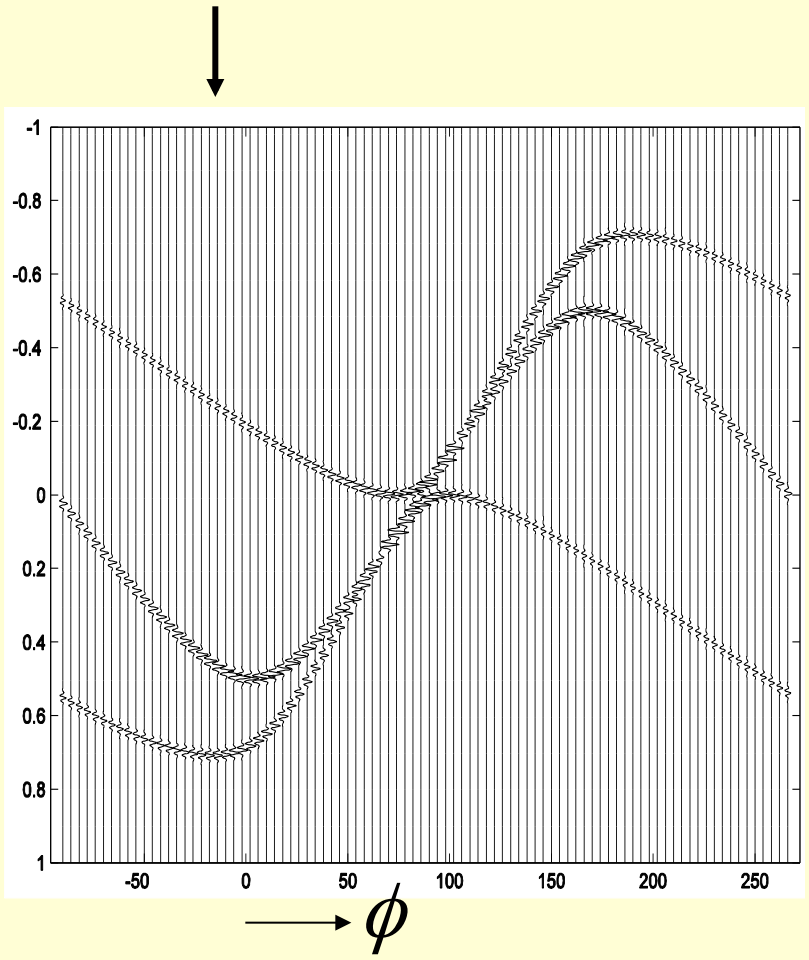

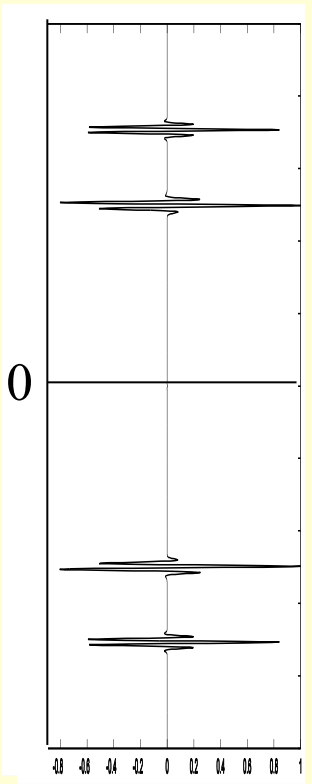

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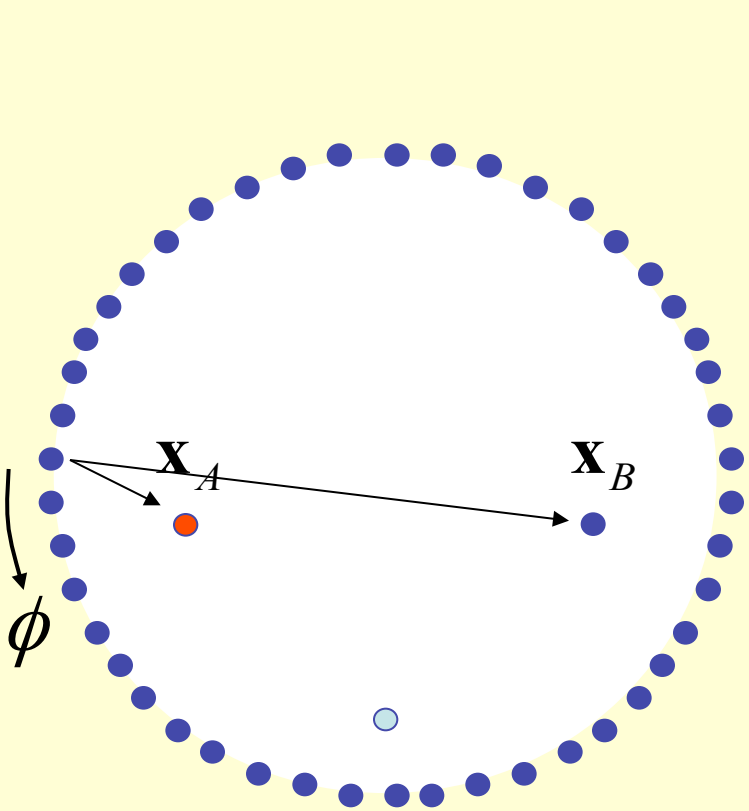
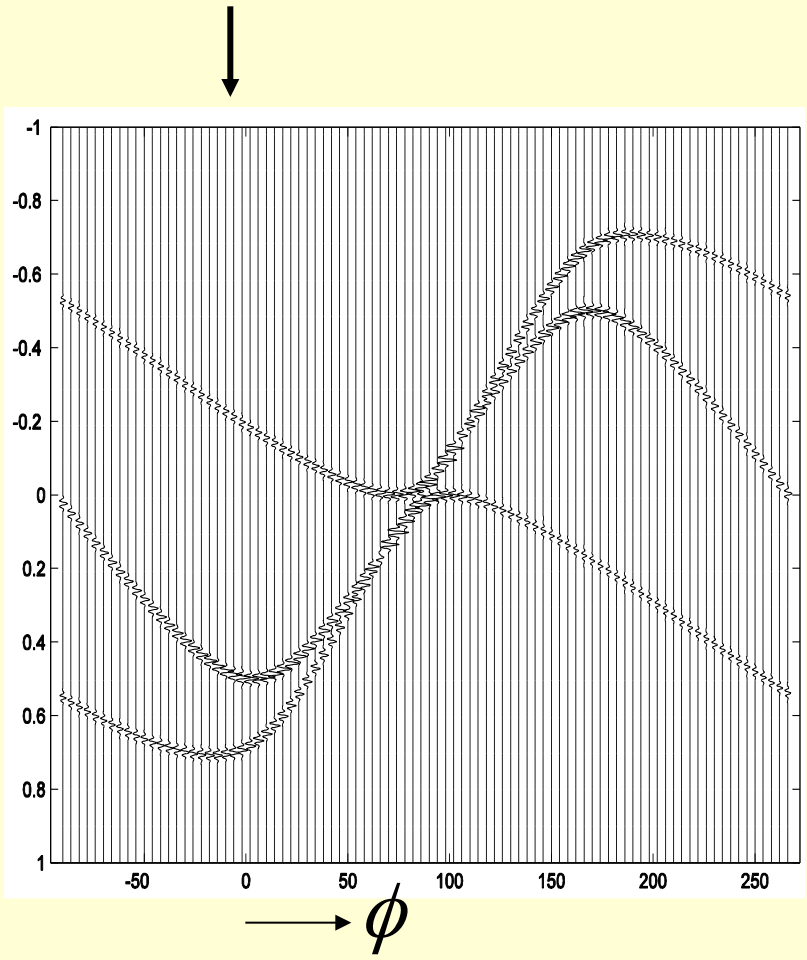
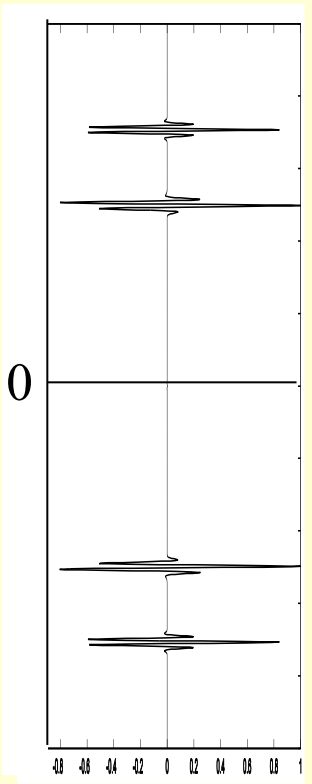
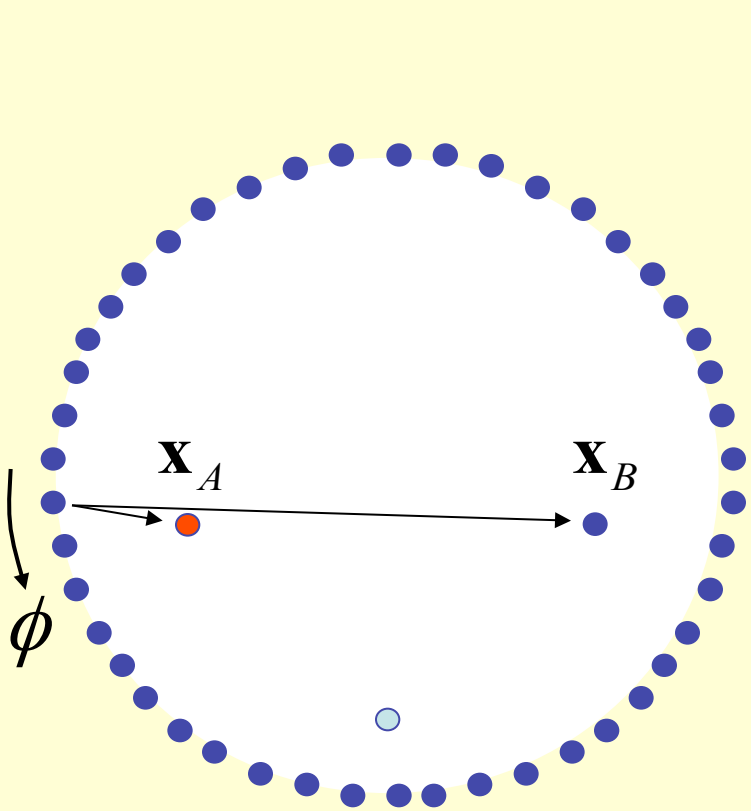
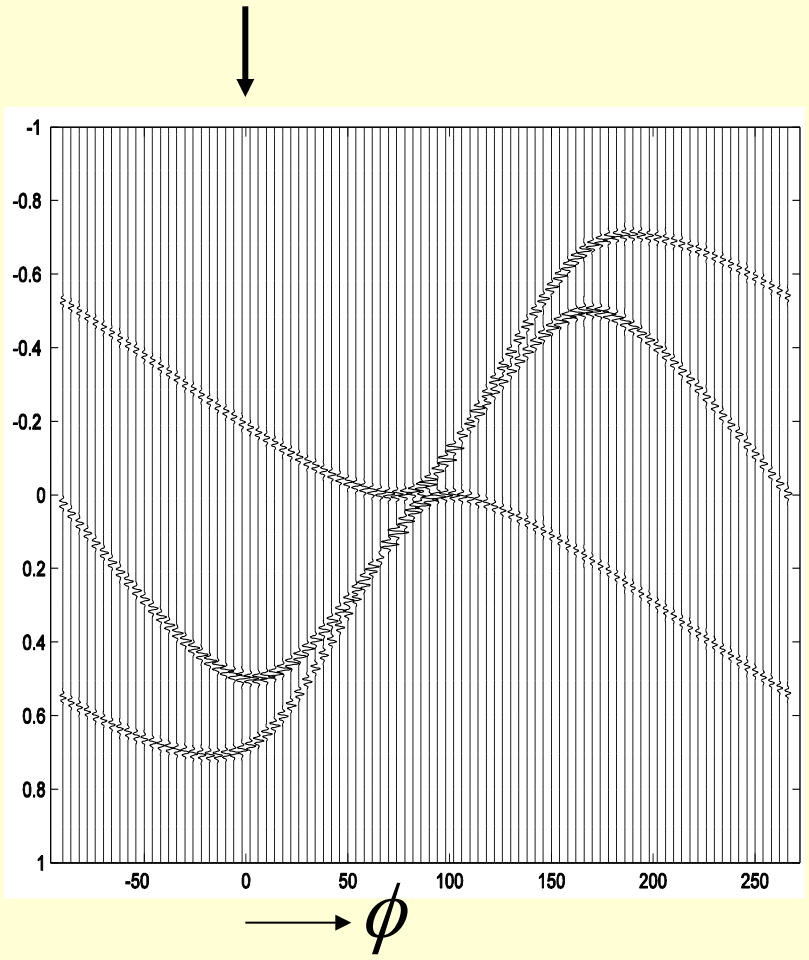


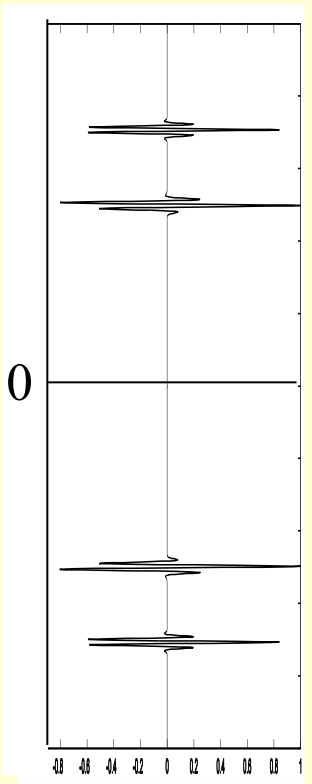




$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$







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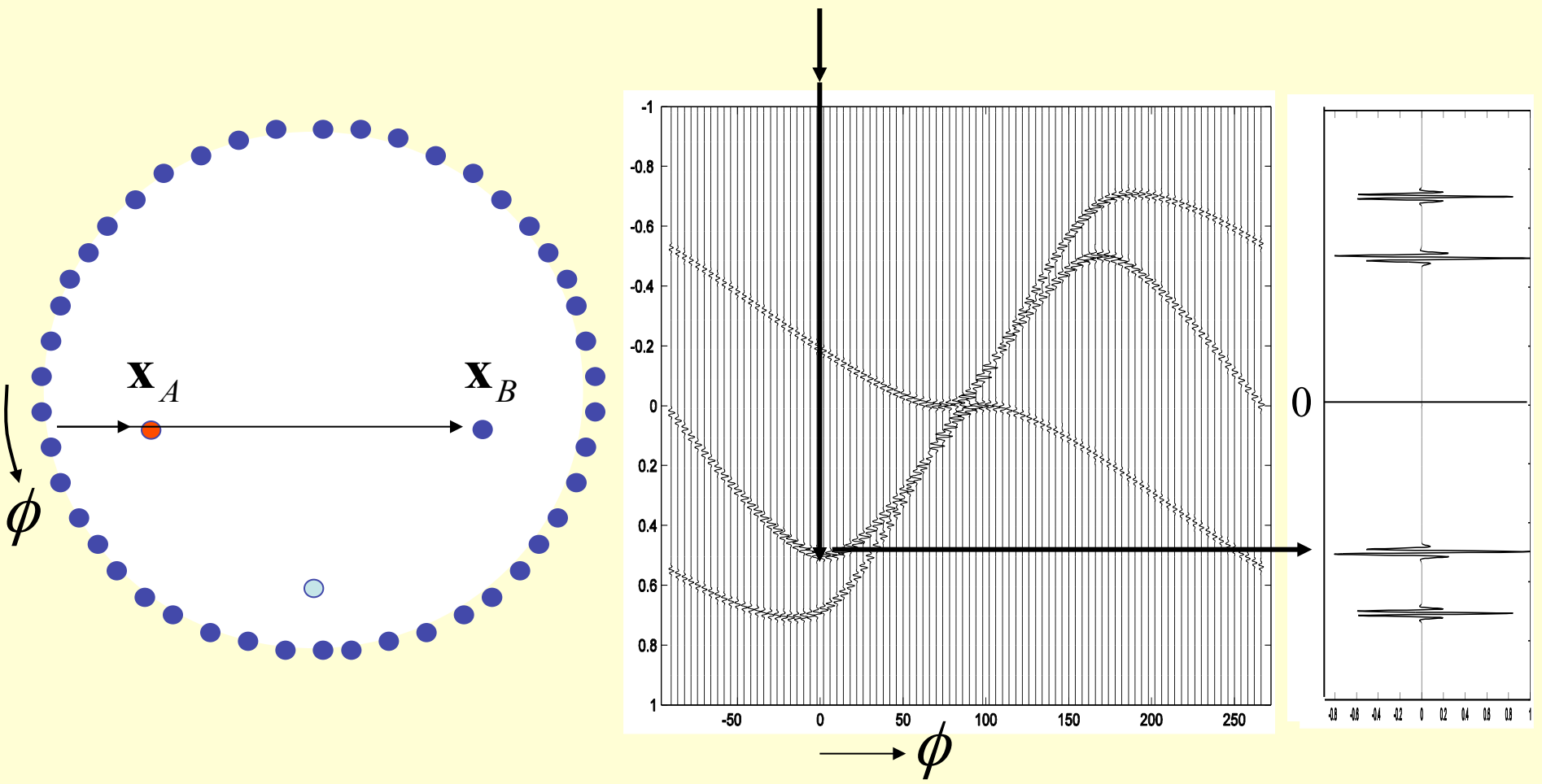

