7 CONCLUSIONS

The behaviour of coda waves in seismograms is one of the observations supporting the existence of small-scale random heterogeneities in the Earth. The direct S wave observed in a seismogram from a local earthquake is followed by complex wave trains with amplitudes smaller than the direct wave and that exponentially decay with time, which are called S-coda. It is widely accepted that coda waves are formed by superposition of incoherent scattered waves from randomly distributed heterogeneities in the lithosphere, such as cracks, faults, folds, and velocity or density anomalies with scale length about the seismic wavelength. S-coda waves have an envelope shape common to all epicentres and stations in a given region after twice the S wave travel time. Total scattering coefficient (g) and coda attenuation (Q_c^{-1}) are the parameters which characterize the coda excitation (which measures the capacity of the medium to originate scattering) and the decay rate of coda envelopes (which is a measure of the attenuation of the medium) within a given frequency band, respectively.

A number of models have been proposed to relate scattering and coda wave amplitudes. One approach to model the coda envelopes is to consider the heterogeneities as randomly and uniformly distributed point-like scatterers. Using this model and on the basis of the energy transport (or radiative transfer) theory, the S-wave coda has been synthesized under the assumption of single isotropic scattering, multiple isotropic scattering and multiple non-isotropic scattering. Most of these models were reviewed with a certain detail in Chapter 2.

Scattering from randomly and non-uniformly distributed heterogeneities has also been studied to explain the features of the observed envelopes of S coda waves. The subject of Chapter 3 was to describe an existing inversion method of coda waveforms from local earthquakes to estimate the inhomogeneous spatial distribution of relative scattering coefficients in the crust. The method is based on the assumption that the fluctuation of the decay curve of the observed coda envelope from a reference curve, which was estimated by assuming single isotropic scattering and spherical radiation from the source, is caused by a non-uniform distribution of scatterers in the crust. This method has proved to be an effective approach to investigate the real heterogeneous structure in the crust of several regions in the world.

Several inversion algorithms have been used to solve the problem in order to obtain the strength of the scattering coefficients: standard inversion methods, recursive stochastic inversion methods, and the Algebraic Reconstruction Technique (ART).

In this thesis the inversion analysis was performed for the first time in this kind of seismological research by means of the Simultaneous Iterative Reconstruction Technique (SIRT) and Filtered Back-Projection method (FBP). We demonstrated that, whereas the first one allows to obtain more exact solutions, the second one is a much faster non-iterative algorithm that has proved to provide very accurate reconstructions.

The inversion analysis required a previous original theoretical development (which is presented in Chapter 4) in order to adapt the Filtered Backprojection algorithm to the geometry defined by the problem to be solved. Then, firstly, the Filtered Backprojection algorithm was derived using a simple approach: the reconstruction of a two-dimensional object from its projections. Secondly, we generalized the result to the two-dimensional case and, finally, by taking into account the special geometry of our problem we devised an algorithm adapted to our case.

The resulting algorithm is about 100 times faster than ART, and we showed that the solutions obtained have similar accuracy. Moreover, the speed improvement of our Filtered Backprojection algorithm allows to carry out inversions with a higher resolution.

Then, we applied the method for the first time to real seismic data from two regions with different geotectonic characteristics: a stable region in southern India and an active volcano in south-western Colombia. Both regions have a high scientific interest, since the crustal structural characteristics of these regions were still poorly known. Results from the present work are also important from the social point of view, since they represent a contribution to seismic hazard assessment in the target regions.

Chapter 5 presents the estimation of three-dimensional spatial distribution of relative scattering coefficients for the Gauribidanur seismic array (GBA) site in southern India. Data used consisted of selected 636 vertical-component, short period recordings of microearthquake codas from shallow earthquakes with magnitudes ranging from 0.7 to 3.7 and epicentral distances up to 120 km from the array centre point. Results were almost independent of the inversion method used (SIRT and Filtered Backprojection) and they were frequency dependent. They showed a remarkably uniform distribution of the scattering strength in the crust around GBA. However, a shallow (0-24 km) strong scattering structure, which is only visible at low frequencies, seems to coincide with the Closepet granitic batholith which is the boundary between the eastern and western parts of the Dharwar craton.