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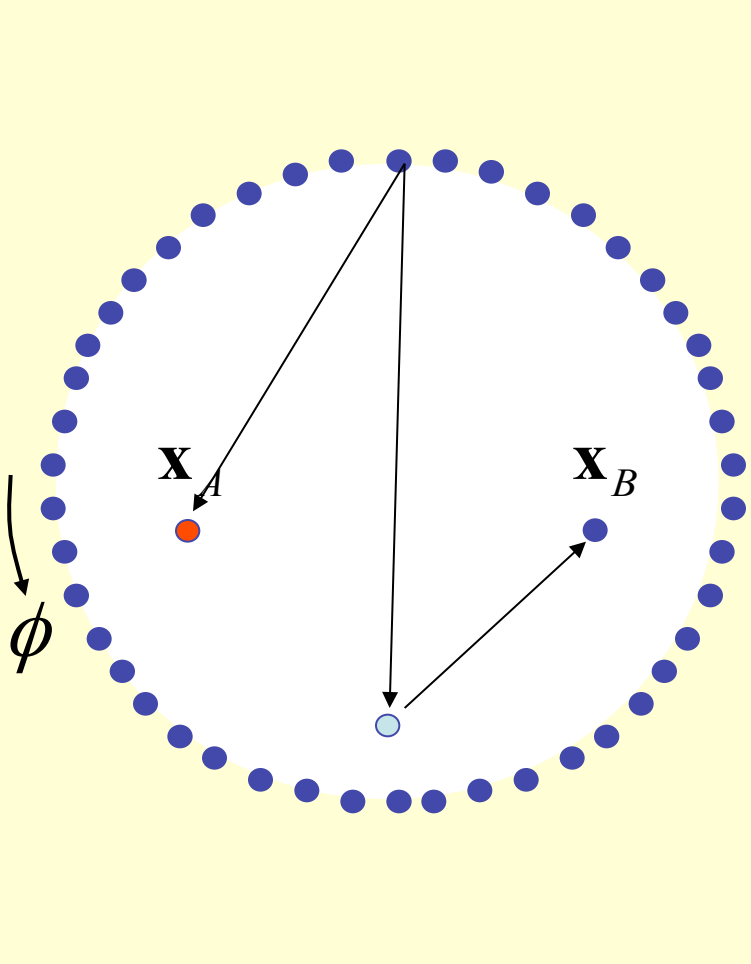
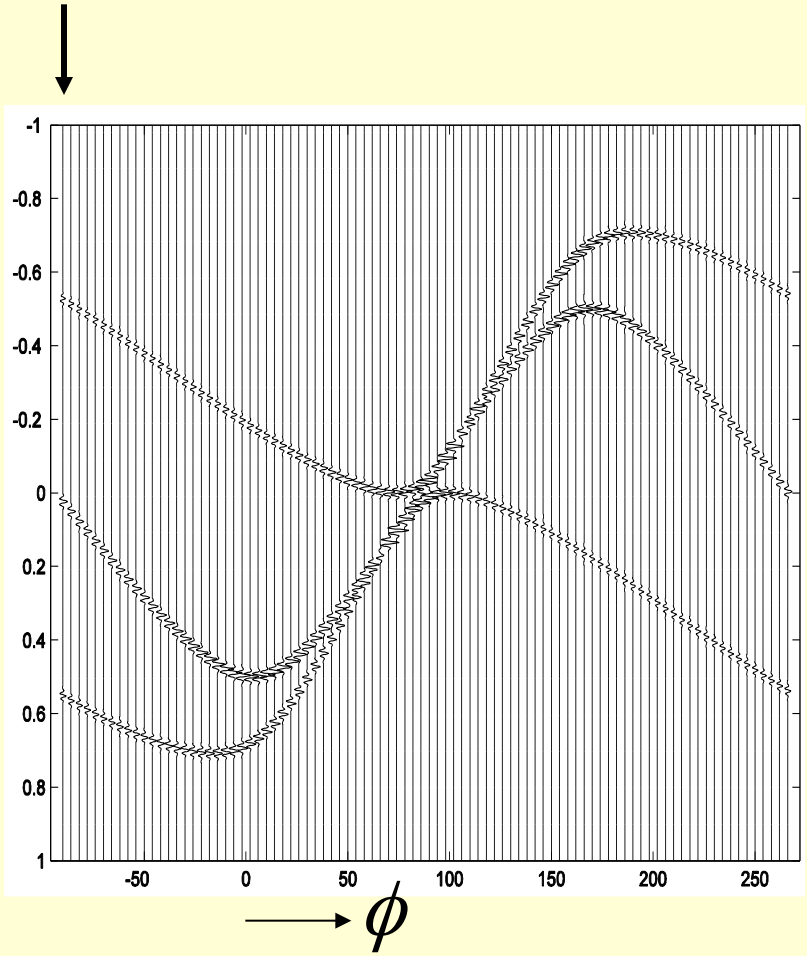
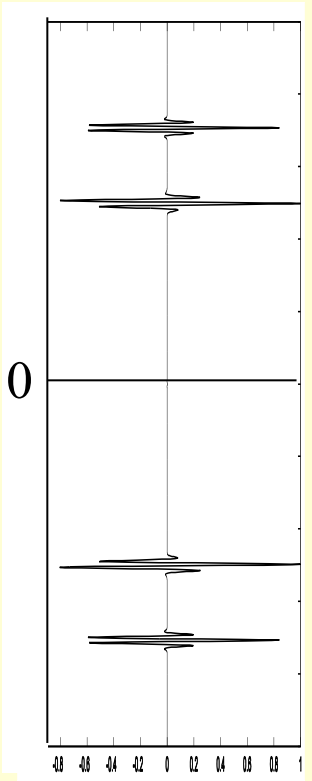
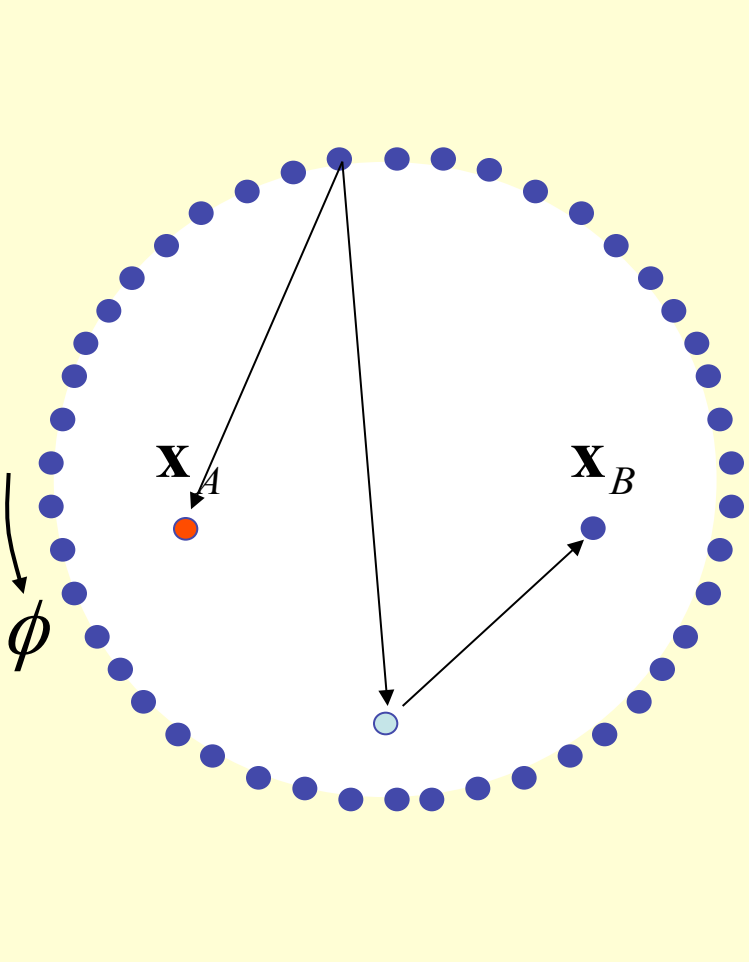
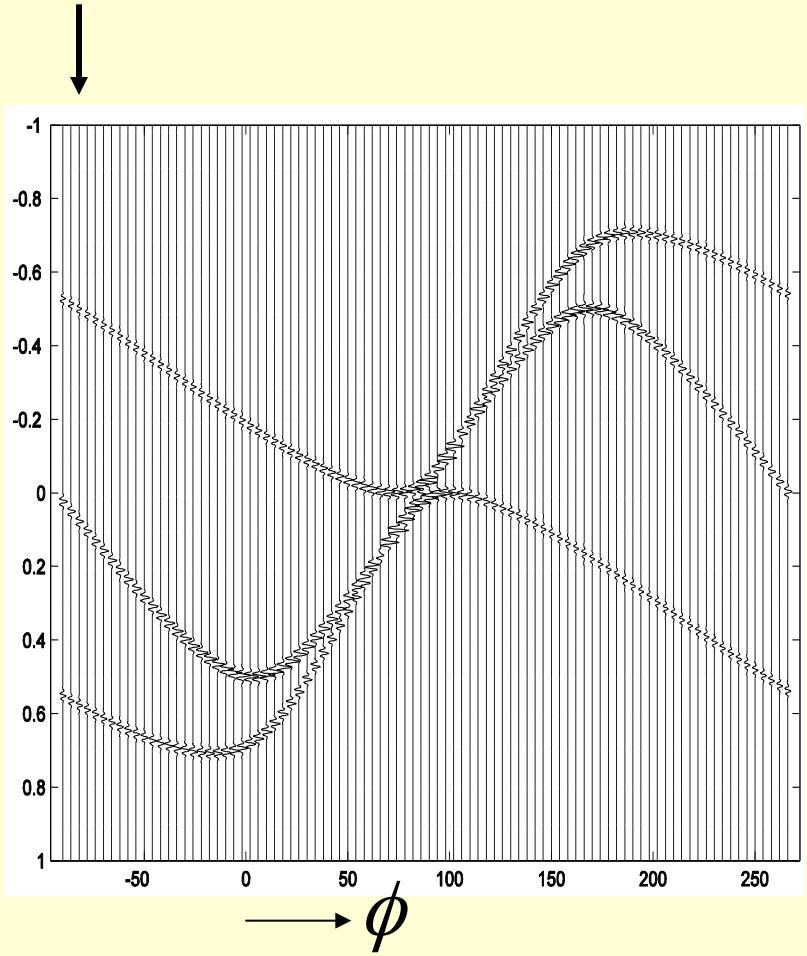


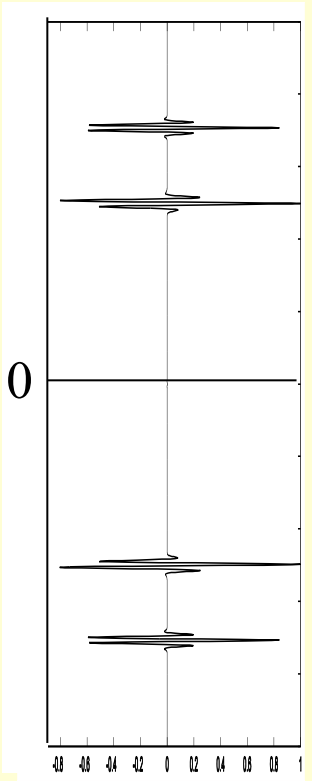




$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$







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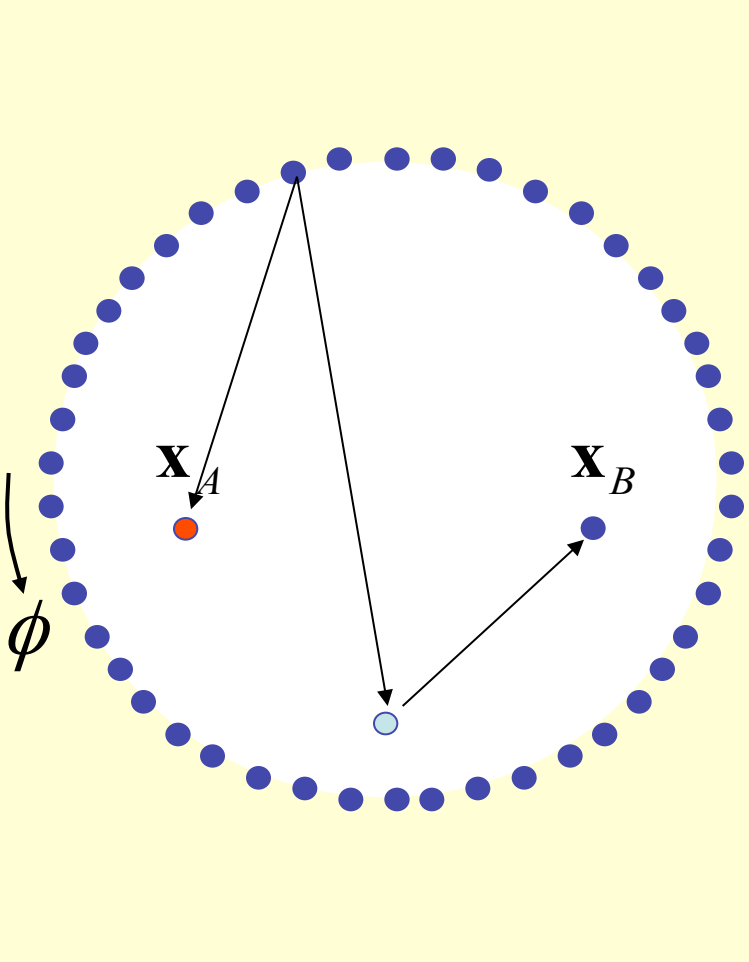

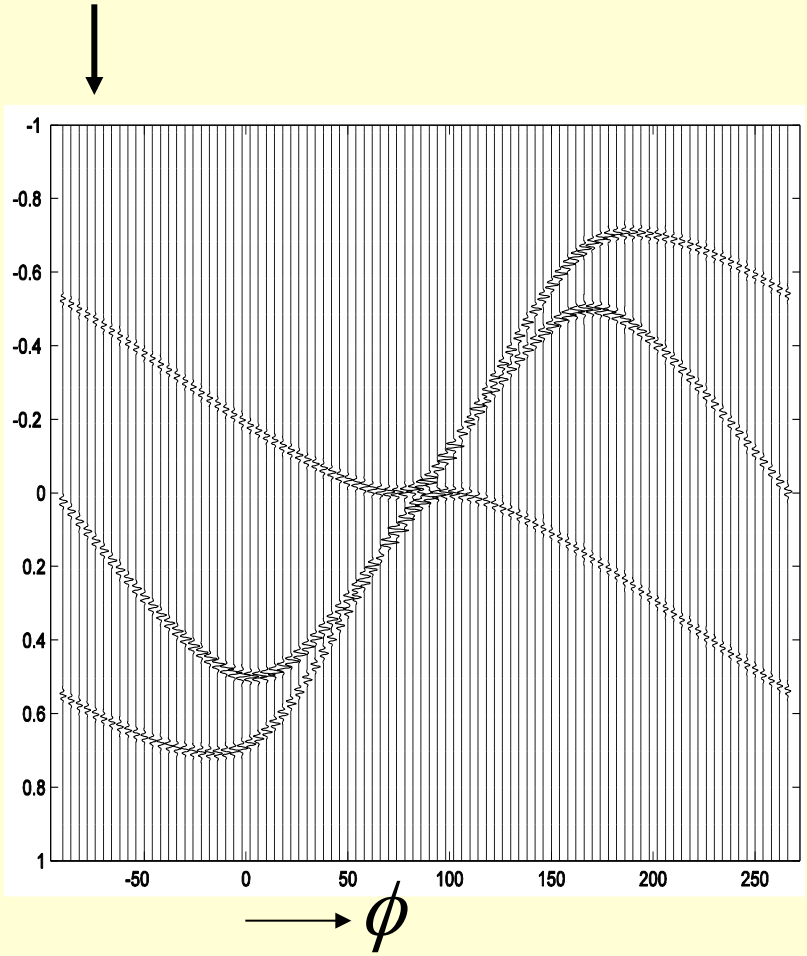

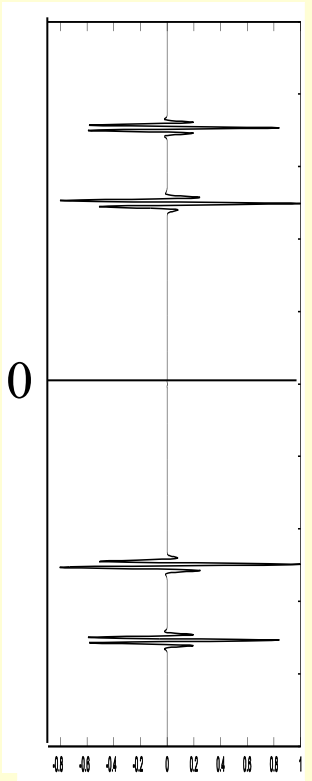

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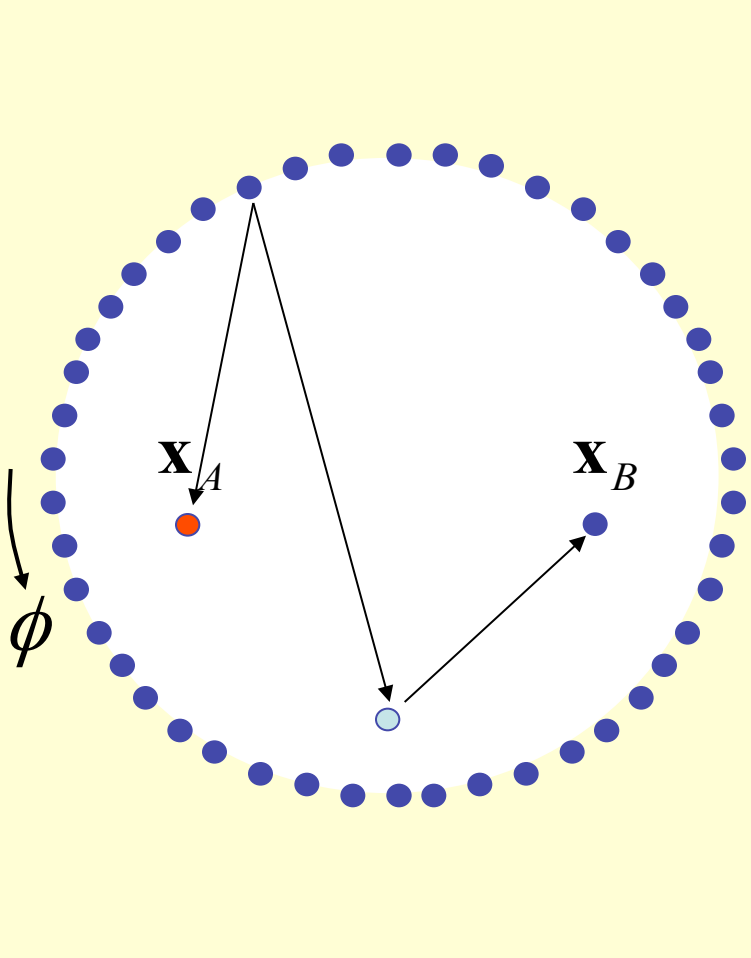
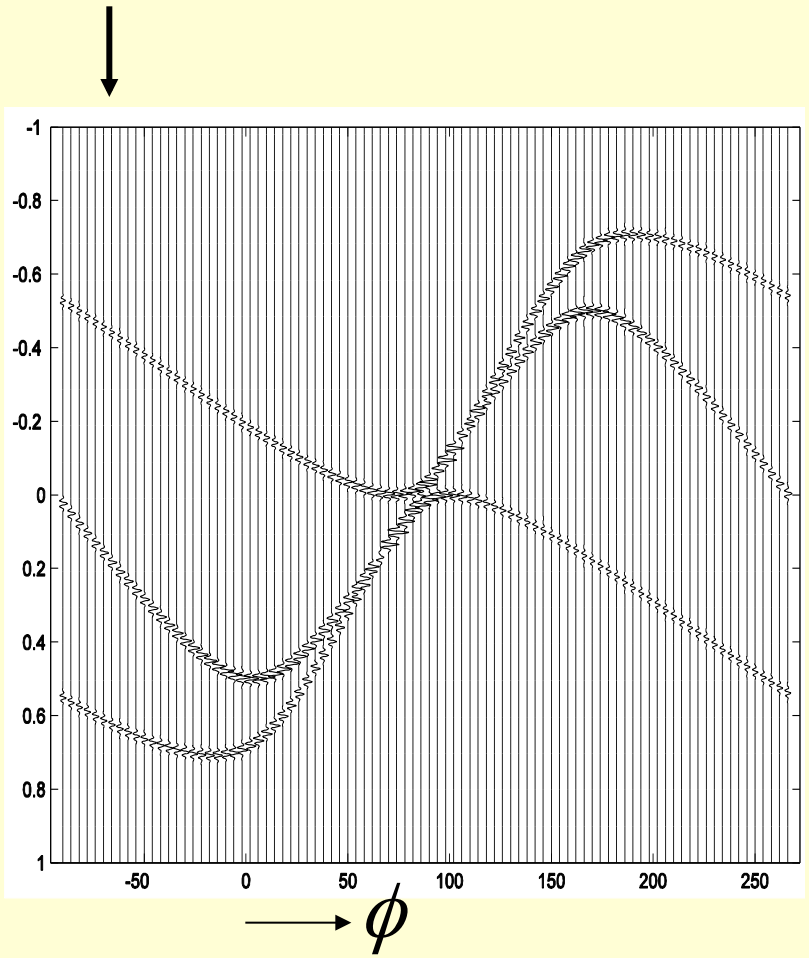
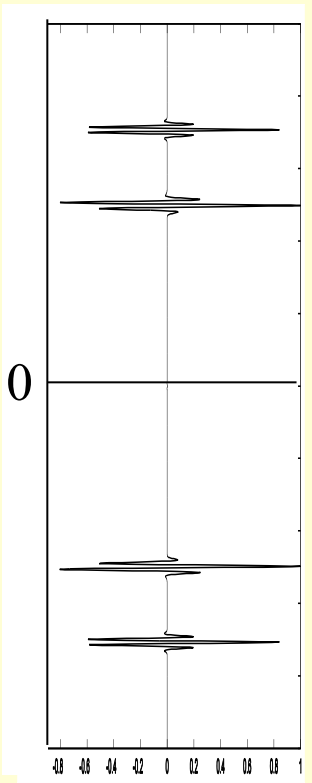
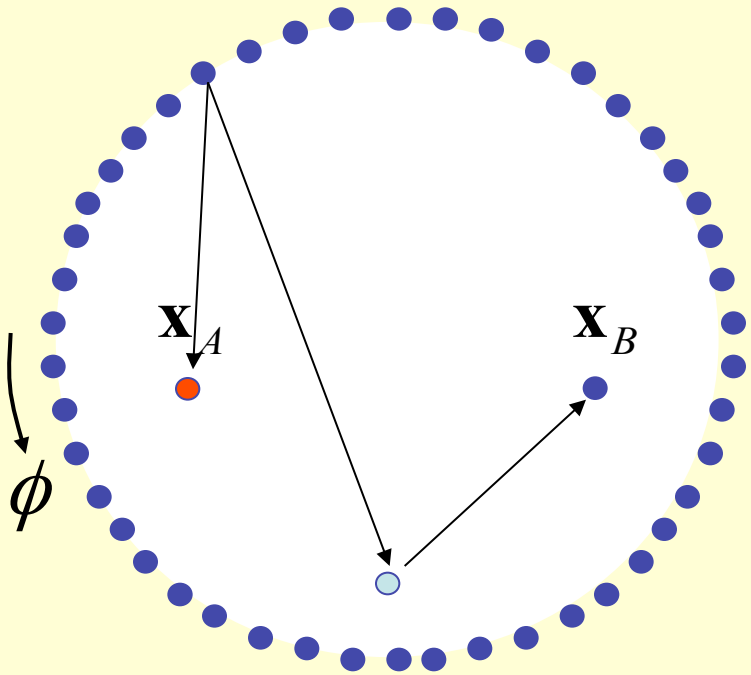
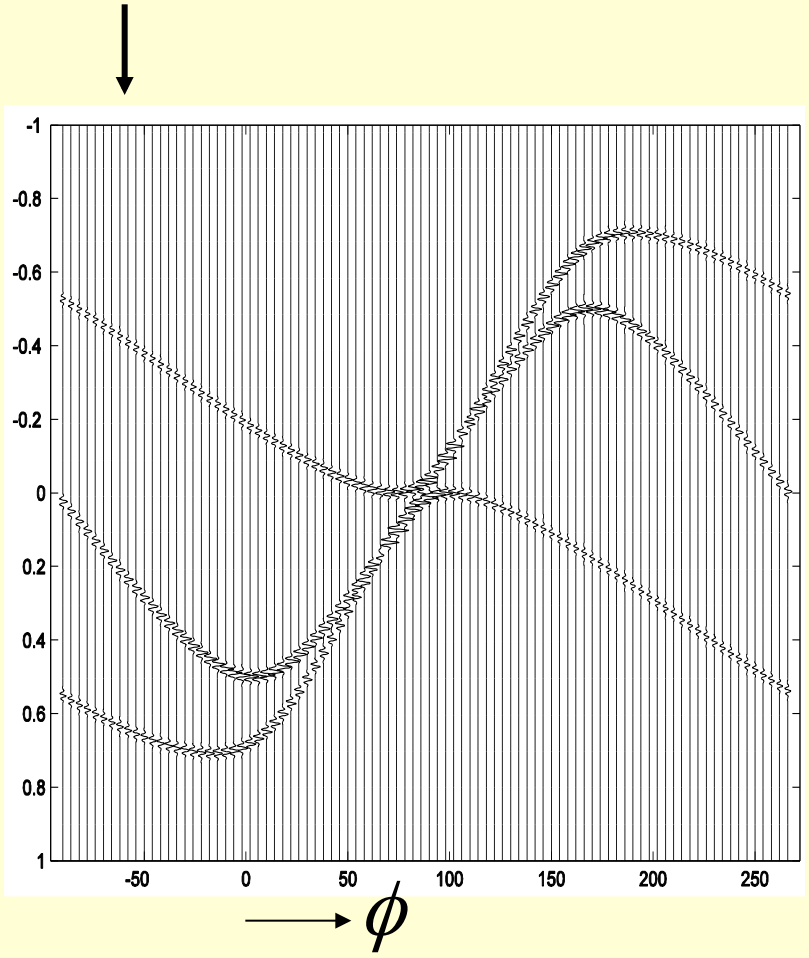


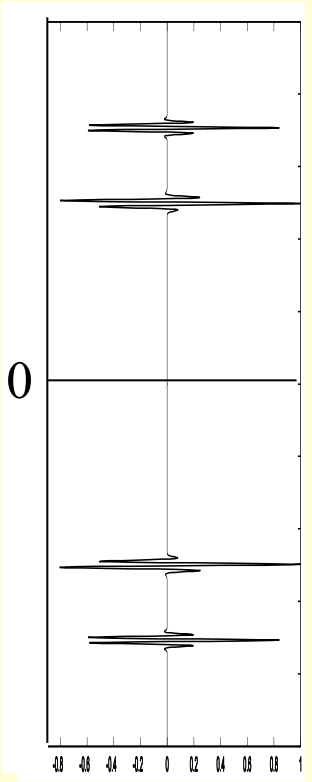




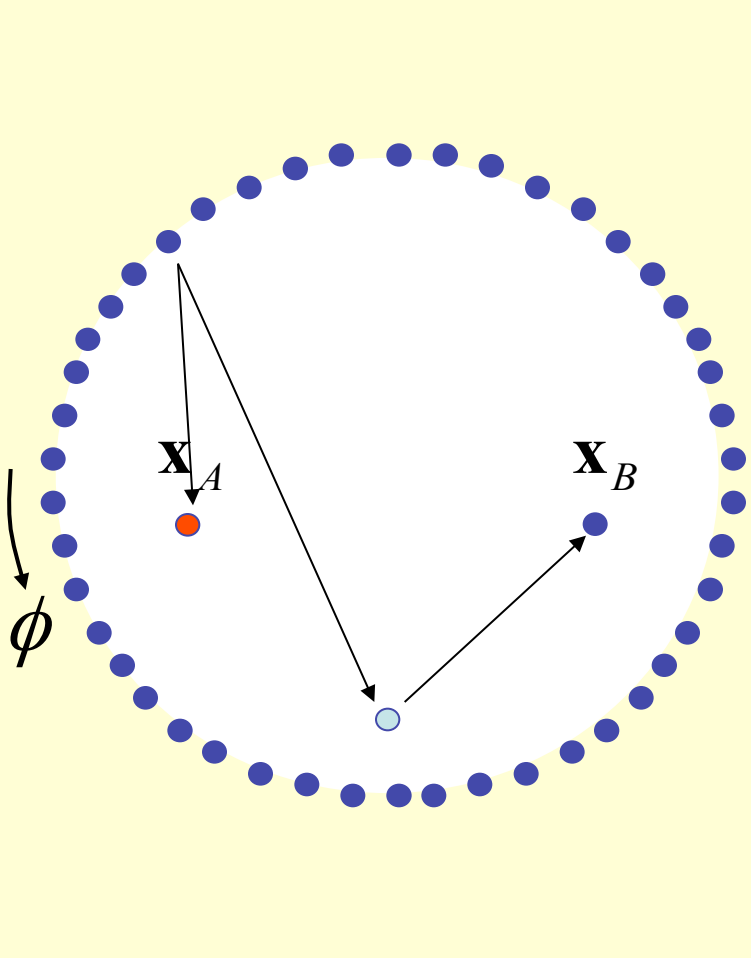
$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$

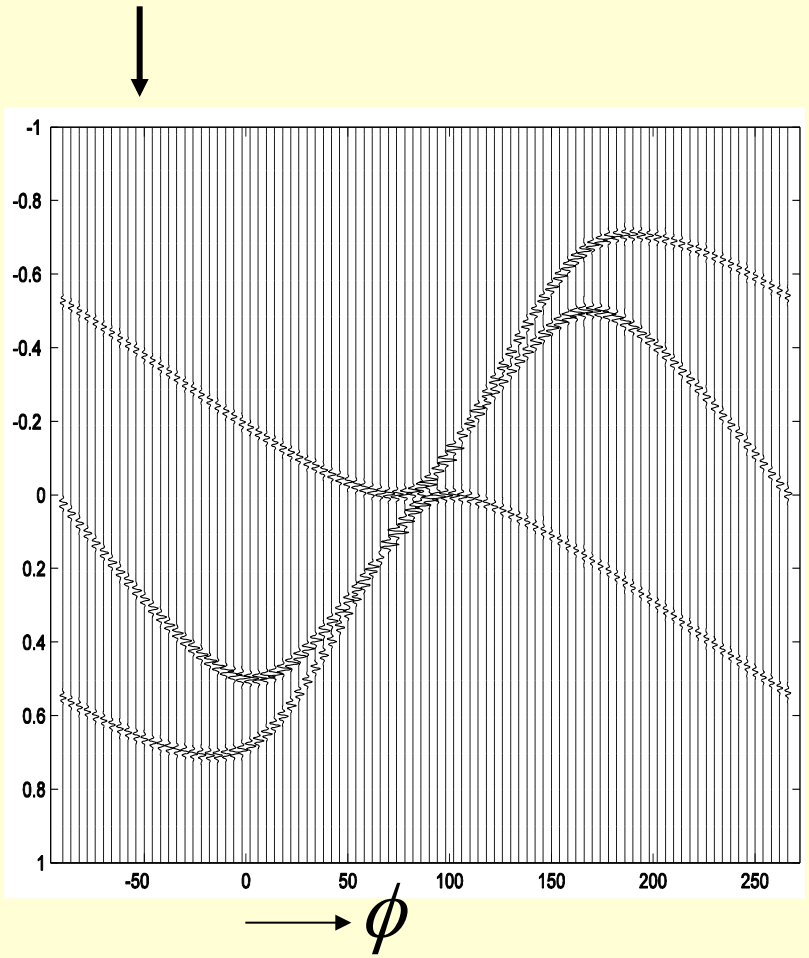


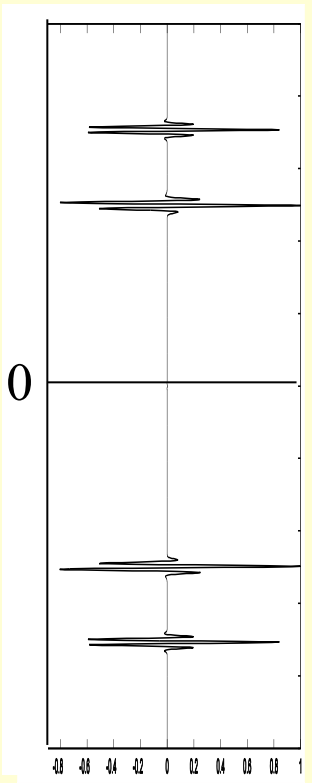




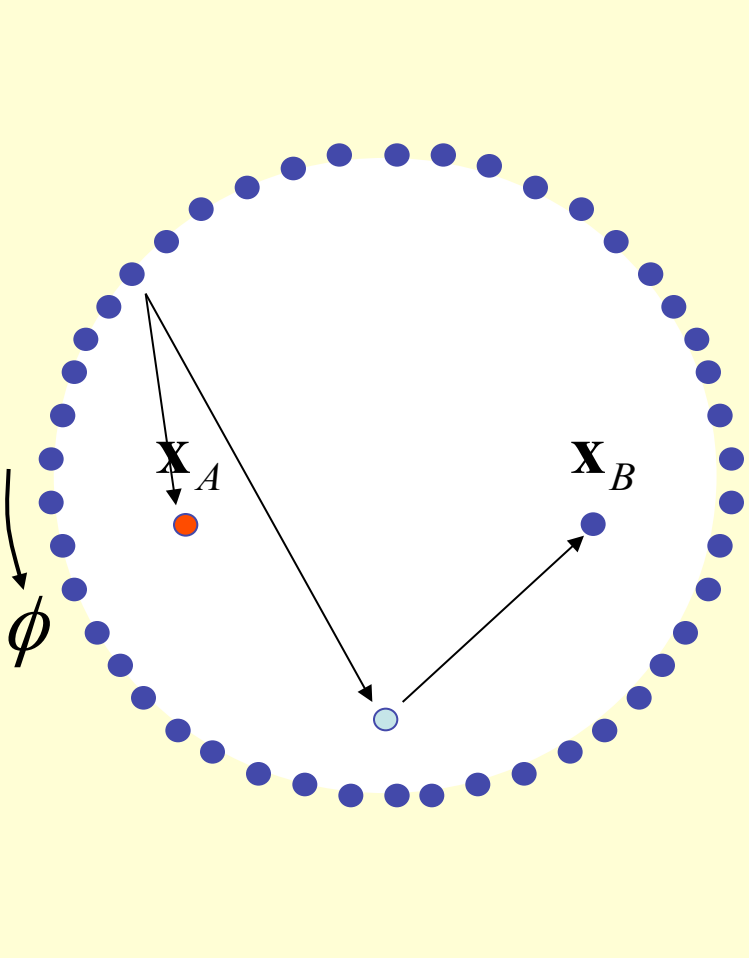
$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$

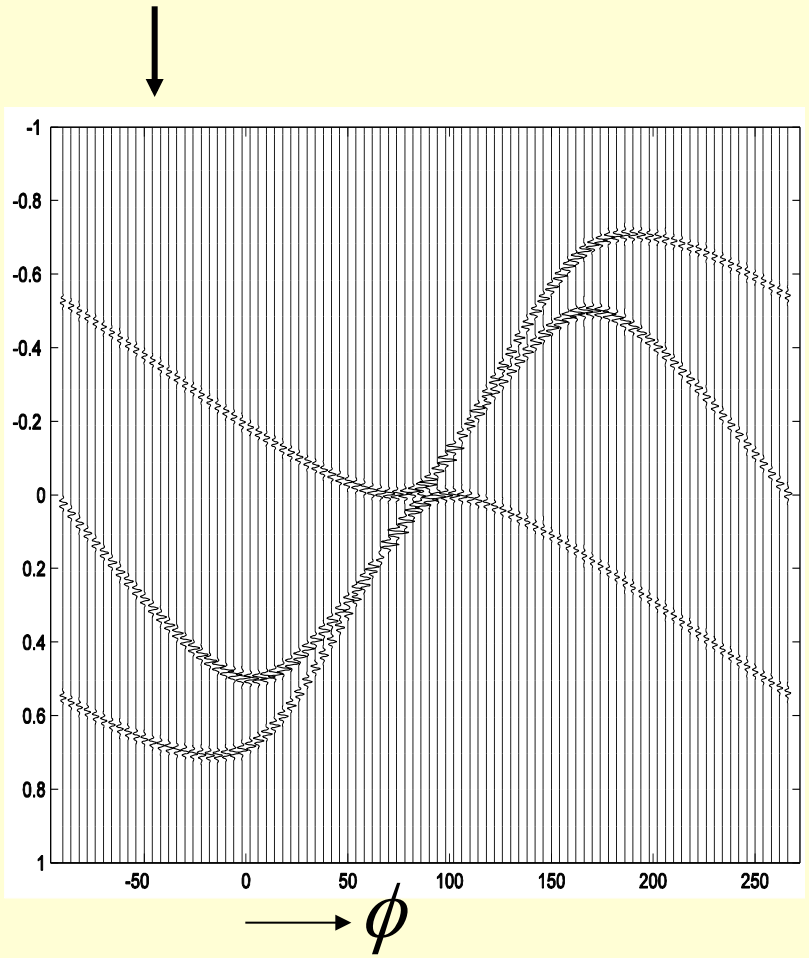


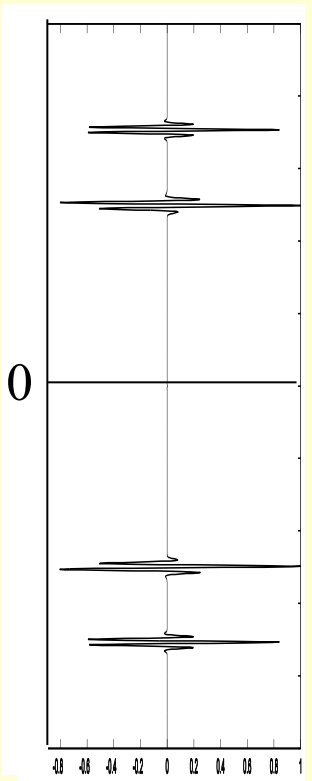




$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$







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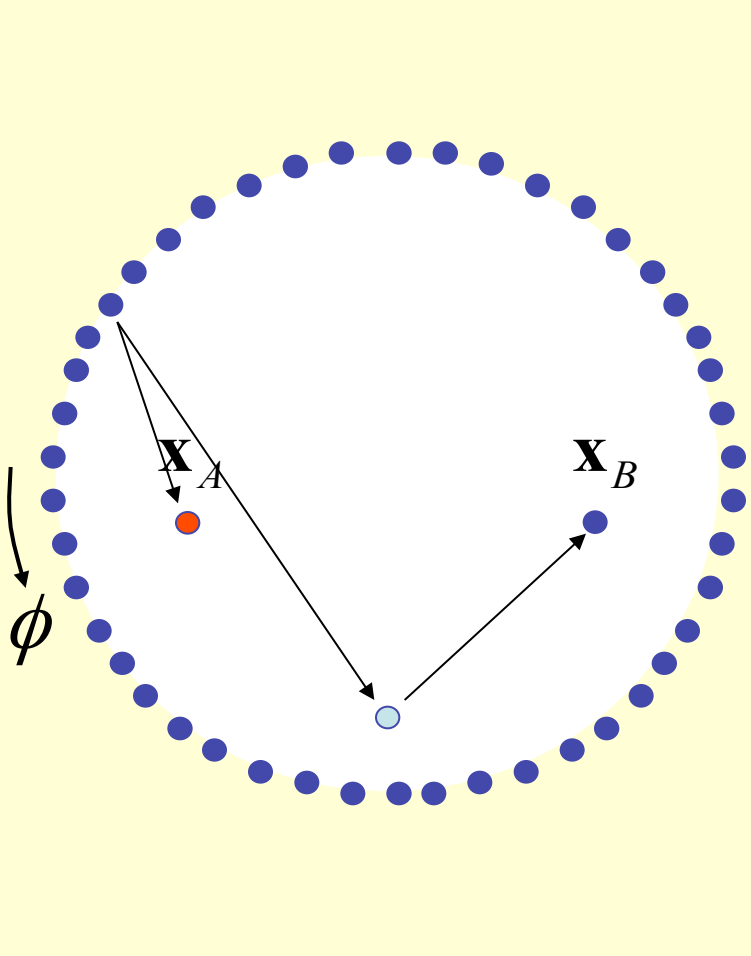
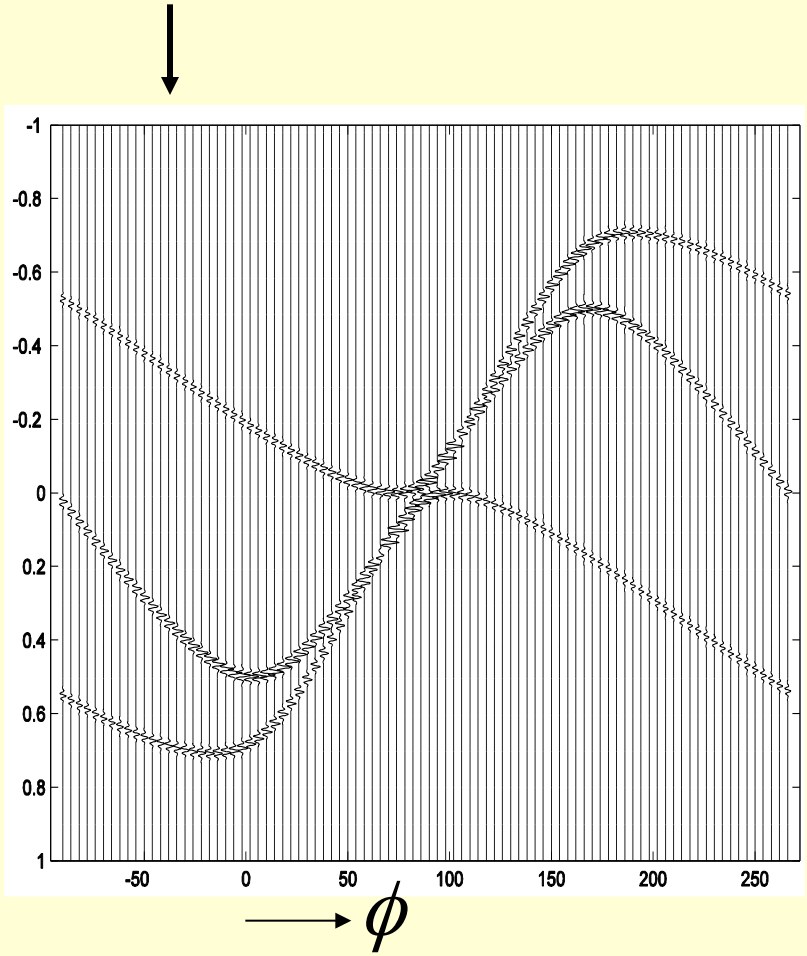
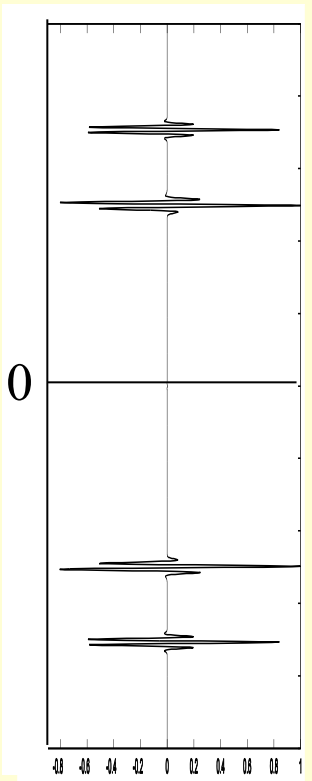
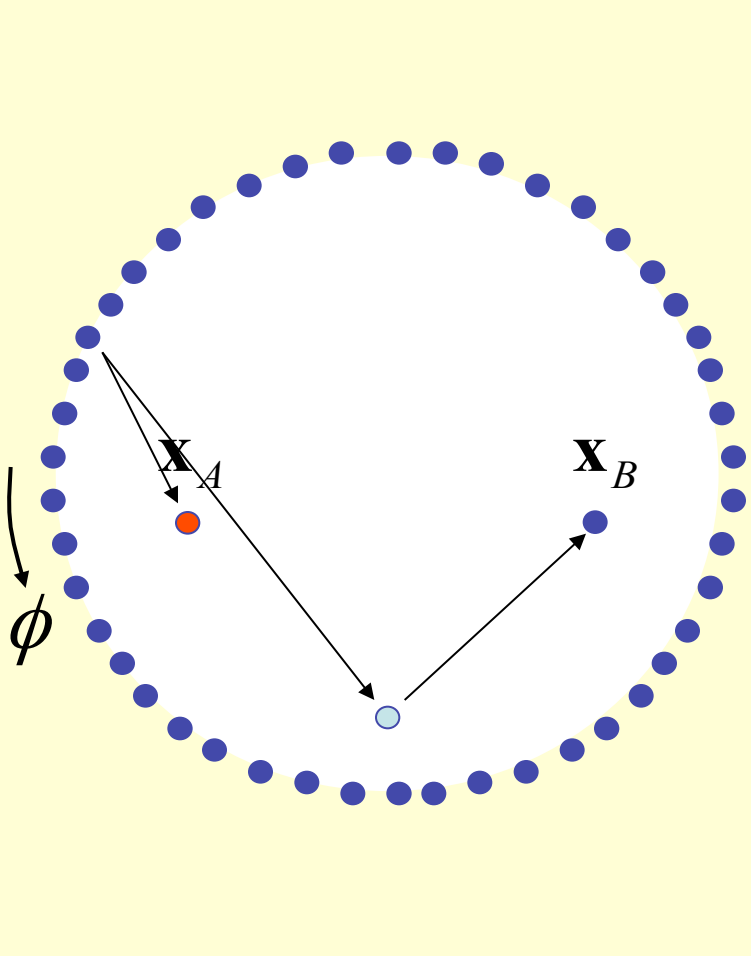
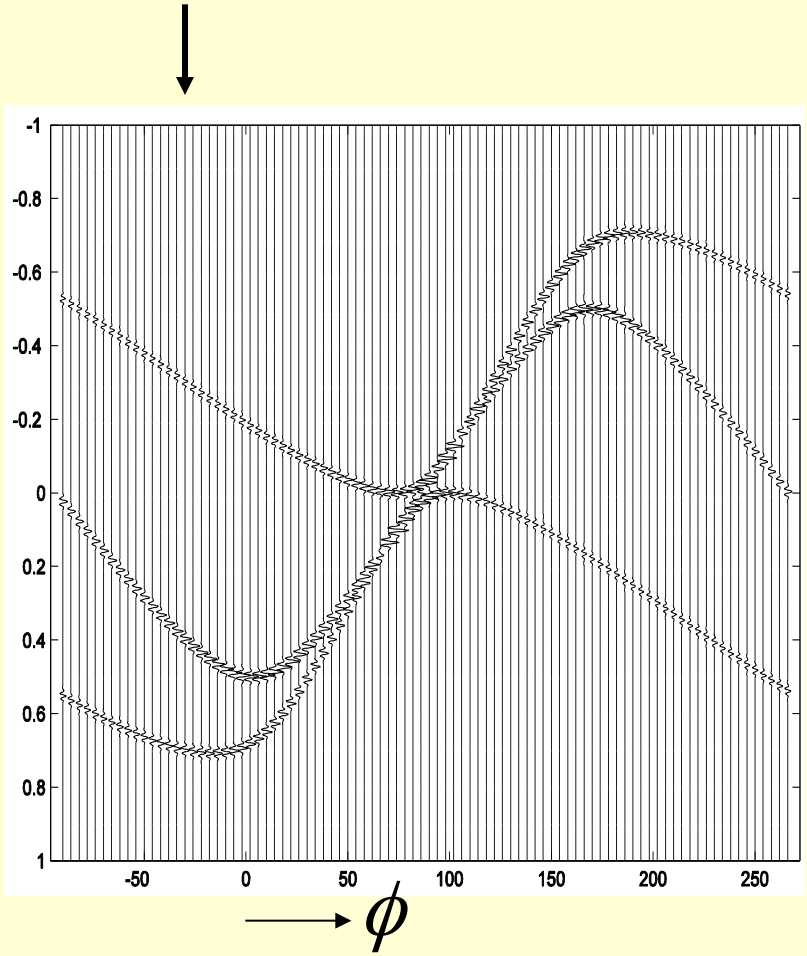