Finally, Chapter 6 presents the three-dimensional spatial distribution of relative scattering coefficients for the Galeras volcano, Colombia. Coda wave envelopes came from 1564 high quality seismic recordings by 31 stations of the Galeras seismograph network. Results revealed a highly non-uniform distribution of relative scattering coefficients in the region for the two analyzed frequency bands (4-8 and 8-12 Hz). Strong scatterers showed frequency dependence, which was interpreted in terms of the scale of the heterogeneities producing scattering. Two zones of strong scattering were detected: the shallower one is located at a depth from 4 km to 8 km under the summit whereas the deeper one is imaged at a depth of ~37 km from the Earth's surface. Both zones may be correlated with the magmatic plumbing system beneath Galeras volcano. The second strong scattering zone may be related to the deeper magma reservoir that feeds the system.

Although the analysis method used assumes simple models of scattering, seismic source radiation, attenuation and velocity structure, the scattering images obtained appear to be coherent with the available geological information. The synthetic tests performed corroborate this assertation.

Concluding, the coda analysis method presented in this thesis seems to be one of effective approaches to investigate the real heterogeneous structure in the crust deterministically. We believe it is a very useful method for this purpose and we encourage further applications to other seismically active regions in the world. The improvement of the underlying scattering model to a more realistic one would be also necessary.

APPENDIX A. EVENTS AT GBA REGION

In this appendix the events at the Gauribidanur seismic array region corresponding to the period 1992-1995 are identified with the corresponding date, origin time, distance (in km) to the array centre point, location coordinates and local magnitude. Depth of hypocenter is about 10 km for all the events.

Date			Origin Time (GMT)			Coordinates Hypocenter			Magnitude
d	m	y	hr	min	sec	D(km)	Lat (°N)	Long (°E)	
18	1	1992	11	12	31.0	51	13.37	77.02	2.2
4	2	1992	6	17	34.0	18	13.51	77.30	1.6
5	2	1992	7	10	34.0	91	13.14	76.74	1.0
23	2	1992	13	11	39.0	73	13.08	77.03	1.0
27	2	1992	12	18	49.0	93	14.42	77.63	1.1
7	3	1992	11	16	54.0	23	13.50	77.25	1.1
23	7	1992	8	49	54.0	81	14.31	77.23	1.2
3	8	1992	7	48	13.0	25	13.47	77.25	0.9
9	8	1992	12	6	24.0	31	13.84	77.59	0.7
9	8	1992	9	18	23.0	91	12.85	77.10	1.1
9	8	1992	9	35	16.0	91	12.85	77.10	1.0
12	8	1992	7	45	35.0	40	13.91	77.63	1.8
14	8	1992	12	4	48.0	44	13.94	77.65	1.4
16	8	1992	7	48	9.0	46	13.92	77.72	1.5
18	8	1992	13	20	21.0	41	13.88	77.70	0.8
4	11	1992	7	41	21.0	84	12.98	77.88	1.1
24	11	1992	6	59	32.0	104	14.47	77.82	2.1
24	12	1992	8	48	13.0	111	14.46	76.90	1.4
28	1	1993	9	23	36.0	41	13.59	77.05	1.7
6	4	1993	18	40	11.4	70	14.15	77.45	3.0
24	7	1993	6	6	7.0	75	12.94	77.59	2.9
28	7	1993	13	2	39.0	84	13.06	76.90	1.3
30	8	1993	8	49	21.0	85	13.23	78.13	1.6
12	10	1993	3	1	58.0	82	13.08	77.97	2.9
9	11	1993	13	34	46.0	59	13.07	77.41	2.0
12	2	1994	9	1	56.0	111	12.83	78.09	1.6
7	4	1994	5	9	49.0	90	14.30	77.86	1.7
2	5	1994	12	40	14.0	80	14.19	77.87	1.4
9	5	1994	11	49	40.0	81	13.84	78.15	2.8
18	6	1994	13	0	28.0	97	14.41	77.78	2.0
21	6	1994	12	48	19.0	97	14.27	78.03	1.6
23	6	1994	12	20	35.0	91	12.78	77.44	2.1
25	6	1994	13	57	55.0	96	14.31	77.95	2.0
29	6	1994	8	56	37.0	100	13.88	78.32	1.4