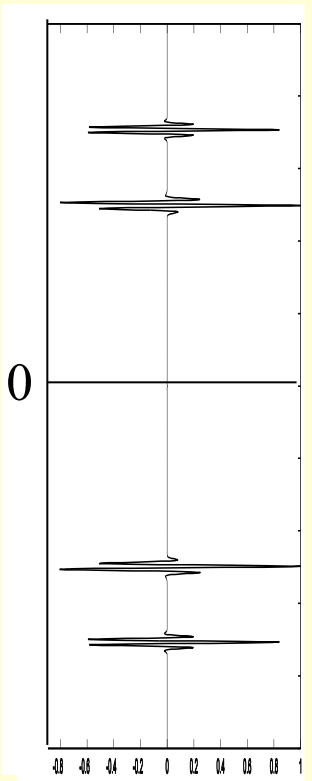




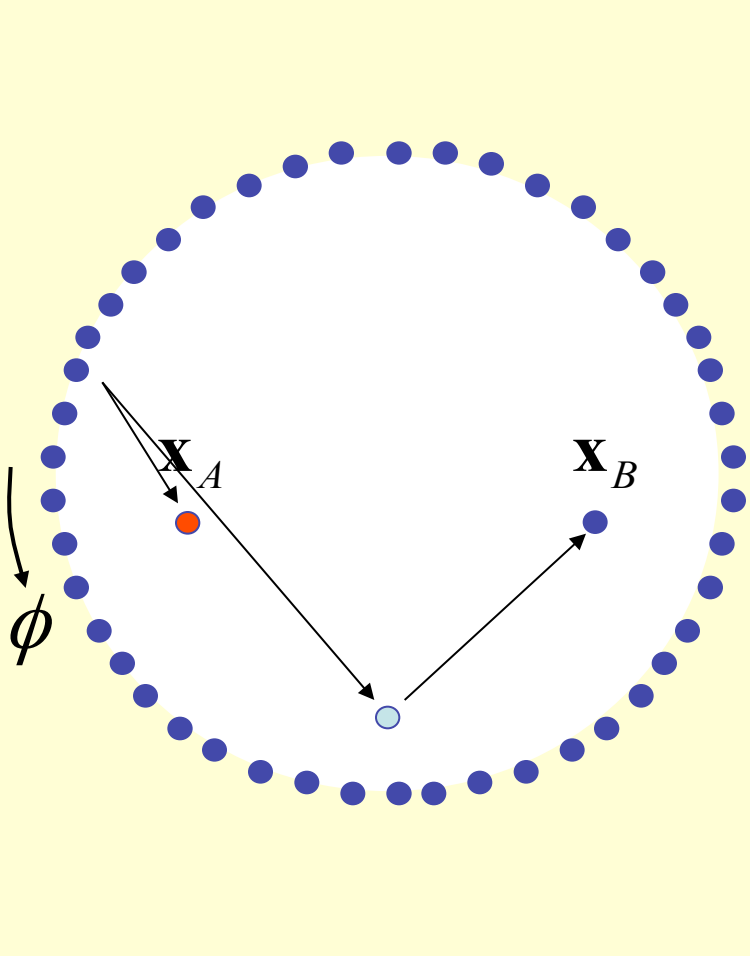
$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$

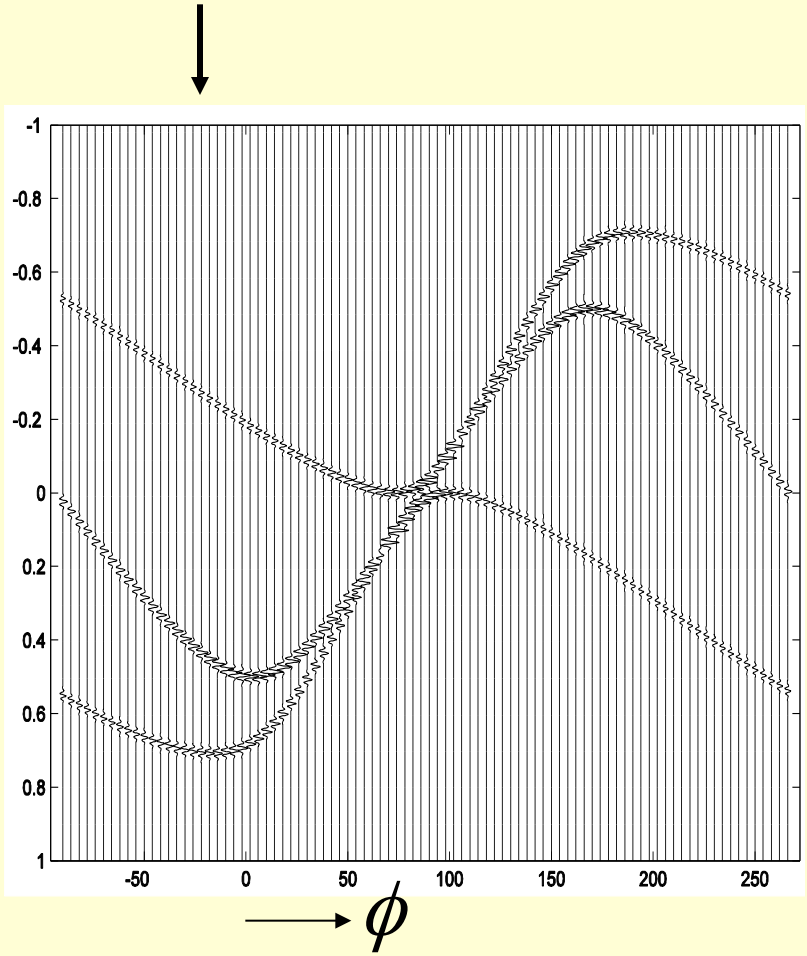


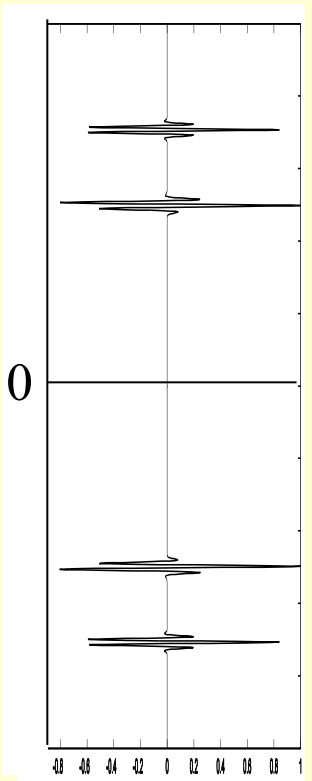




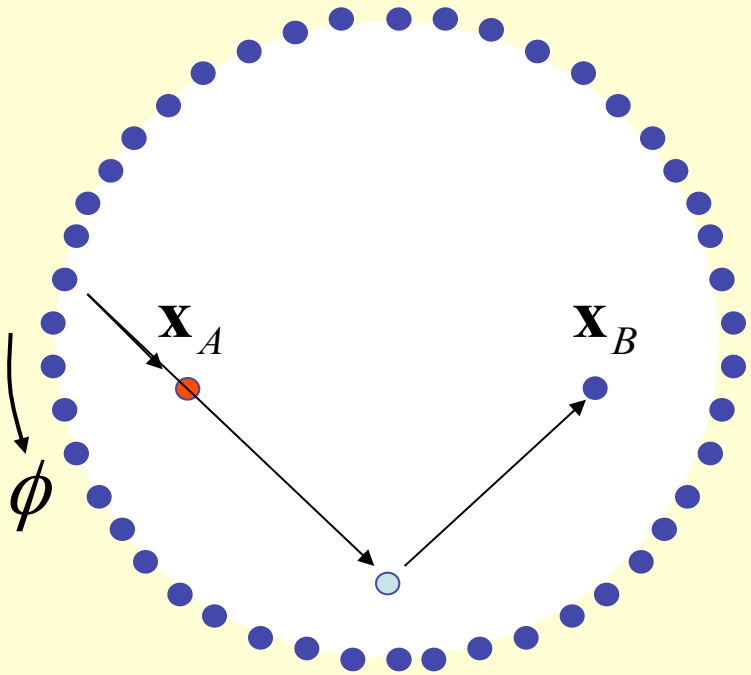
$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$

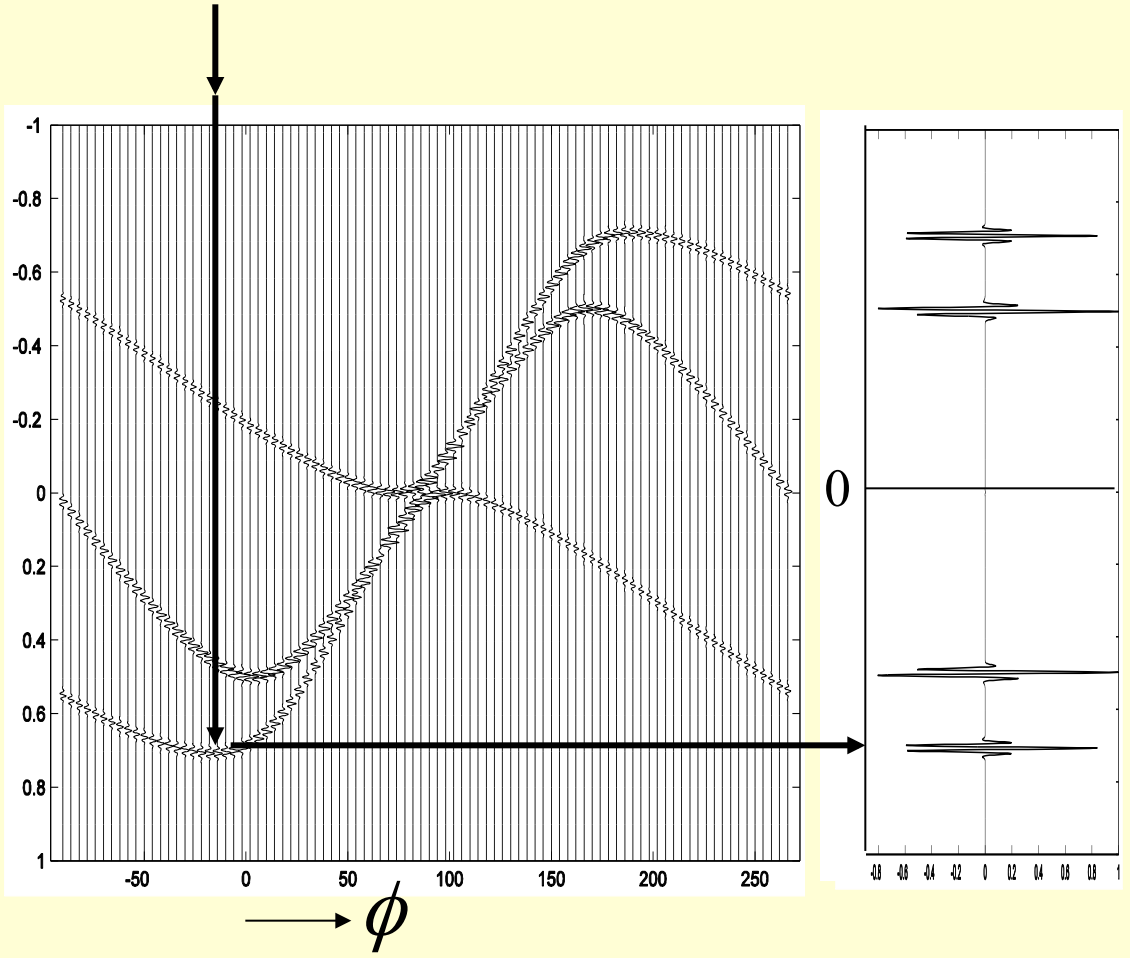




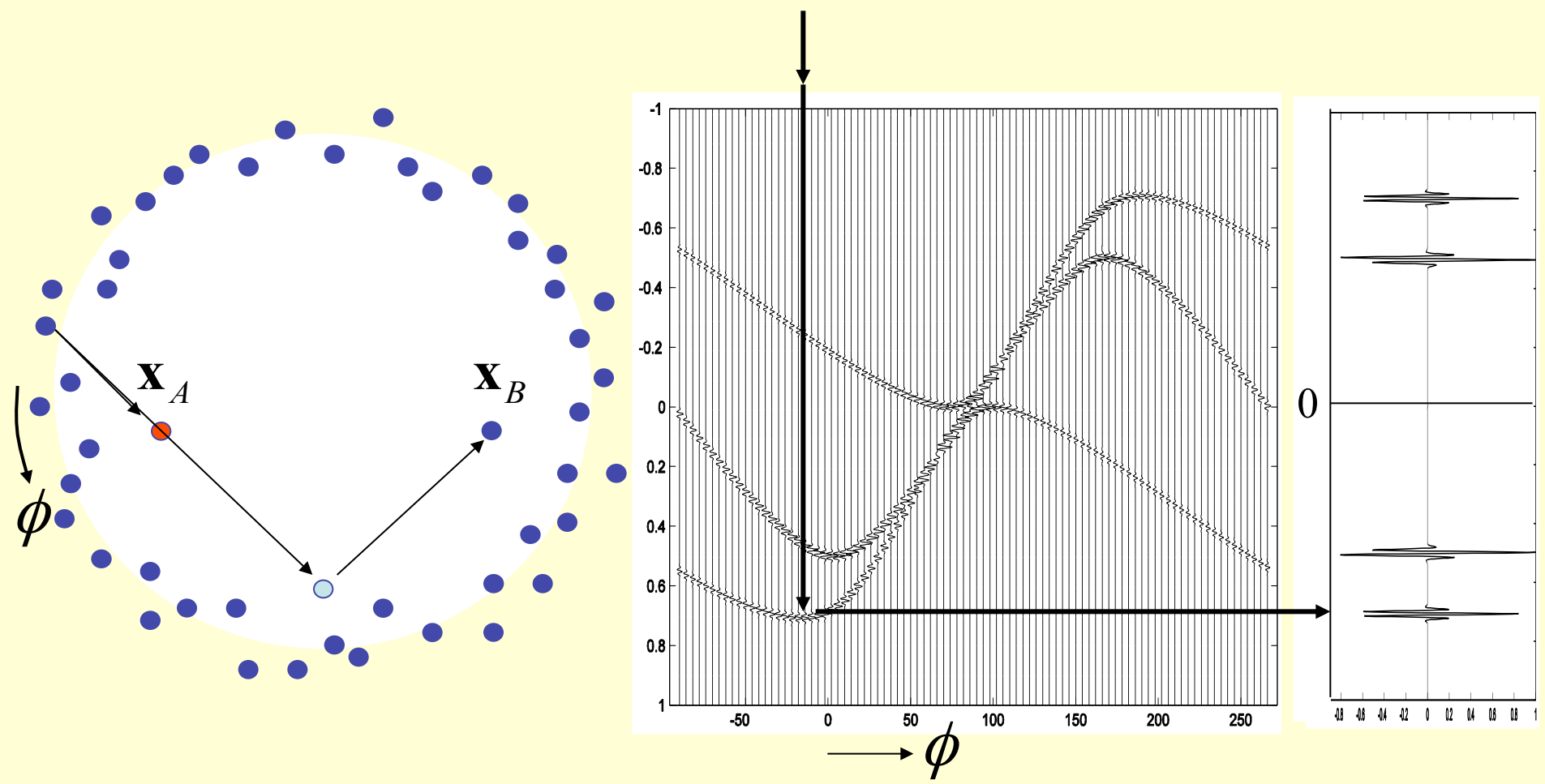


$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$

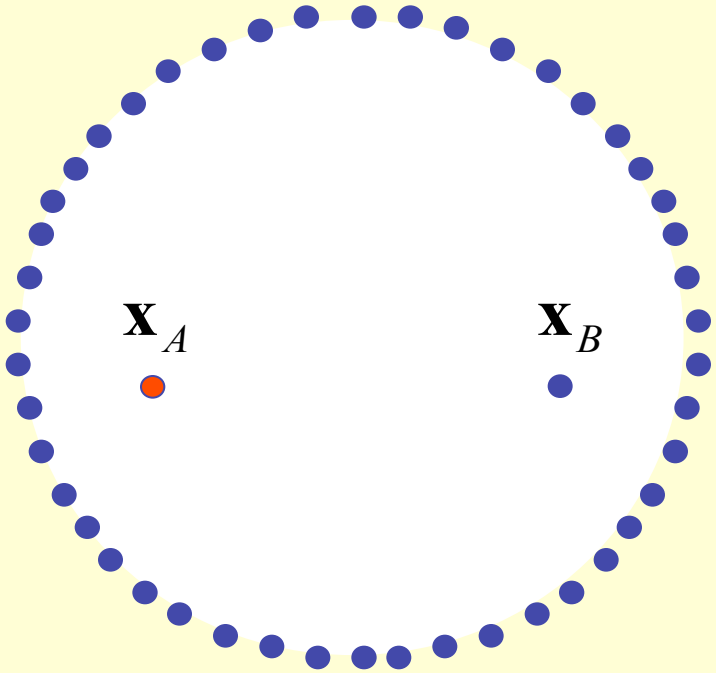




$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$



$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_S G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$



Uncorrelated noise sources:

$$p(\mathbf{x}_A, t) =$$

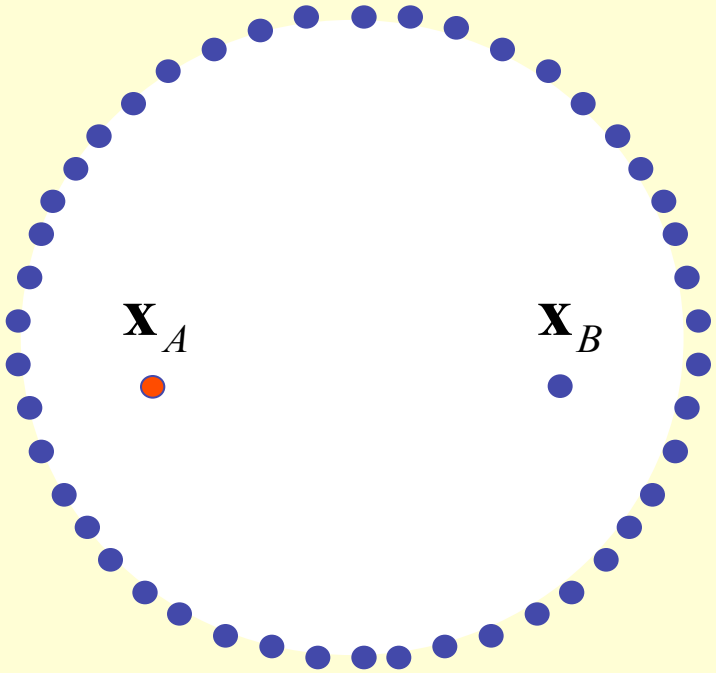
$$\int_S G(\mathbf{x}_A, \mathbf{x}, t) * N(\mathbf{x}, t) d^2\mathbf{x}$$

$$p(\mathbf{x}_B, t) =$$

$$\int_S G(\mathbf{x}_B, \mathbf{x}', t) * N(\mathbf{x}', t) d^2\mathbf{x}'$$

$$G(\mathbf{x}_B, \mathbf{x}_A, t) + G(\mathbf{x}_B, \mathbf{x}_A, -t) \approx$$

$$\frac{2}{\rho c} \int_S G(\mathbf{x}_B, \mathbf{x}, t) * G(\mathbf{x}_A, \mathbf{x}, -t) d^2\mathbf{x}$$



Uncorrelated noise sources:

$$p(\mathbf{x}_A, t) =$$

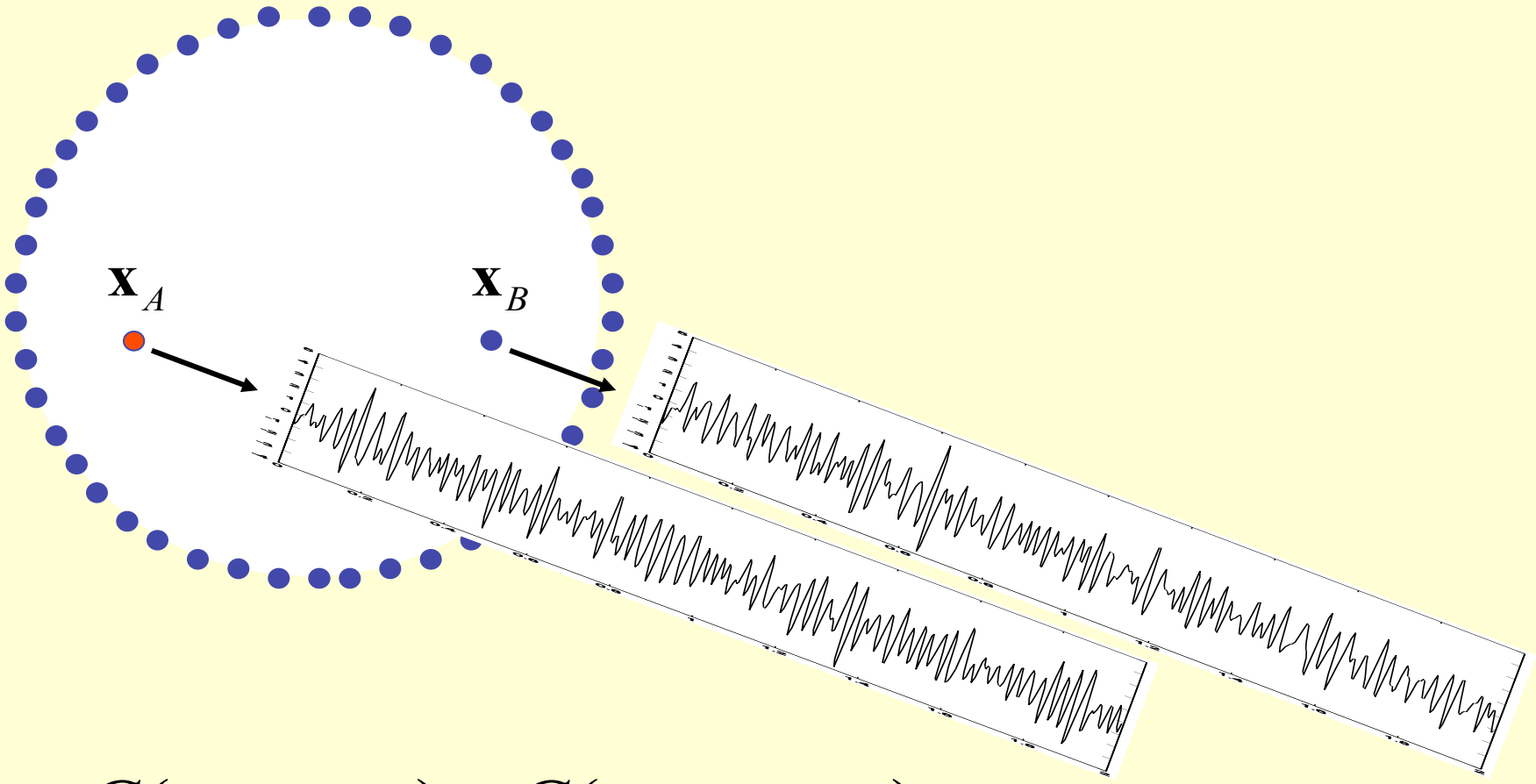
$$\int_S G(\mathbf{x}_A, \mathbf{x}, t) * N(\mathbf{x}, t) d^2\mathbf{x}$$

$$p(\mathbf{x}_B, t) =$$

$$\int_S G(\mathbf{x}_B, \mathbf{x}', t) * N(\mathbf{x}', t) d^2\mathbf{x}'$$

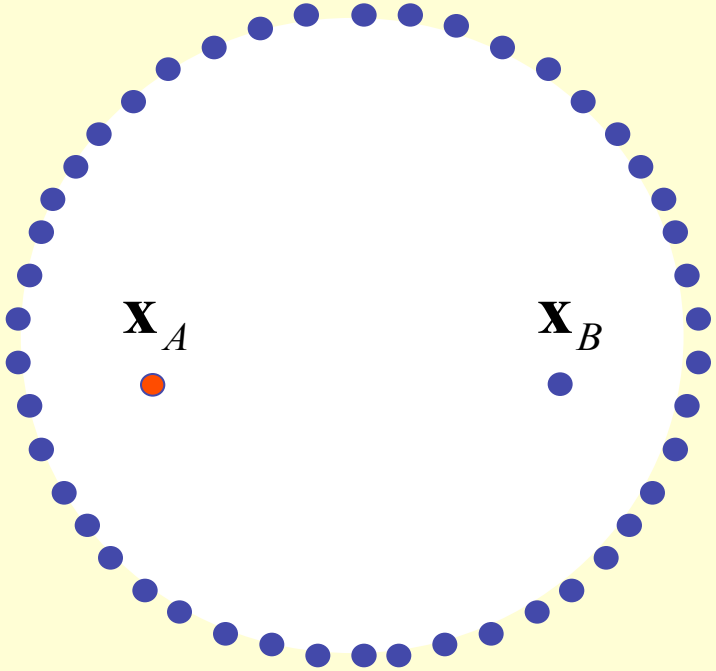
$$G(\mathbf{x}_B, \mathbf{x}_A, t) + G(\mathbf{x}_B, \mathbf{x}_A, -t) \approx$$

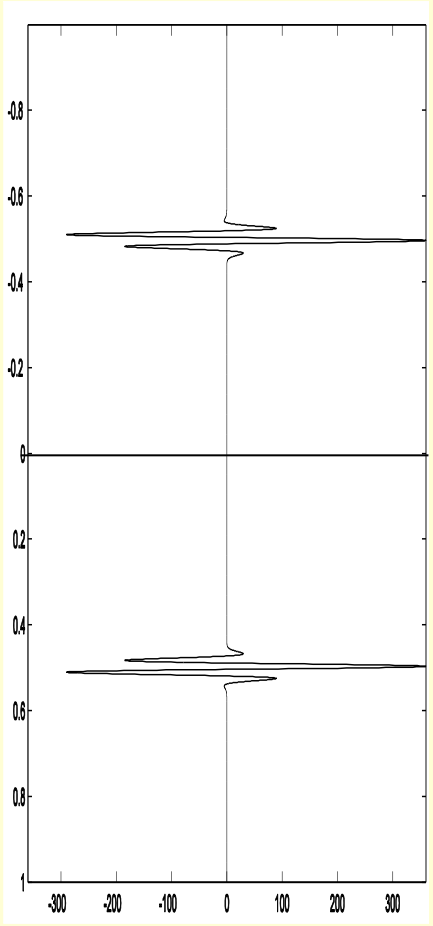
$$\left\langle p(\mathbf{x}_B, t) * p(\mathbf{x}_A, -t) \right\rangle$$

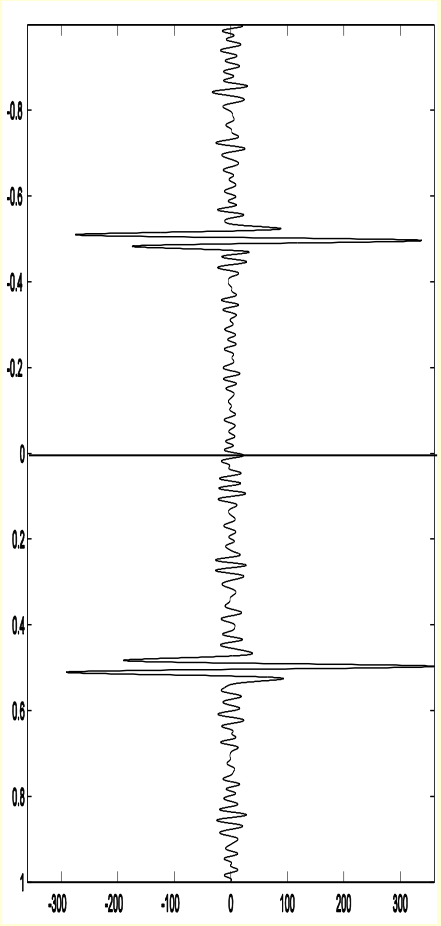


$$G(\mathbf{x}_B, \mathbf{x}_A, t) + G(\mathbf{x}_B, \mathbf{x}_A, -t) \approx$$

$$\left\langle p(\mathbf{x}_B, t) * p(\mathbf{x}_A, -t) \right\rangle$$







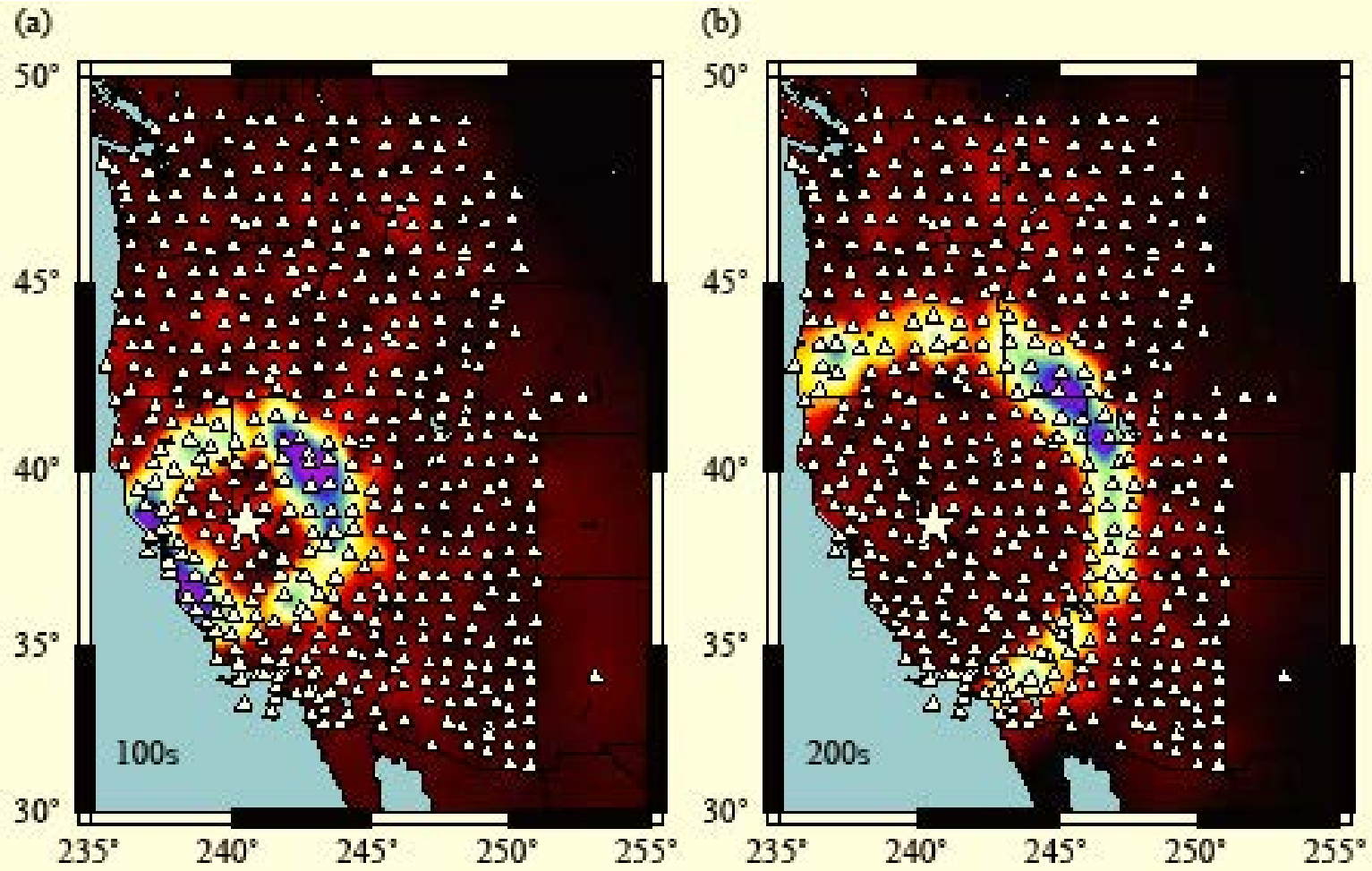
$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t)\ \approx$$

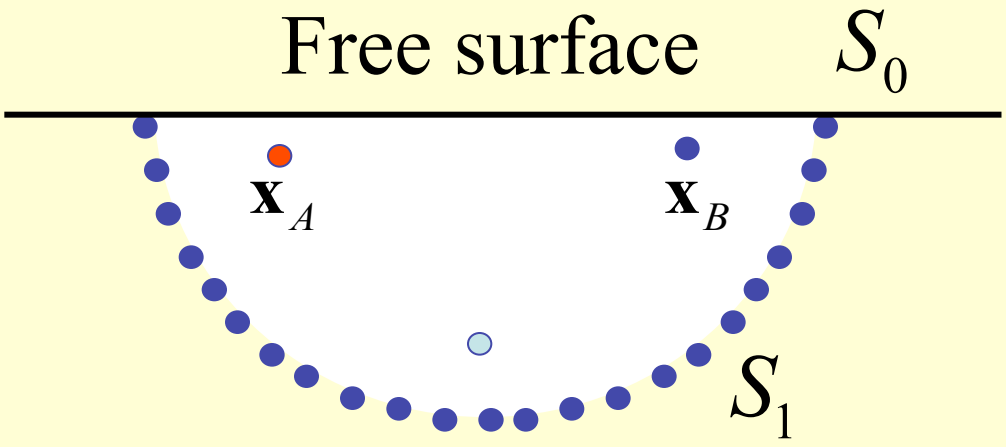
$$\left\langle p(\mathbf{x}_B,t)*p(\mathbf{x}_A,-t)\right\rangle$$

Eikonal tomography: surface wave tomography by phase front tracking across a regional broad-band seismic array

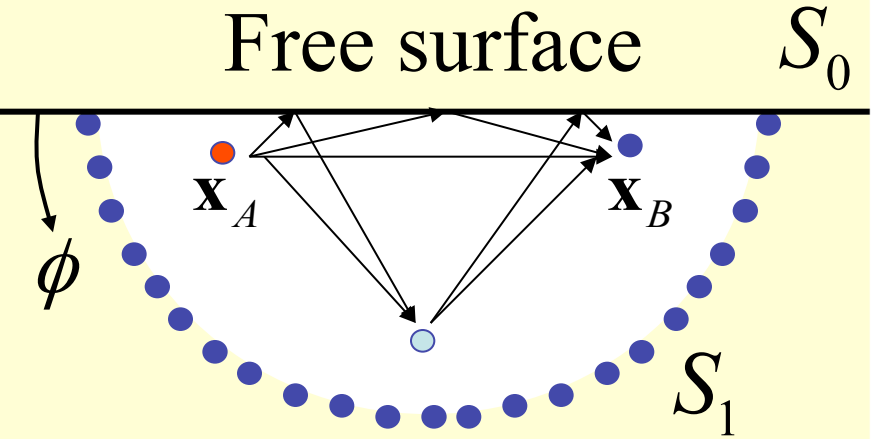
Fan-Chi Lin,[1] Michael H. Ritzwoller[1] and Roel Snieder[2]

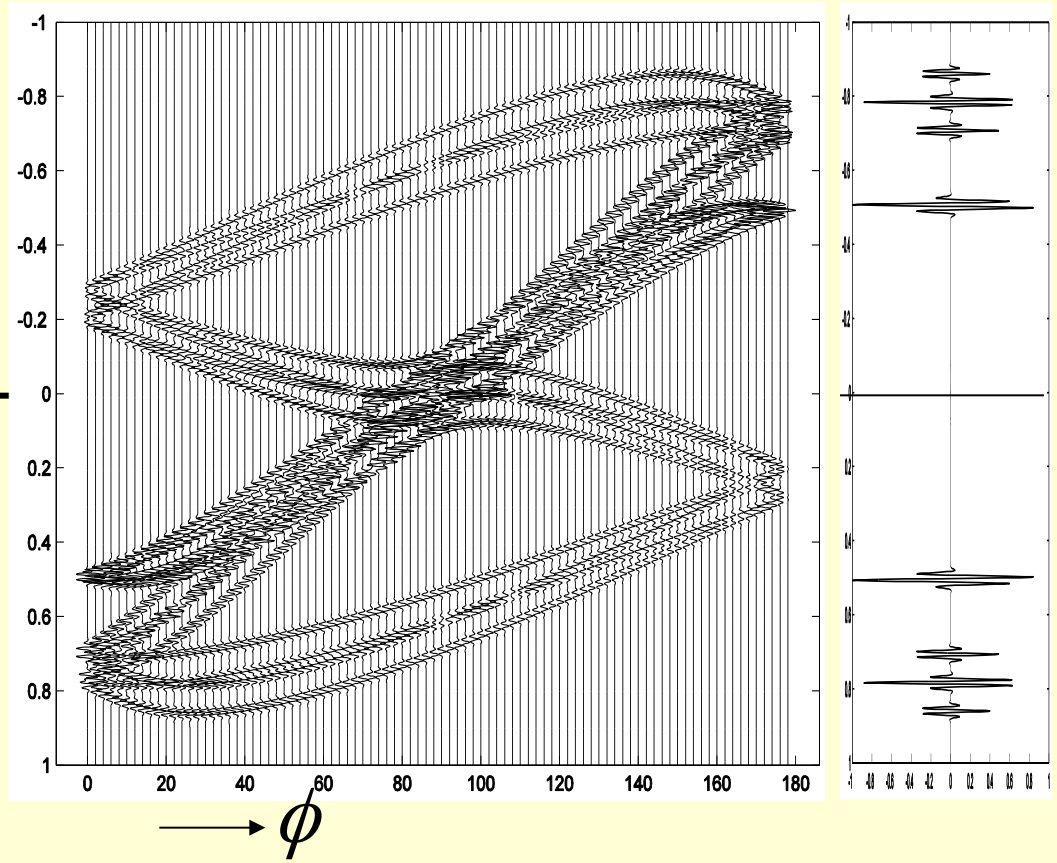
Geophys. J. Int. (2009) **177,** 1091–1110





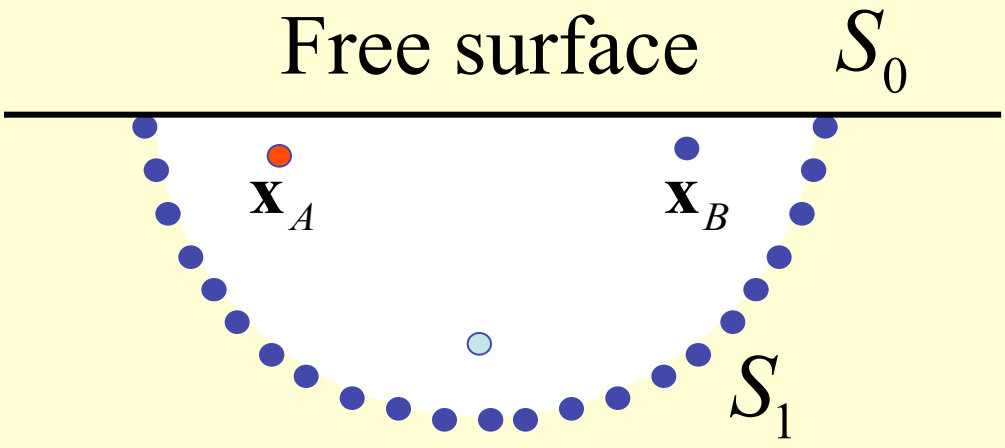
$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t) \approx \frac{2}{\rho c}\int_{S_1} G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$





$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t)\approx$$

$$\frac{2}{\rho c}\int_{S_1} G(\mathbf{x}_B,\mathbf{x},t)*G(\mathbf{x}_A,\mathbf{x},-t)d^2\mathbf{x}$$



Uncorrelated noise sources

$$p(\mathbf{x}_A,t)=\int_{S_1} G(\mathbf{x}_A,\mathbf{x},t)*N(\mathbf{x},t)d^2\mathbf{x}$$

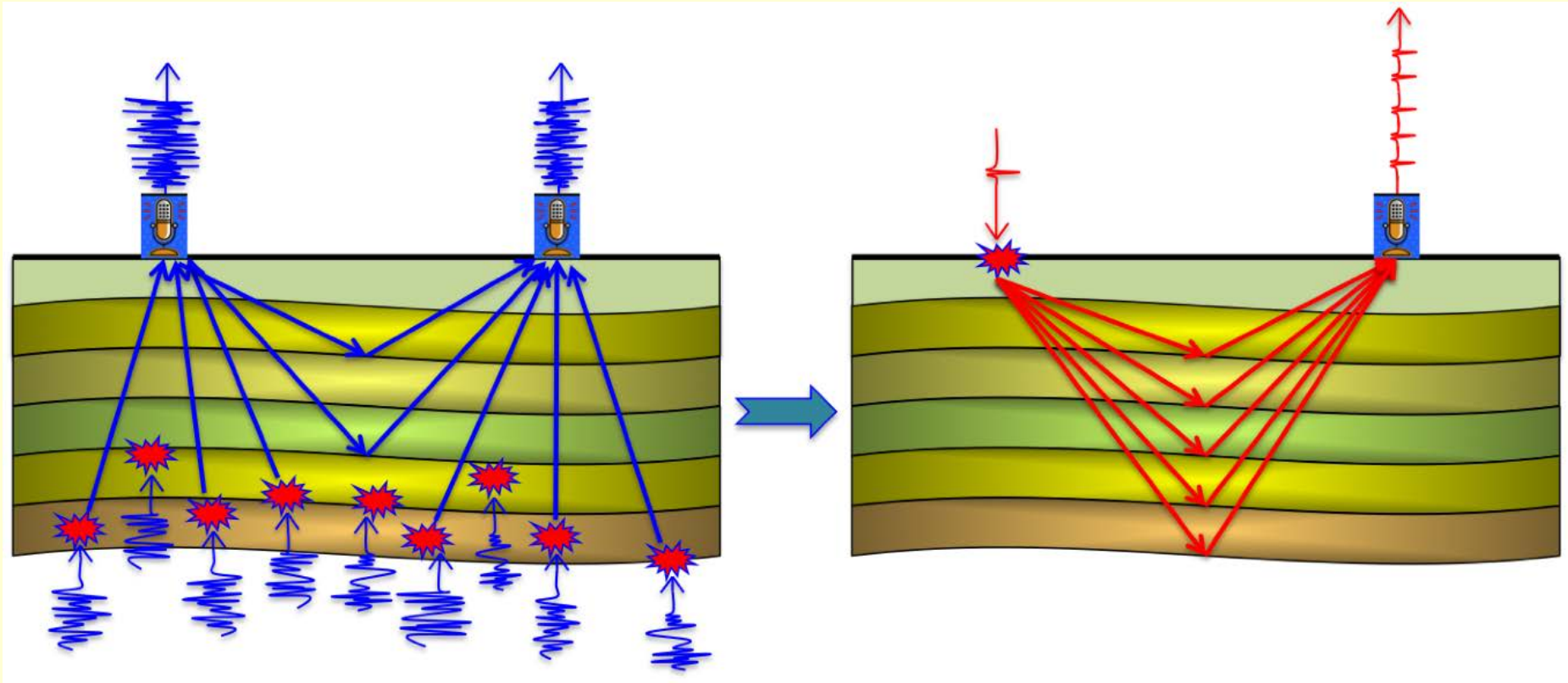
$$p(\mathbf{x}_B,t)=\int_{S_1} G(\mathbf{x}_B,\mathbf{x},t)*N(\mathbf{x},t)d^2\mathbf{x}$$