Date			Origin Time (GMT)			Coordinates Hypocenter			Magnitude
d	m	y	hr	min	sec	D(km)	Lat (ºN)	Long (ºE)	
29	6	1994	12	27	56.0	101	14.34	77.99	1.9
30	6	1994	8	14	51.0	100	13.91	78.31	1.7
25	1	1995	23	24	39	116	12,62	77,79	1,5
12	2	1995	5	6	36	100	12,91	76,85	1,5
12	2	1995	23	0	7	105	12,87	76,82	2,3
20	2	1995	3	54	0	63	13,92	77,92	1
12	3	1995	23	8	16	115	12,62	77,78	1,2
26	4	1995	6	28	18	79	13,66	78,17	1,9
25	5	1995	2	2	22	98	14,31	77,98	1,3
21	8	1995	11	57	50	91	13,11	76,76	1,3
26	8	1995	8	22	46	91	13,14	76,74	1,3
7	9	1995	12	53	36	17	13,73	77,35	0,9
17	9	1995	4	49	33	84	12,85	77,47	1,4
19	9	1995	11	35	37	95	13,09	76,73	1,3
1	10	1995	4	59	33	65	13,02	77,54	2,4
8	11	1995	12	27	50	111	14,46	77,99	1,5
15	11	1995	7	16	36	119	13,04	76,5	1,3
22	11	1995	12	8	10	118	14,51	78,02	1,2
4	12	1995	9	31	5	83	12,89	77,69	2,4
13	12	1995	16	26	27	109	14,48	77,9	1,4
15	12	1995	22	45	15	92	12,8	77,21	1,8
29	12	1995	12	49	59	113	14,47	77,99	1,9

APPENDIX B. EVENTS AT GALERAS VOLCANO

In this appendix the events at Galeras volcano corresponding to the period 1989-1992 and 1993-2002 are identified with a number, the corresponding date and origin time, location coordinates depth and local magnitude.

Events from 1982 to 1992

N	Code	Origin Time			Latitude		Longitude		Depth	Mag.
	yymmddx	Hour	Min.	Sec.	Deg.	Min.	Deg.	Min.	km	
0	8908040i	15	16	14.99	1	14.85	77	21.85	5	0.96
1	8908130u	23	28	2.97	1	13.26	77	22.15	3.49	1.15
2	8908150b	11	27	44.09	1	13.24	77	22.34	2.61	0.46
3	89091701	1	8	59.01	1	13.39	77	23.68	0.94	-0.32
4	89092607	7	9	15.92	1	12.24	77	20.76	0.85	0.81
5	89100111	22	22	46.38	1	13.21	77	22.02	2.99	0.58
6	8910220v	23	21	11.74	1	13.36	77	22.93	3.71	0.61
7	8910250c	7	4	17.75	1	12.51	77	21.76	4.91	1.2
8	89110505	2	29	40.92	1	13.53	77	23.19	3.13	0.37
9	89110605	3	31	25.13	1	13.37	77	22.99	2.69	1.04
10	89111804	2	53	55.07	1	13.31	77	22.67	2.4	0.79
11	8911261q	15	43	9.71	1	12.93	77	21.71	3.12	0.35
12	8912062k	17	29	44.43	1	13.26	77	23.01	3.3	0.81
13	8912062m	17	32	58.61	1	13.18	77	23.06	3.2	0.94
14	8912100u	20	26	56.46	1	13.13	77	22.83	5	0.82
15	89121303	4	14	31.39	1	12.8	77	23.01	5	0.66
16	8912230c	3	50	4.21	1	13.26	77	22.98	2.82	0.81
17	9001131u	21	55	37.82	1	12.7	77	22.4	2.44	0.67
18	9001181o	8	19	13.69	1	13.23	77	22.98	3.74	0.5
19	9001250g	13	17	24.84	1	13.34	77	21.92	3.99	0.15
20	90012802	4	51	39.5	1	13.27	77	22.98	3.44	1.05
21	90012803	4	57	8.66	1	13.25	77	23.07	4.85	0.76
22	90020415	14	24	17.14	1	12.73	77	23.04	2.99	0.86

N	Code	Origin Time			Latitude		Longitude		Depth	Mag.
	yymmddx	Hour	Min.	Sec.	Deg.	Min.	Deg.	Min.	km	
23	90020504	2	51	17.75	1	12.67	77	22.11	4.95	0.71
24	90020602	1	8	47.58	1	13.53	77	23.66	3.14	1
25	90020809	6	30	30.11	1	12.6	77	21.83	4.1	0.62
26	90020901	2	21	12.17	1	13.63	77	23.32	5.29	1.05
27	90022109	10	15	40.65	1	13	77	25.29	5.45	0.8
28	90022308	14	25	13.74	1	13.24	77	23.46	3.53	0.46
29	90022309	14	26	9	1	13.24	77	23.47	3.66	1.19
30	90022408	11	13	41.55	1	13.25	77	23.5	2.96	0.88
31	90030403	3	39	11.88	1	13.27	77	23.59	3.29	0.75
32	90030406	7	44	59.89	1	13.3	77	23.59	3.56	0.74
33	90030408	7	49	50.63	1	13.37	77	23.6	3.09	0.76
34	9003040a	9	44	44.63	1	13.34	77	23.56	3.27	0.81
35	90030801	2	17	28.09	1	13.24	77	23.11	3.51	0.94
36	90031702	2	24	35.22	1	13.26	77	23.61	4.29	0.75
37	9003261m	19	38	51.3	1	14.91	77	21.83	6.81	0.71
38	90032920	19	56	30.77	1	12.81	77	21.61	3.73	0.07
39	9004011h	11	37	17.8	1	13.49	77	23.08	4.4	0.62
40	90040409	3	44	16.33	1	13.43	77	22.85	3.91	0.59
41	9004040g	5	52	11.33	1	13.75	77	22.78	4.52	0.37
42	9004040l	7	31	2.38	1	13.27	77	22.57	6.3	0.89
43	90040417	11	5	5.87	1	13.46	77	22.74	3.22	0.47
44	9004041r	15	3	27.45	1	12.74	77	22.94	4.39	0.34
45	90042605	1	39	28.77	1	13.09	77	22.22	2.68	0.77
46	90050506	0	42	46.1	1	12.68	77	21.97	3.62	0.79
47	9005050a	1	53	39.07	1	13.67	77	23.1	3.08	1.16
48	9005050m	5	41	59.64	1	13.67	77	23.14	3.29	0.69
49	9005050r	7	9	0.98	1	12.74	77	21.82	3.55	0.9
50	9005060f	5	18	9.79	1	13.77	77	23.1	3.05	0.73
51	90051102	3	7	44.14	1	13.23	77	23.47	2.8	0.7
52	9005110h	9	58	51.6	1	13.4	77	22.47	2.49	0.46