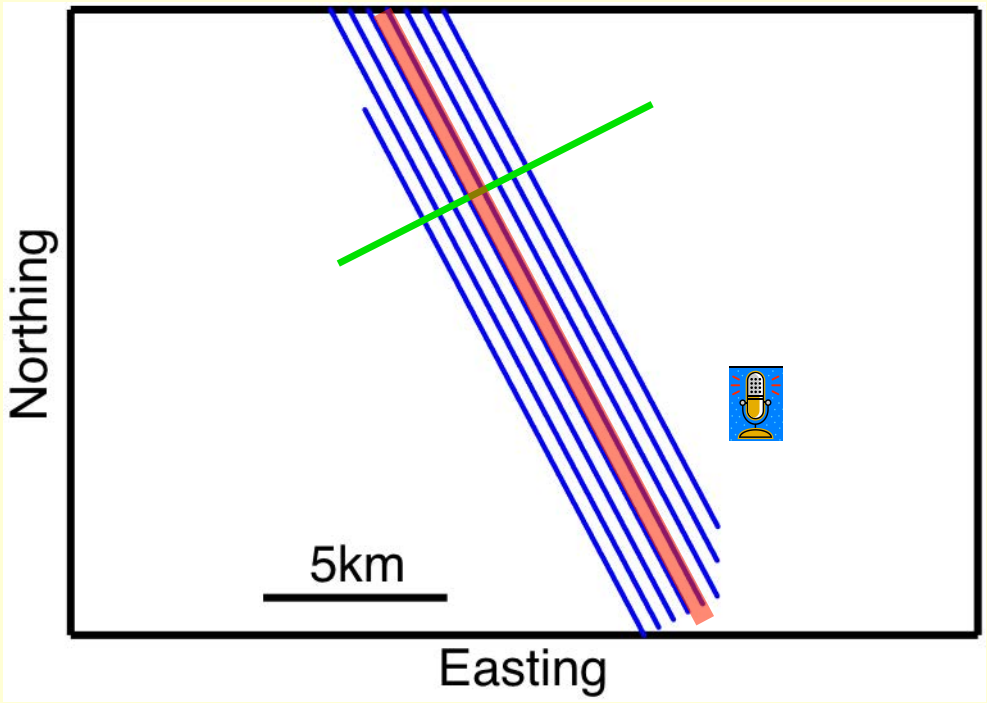
$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t)\approx\left\langle p(\mathbf{x}_B,t)*p(\mathbf{x}_A,-t)\right\rangle$$

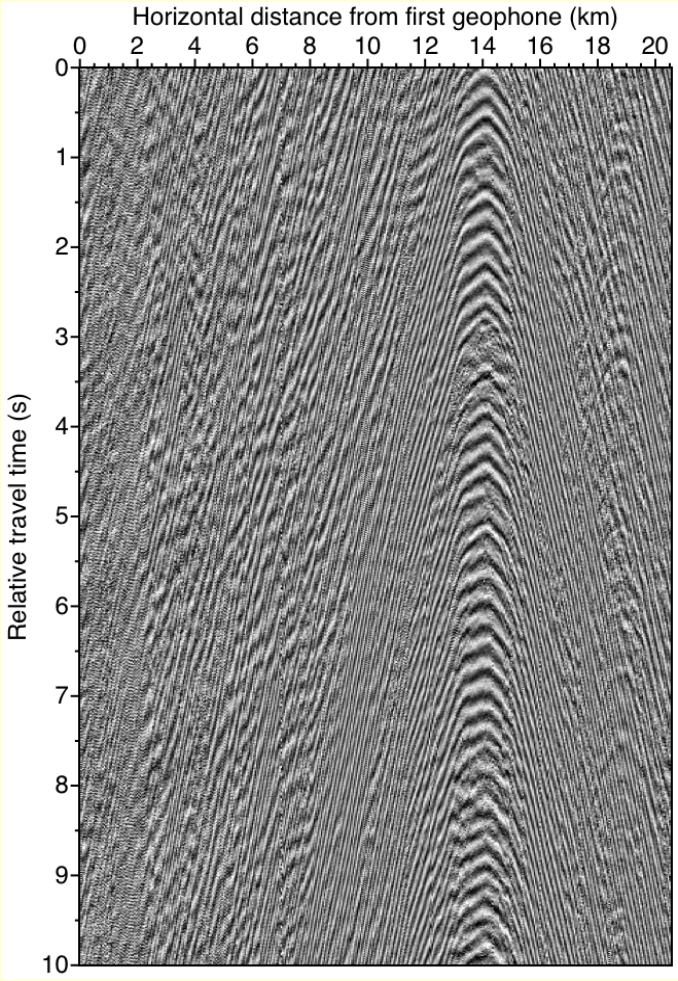
GEOPHYSICS, VOL. 74, NO. 5 (SEPTEMBER-OCTOBER 2009); P. A63–A67, 5 FIGS.
10.1190/1.3193529

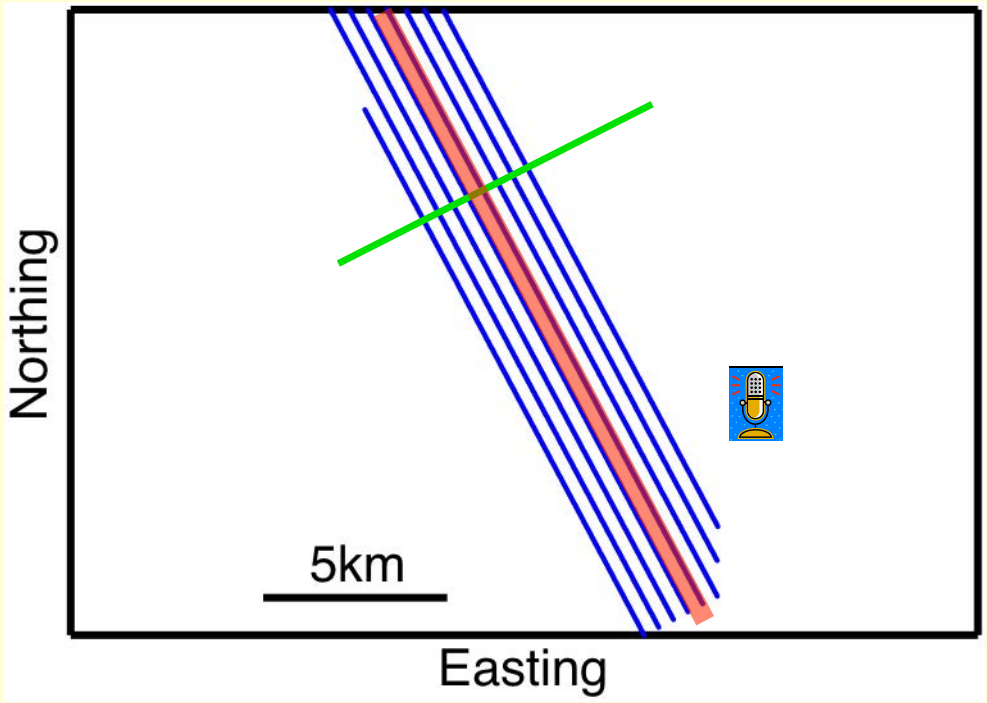
Reflection images from ambient seismic noise

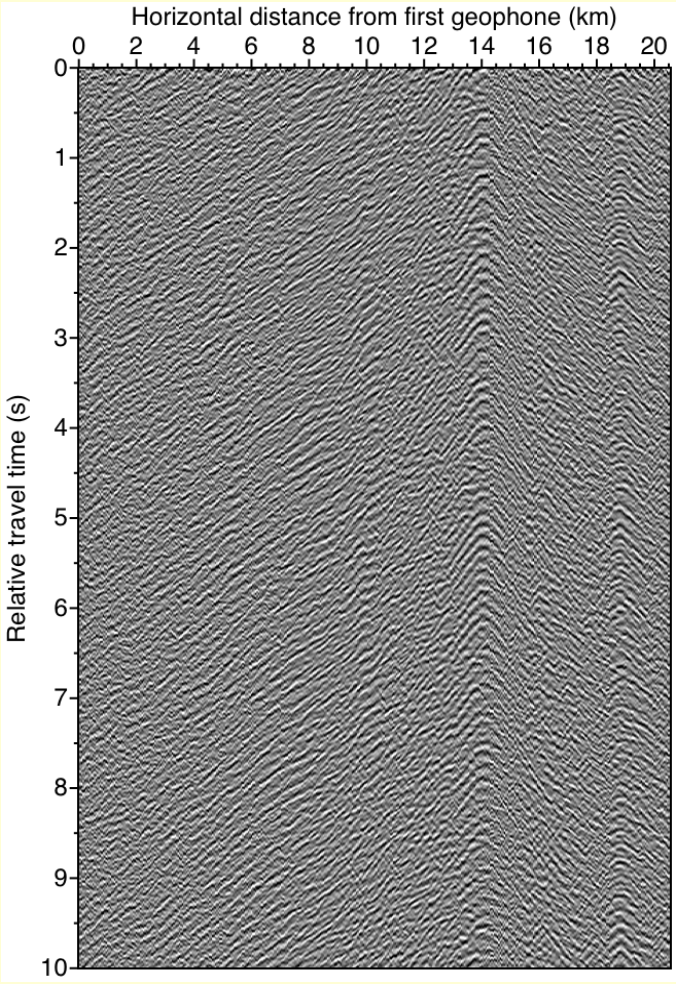
Deyan Draganov[1], Xander Campman[2], Jan Thorbecke[1], Arie Verdel[2], and Kees Wapenaar[1]



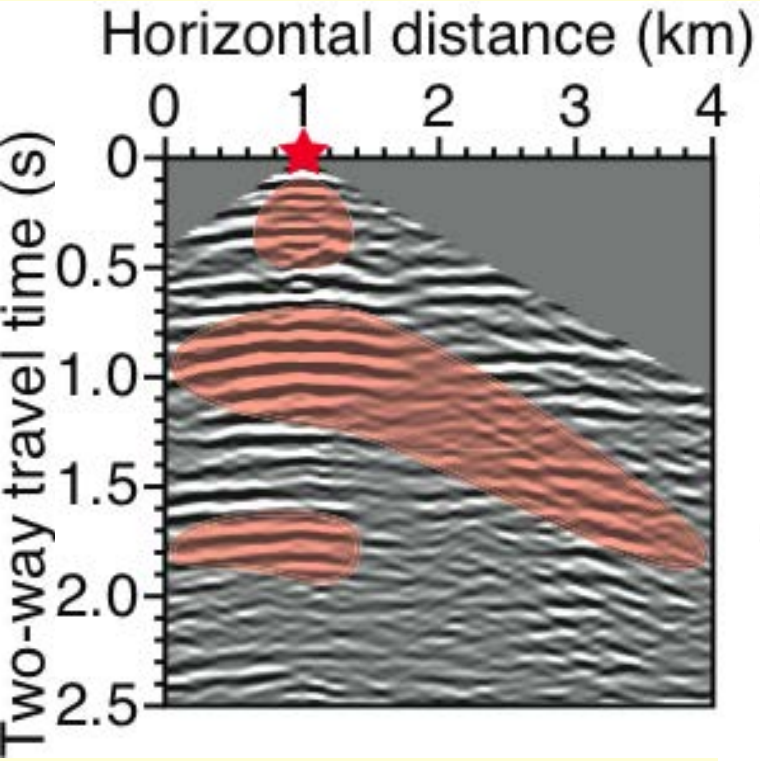

Northing
5km
Easting

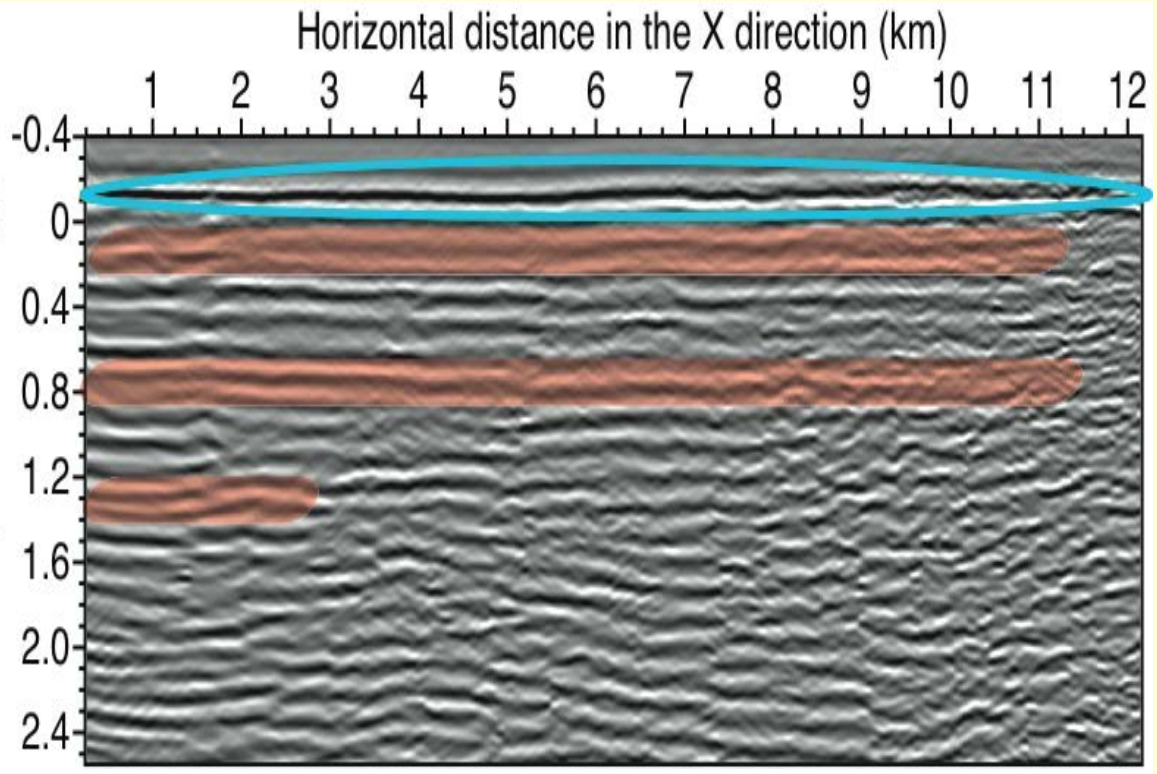

Horizontal distance from first geophone (km)
0
2
4
6
8
10
12
14
16
18
20
Relative travel time (s)
0
1
2
3
4
5
6
7
8
9
10


Northing
5km
Easting

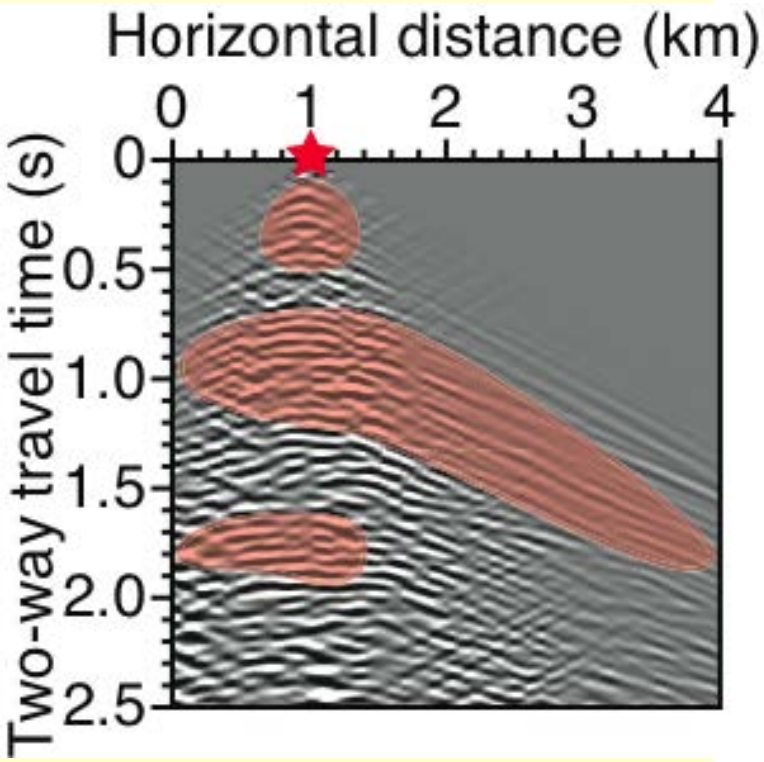

Horizontal distance from first geophone (km)
0
2
4
6
8
10
12
14
16
18
20
Relative travel time (s)
0
1
2
3
4
5
6
7
8
9
10

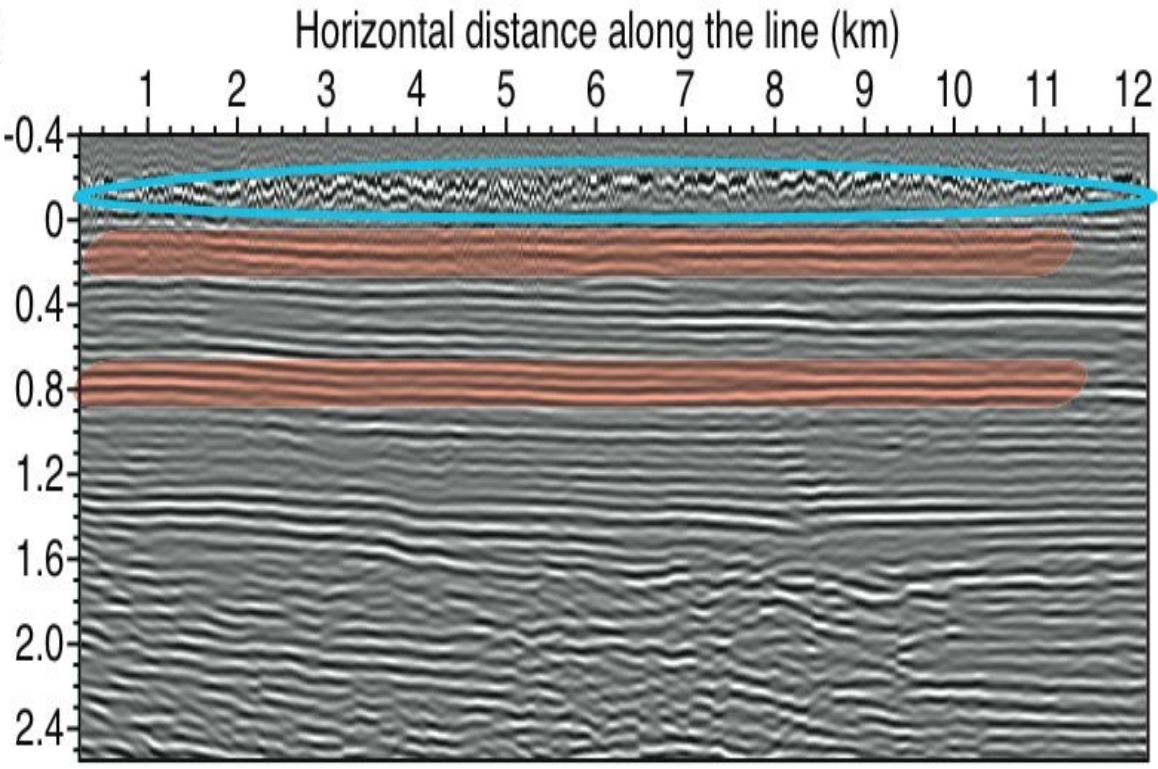
Passive data

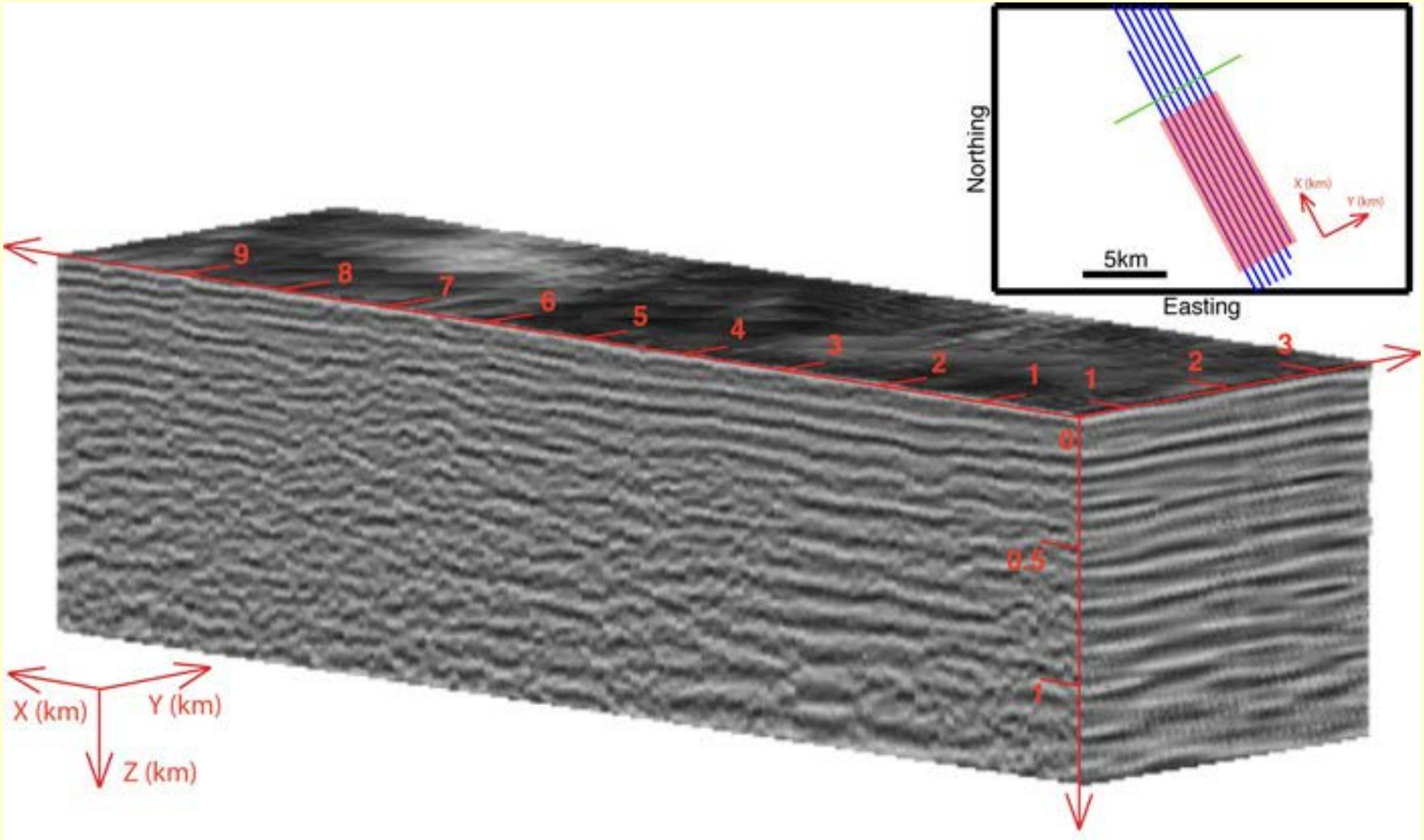




Active data

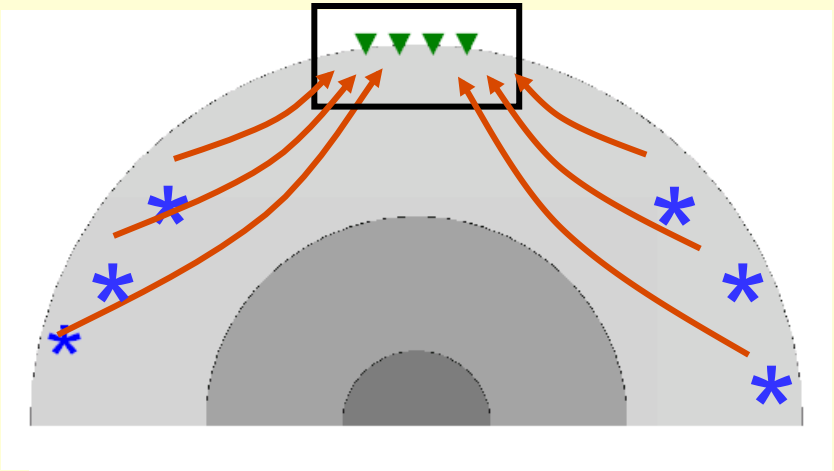

Horizontal distance (km)
0
1
2
3
4
Two-way travel time (s)
0
0.5
1.0
1.5
2.0
2.5


Horizontal distance along the line (km)
1
2
3
4
5
6
7
8
9
10
11
12
-0.4
0
0.4
0.8
1.2
1.6
2.0
2.4


Northing
Easting
5km
X (km)
Y (km)
9
8
7
6
5
4
3
2
1
1
2
3
0
0.5
1
X (km)
Y (km)
Z (km)

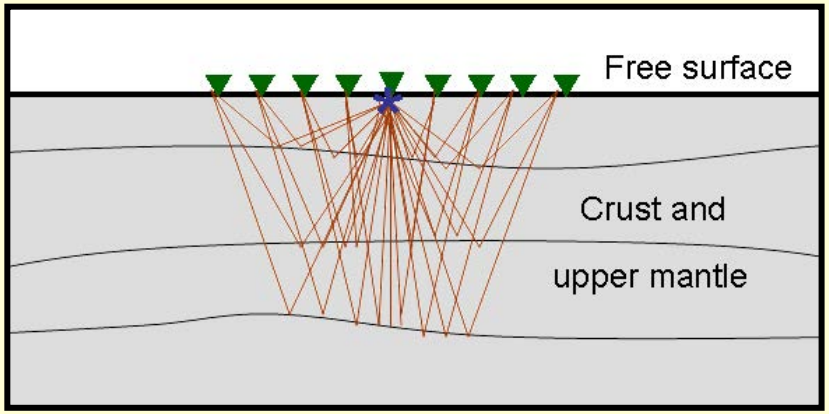
Lithospheric imaging with seismic inteferometry

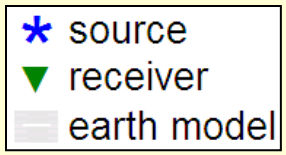
Ruigrok et al., 2010, GJI, 183, 339-357



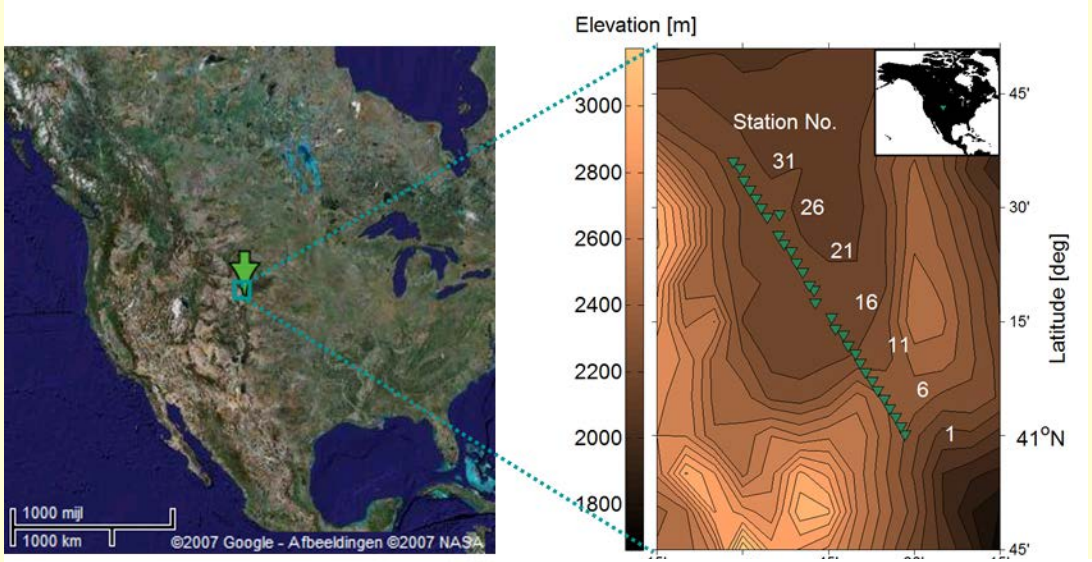
Seismic Interferometry (SI)

(by cross-correlation)



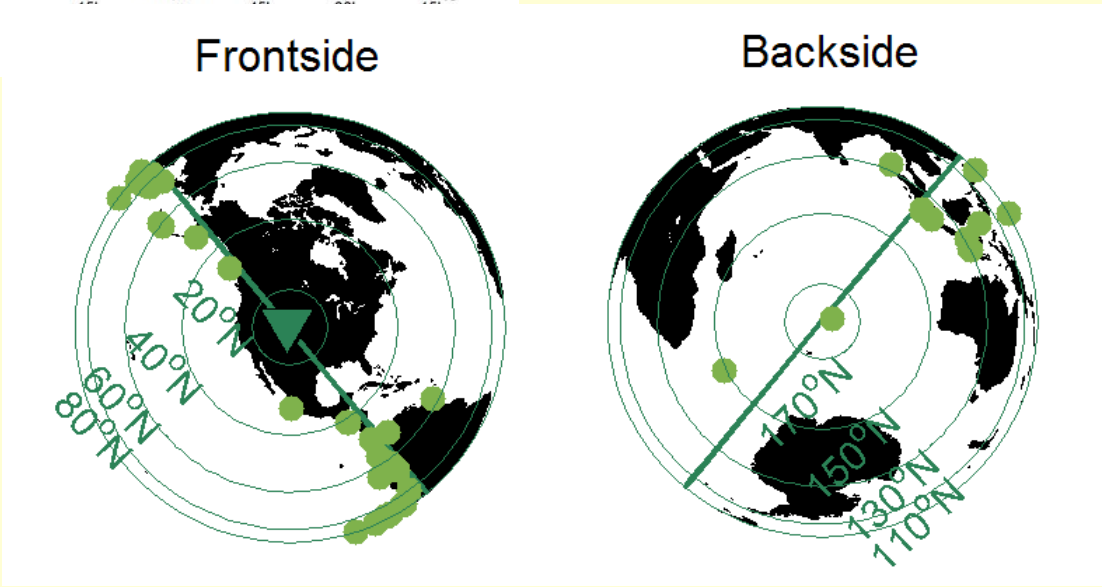


Laramie array

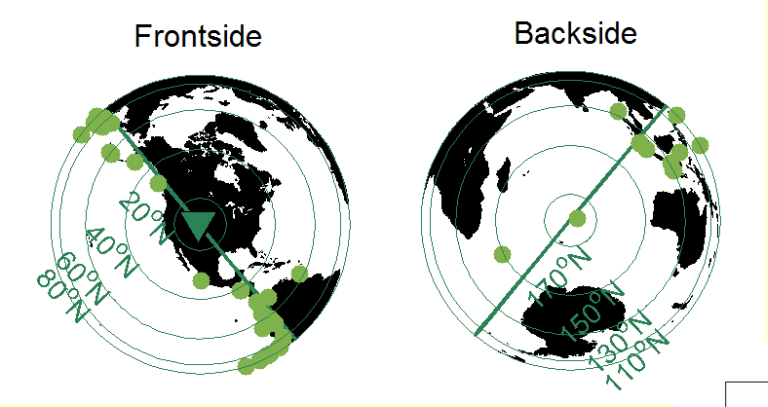


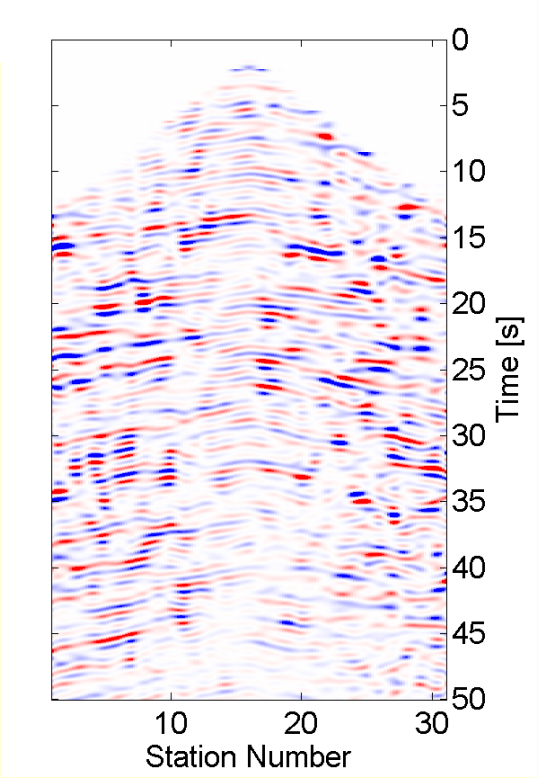
Receiver configuration

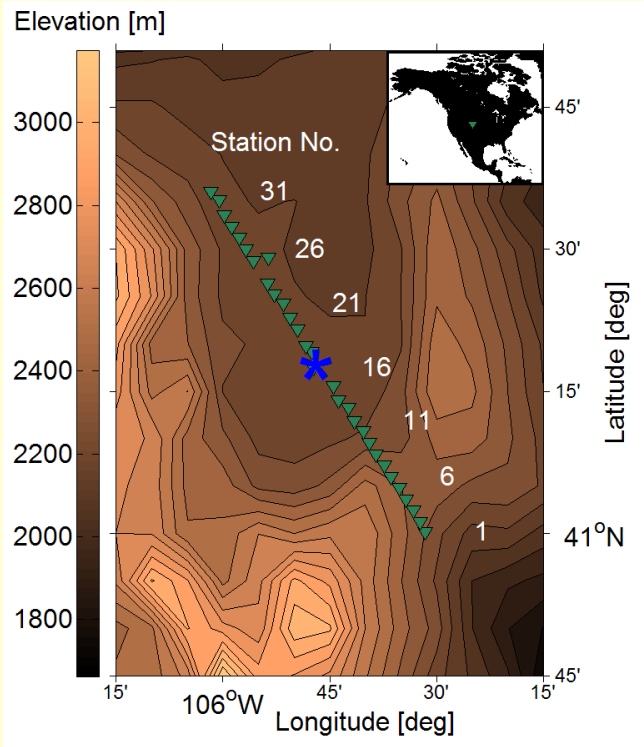
Source configuration



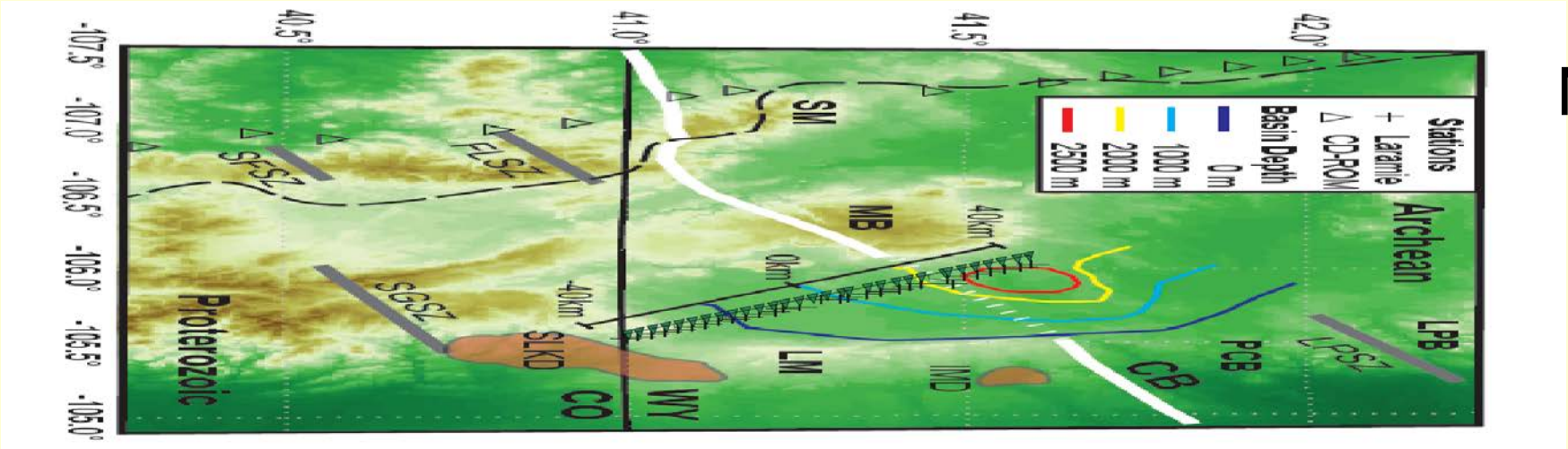
Retrieved reflection response



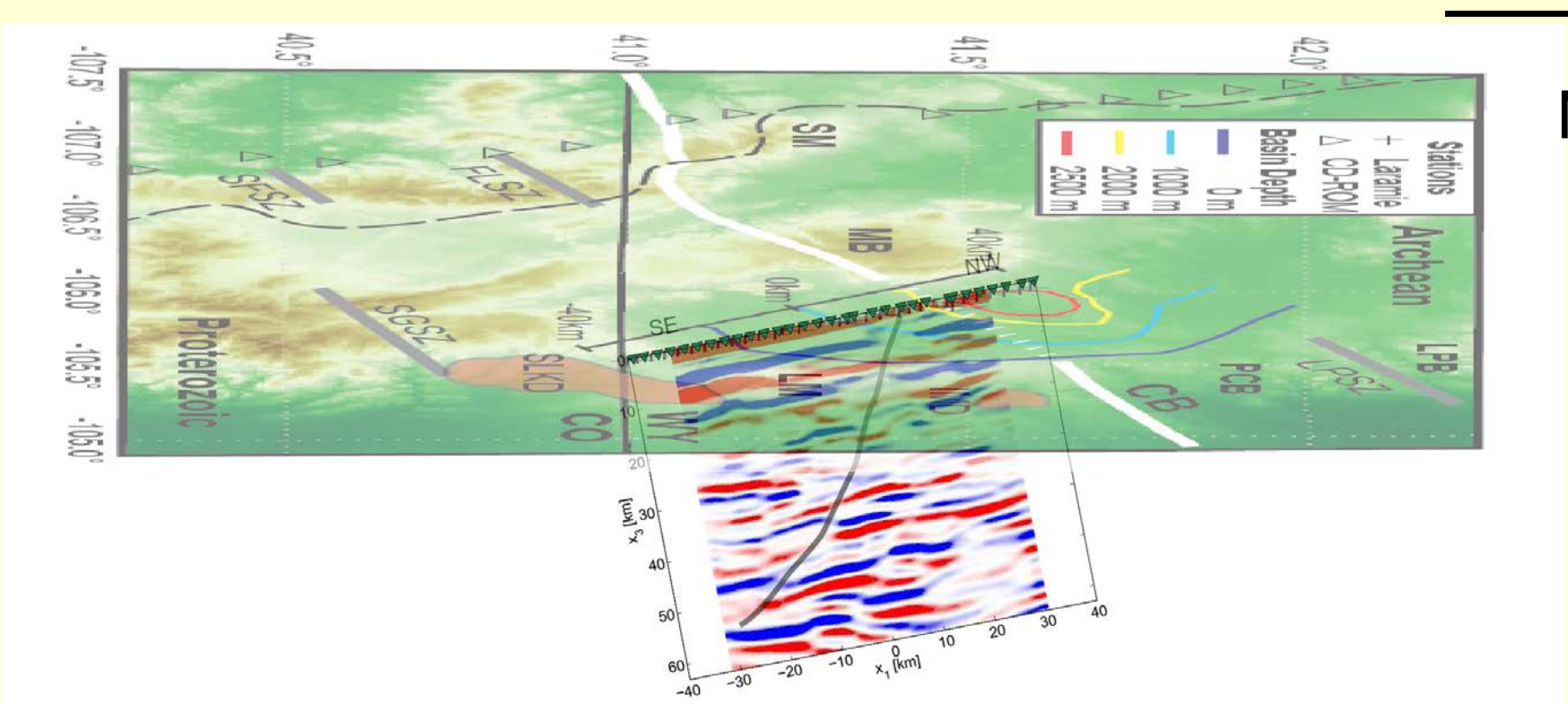




Final image

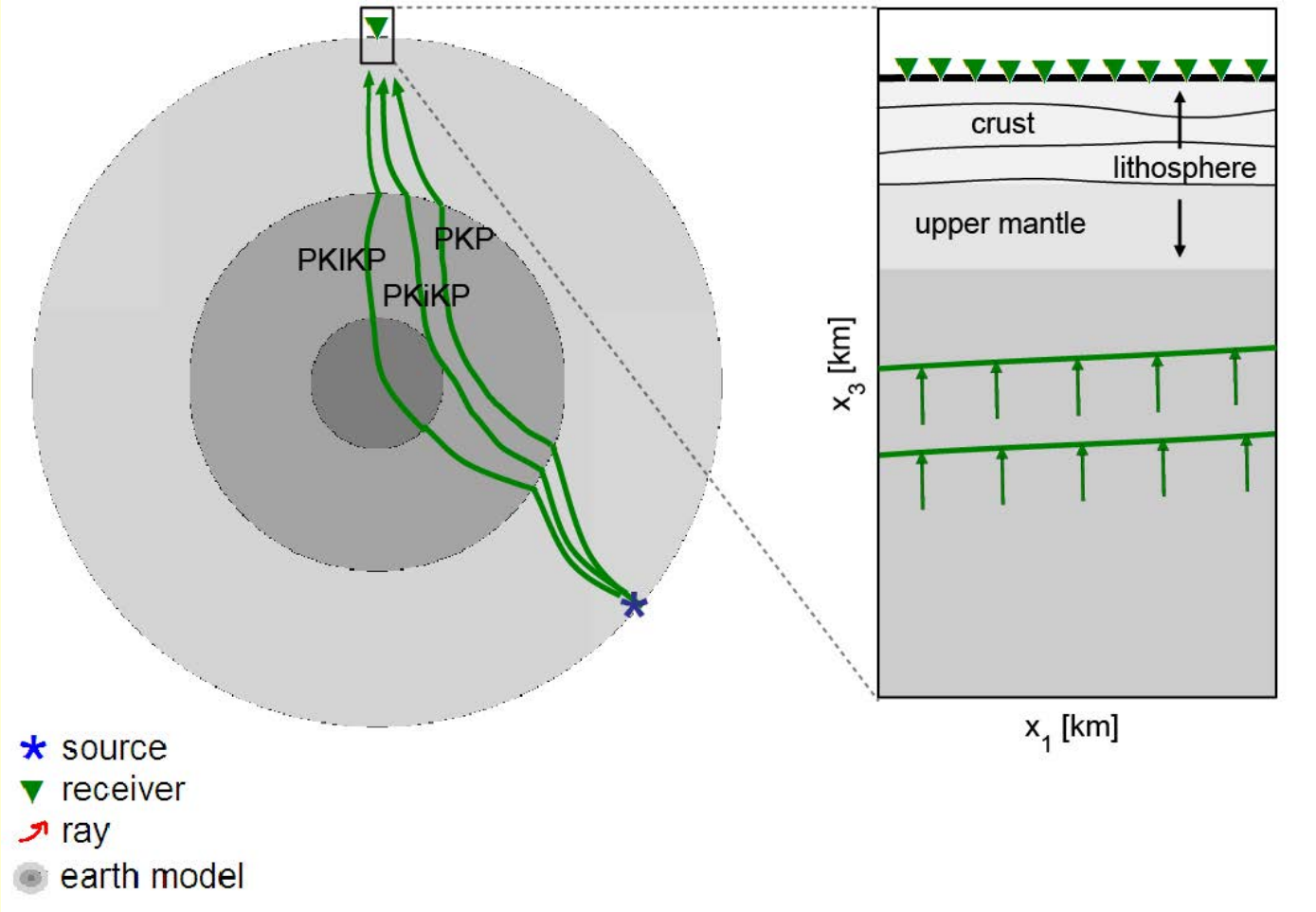

N
Stations
Laramie
CD-ROM
Basin Depth
0 m
1000 m
2000 m
2500 m
Archean
LPB
PCB
CB
IMD
LM
WY
MB
SM
CO
SLKD
Proterozoic
40km
0km
-40km
42.0°
41.5°
41.0°
40.5°
-107.5°
-107.0°
-106.5°
-106.0°
-105.5°
-105.0°

Final image

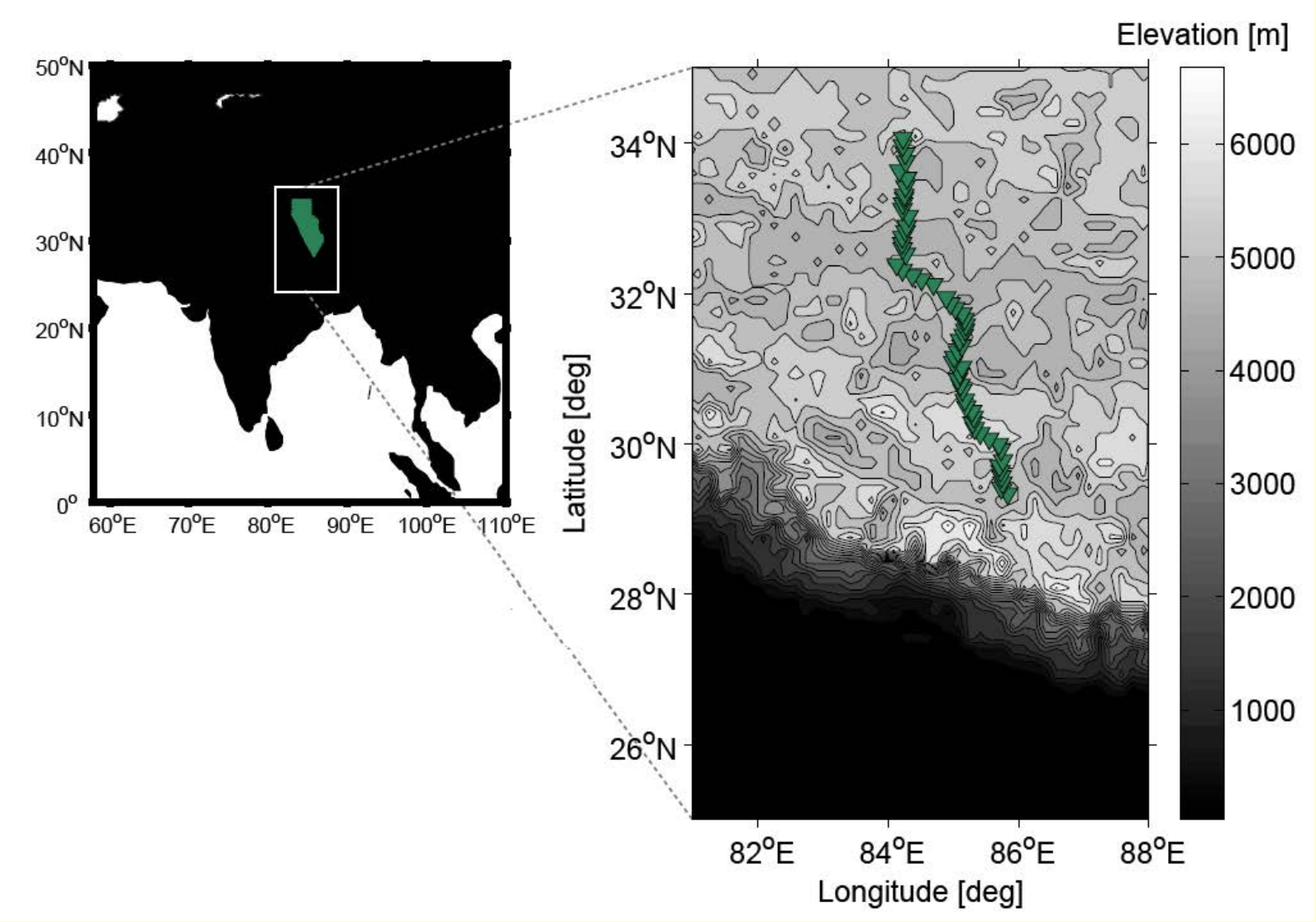

N
-107.5°
-107.0°
-106.5°
-106.0°
-105.5°
-105.0°
40.5°
41.0°
41.5°
42.0°
Stations
Laramie
CD-ROM
Basin Depth
0 m
1000 m
2000 m
2500 m
Archean
Proterozoic
SM
MB
LIM
WY
CO
KD
PCB
CB
LFB
SLKD
SCCSZ
SE
NW
40km
0km
-40km
x_3 [km]
x_1 [km]

Global-phase seismic interferometry

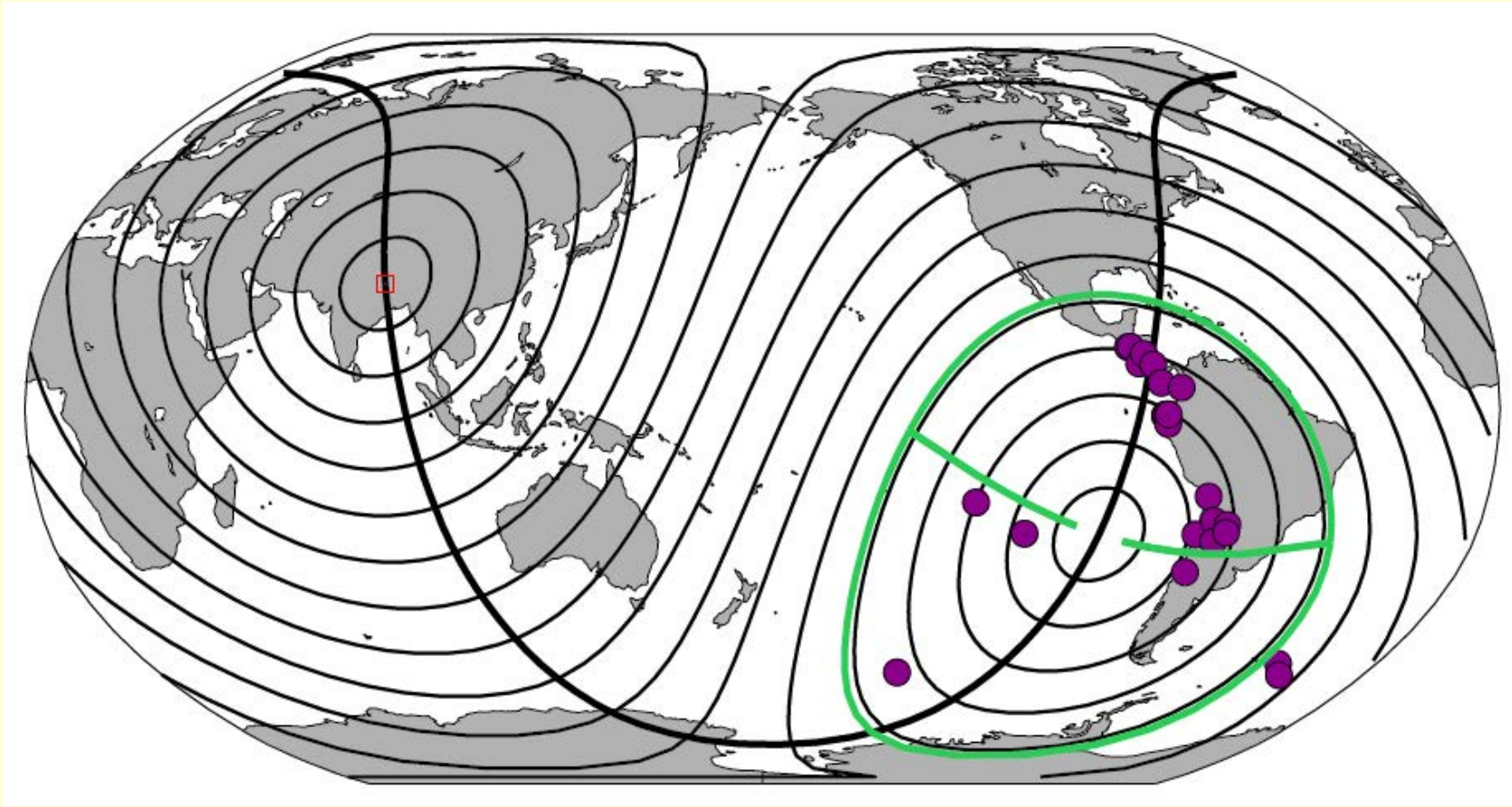
Ruigrok and Wapenaar, 2012, GRL, 39, L11303



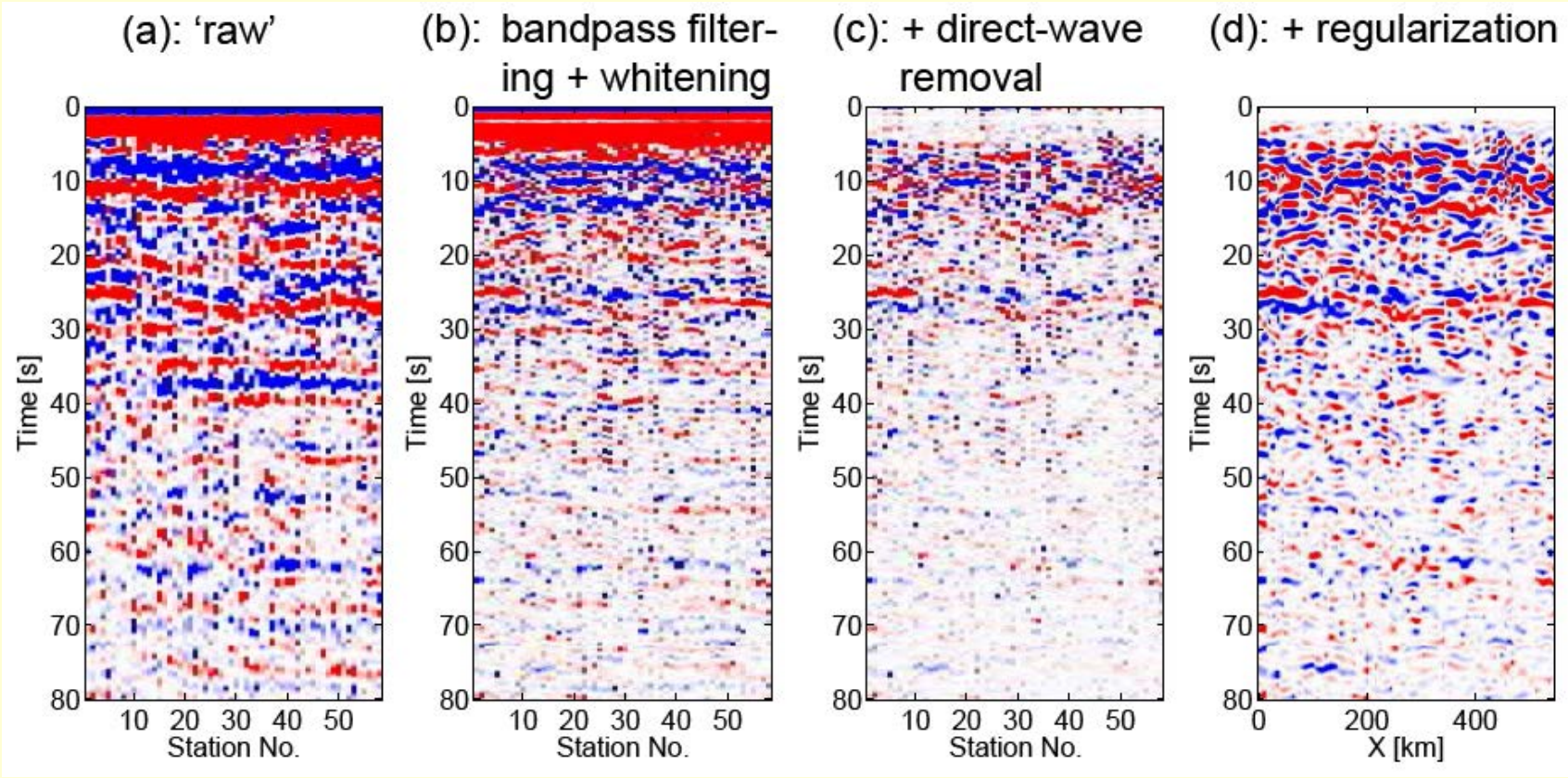
Application to HiCLIMB array



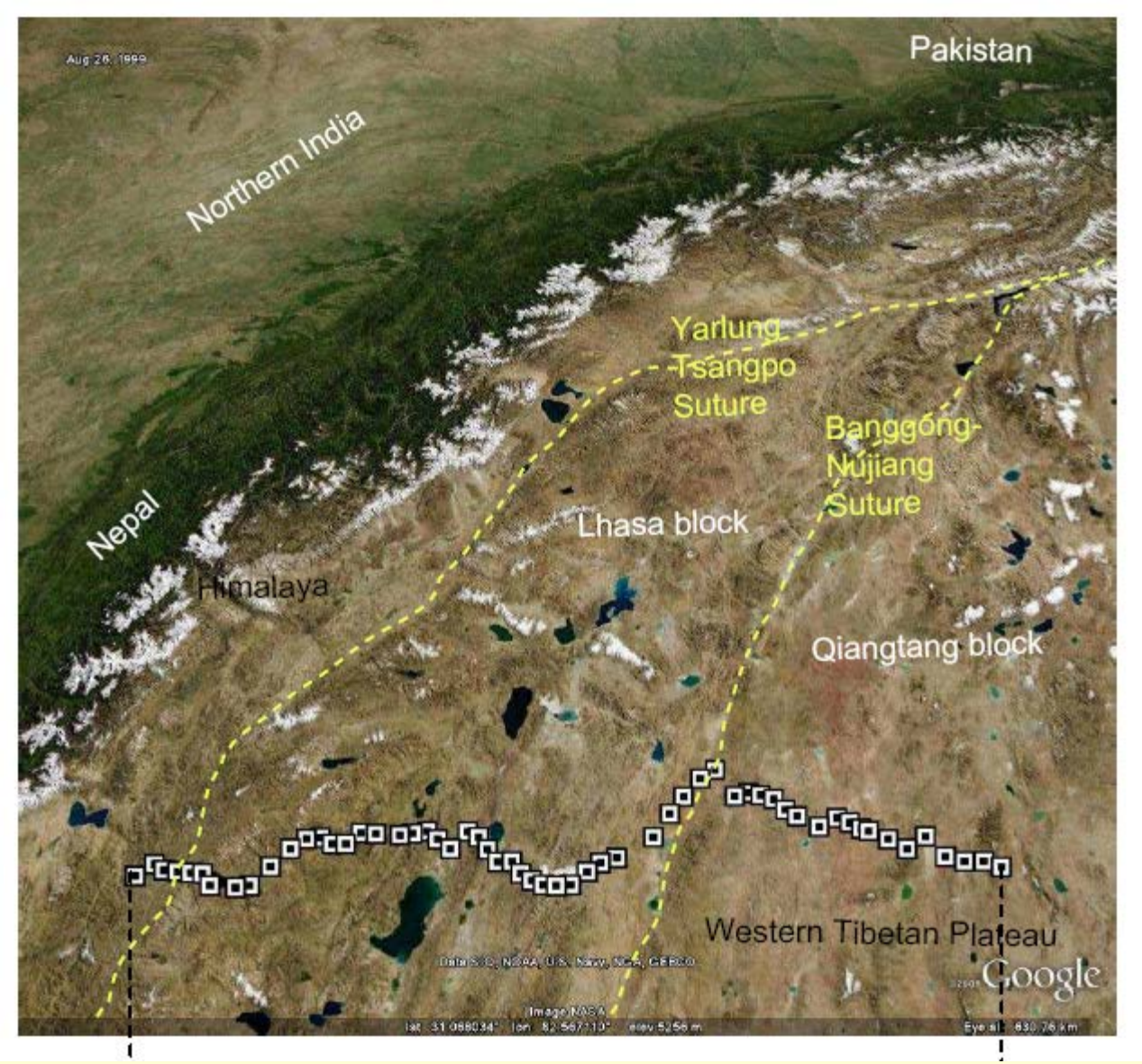
Input: global phases (PKP/PKIKP)



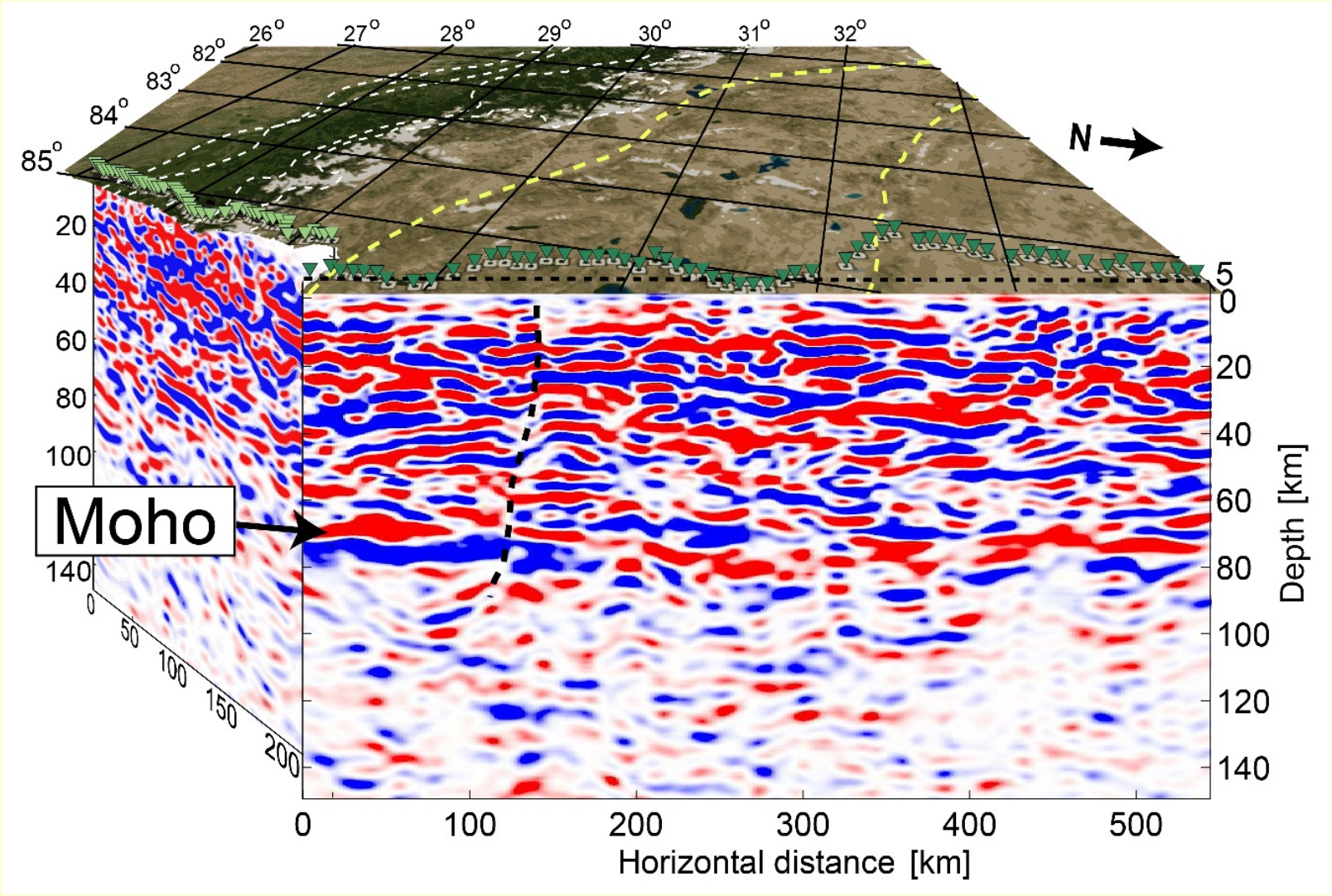
From raw to processed interferometry result



Array + tectonic overview



Final Image


26°
27°
28°
29°
30°
31°
32°
82°
83°
84°
85°
N
20
40
60
80
100
140
0
50
100
150
200
Moho
5
0
20
40
60
80
100
120
140
Depth [km]
0
100
200
300
400
500
Horizontal distance [km]