N	Code	Origin Time			Latitude		Longitude		Depth	Mag.
	yymmddx	Hour	Min.	Sec.	Deg.	Min.	Deg.	Min.	km	
53	90051702	6	59	24.46	1	13.38	77	22.99	3.73	0.2
54	9005270n	14	59	10.51	1	13.79	77	23.43	4.52	0.71
55	90052712	15	51	12.99	1	13.26	77	23.2	3.48	0.89
56	90052800	4	3	39.14	1	13.38	77	22.69	3.85	0.69
57	90052801	8	30	27.83	1	13.36	77	22.85	3.59	0.65
58	9008080l	4	56	50.62	1	12.99	77	23.19	3	0.8
59	9008181f	20	6	17.01	1	12.5	77	22.92	3.15	-0.01
60	90082614	14	42	27.5	1	12.74	77	22.81	3.55	0.8
61	90082700	9	13	35.12	1	12.74	77	23.14	4.3	0.7
62	90082705	12	35	5.38	1	12.95	77	22.93	4.84	0.44
63	9008281b	12	2	18.9	1	12.74	77	22.98	4.62	0.51
64	90083015	14	8	52.05	1	12.97	77	22.89	3.68	0.48
65	90090307	1	3	55.21	1	12.65	77	22.97	4.13	0.53
66	9009061u	18	19	24.61	1	12.88	77	22.73	4.59	1.53
67	90110709	15	17	33.28	1	12.05	77	20.82	4.35	1.17
68	9012071a	17	10	39.82	1	12.98	77	23.12	3.4	1.5
69	9104222v	17	32	5.81	1	12.68	77	23.56	2.43	1.03
70	91042233	17	58	14.09	1	12.5	77	23.6	4.24	1.48
71	91050111	18	20	55.27	1	12.41	77	23.72	2.97	1.27
72	91052906	2	13	12.59	1	13.21	77	22.79	4.27	0.99
73	91052907	2	17	44.05	1	13.1	77	22.97	4.03	0.68
74	9109191r	8	18	45.39	1	14.29	77	21.26	3.48	0.78
75	9206020u	21	34	5.28	1	13.28	77	21.46	3.17	0.7
76	92080404	5	49	5.26	1	13.44	77	21.91	0.8	0.92
77	92081616	15	24	5.21	1	13.44	77	22.01	0.79	1.01

Events from 1993 to 2002

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
78	93040800	6	4	2.99	1 13.49	77 22.12	1.48	1
79	93041100	2	59	26.93	1 13.17	77 22.65	6	1.03
80	9304262u	17	0	55.18	1 14.75	77 22.11	3.51	1.29
81	9304270a	0	54	0.98	1 14.85	77 22.04	4.36	1.25
82	9304270d	1	2	50.22	1 14.81	77 22.14	4.24	1.37
83	9304270f	1	12	9.87	1 14.88	77 21.95	4.24	1.33
84	9304270p	2	2	24.36	1 13.51	77 21.96	3.82	0.87
85	9304270u	2	10	2.72	1 15.06	77 21.76	4.62	1.19
86	93042707	0	52	6.08	1 14.89	77 22.07	4.25	1.59
87	93042708	0	52	6.07	1 14.91	77 22.07	4.32	1.22
88	9304271b	5	12	9.68	1 15.35	77 21.97	4.92	1.11
89	9304271g	8	30	10.6	1 15.19	77 22.06	4.67	1.41
90	9304271x	16	56	56.41	1 14.63	77 22.27	3.59	1.68
91	93042712	3	6	57.38	1 15.24	77 21.97	4.69	1.12
92	9304272d	20	23	23.01	1 15.18	77 21.95	4.36	1.53
93	93042802	0	41	49.18	1 15.45	77 21.93	5.41	1.45
94	93042808	3	46	4.02	1 14.90	77 21.93	3.83	1.6
95	9304290l	12	14	30.4	1 14.68	77 22.15	3.64	1.32
96	93050102	2	37	41.82	1 14.80	77 21.95	4.35	1.32
97	9305020l	10	16	52.03	1 15.27	77 21.95	4.62	1.58
98	93050906	3	33	11.93	1 14.84	77 21.47	4.73	1.06
99	9305130x	14	19	11.51	1 14.77	77 21.58	4.79	1.16
100	93051903	6	27	7	1 14.93	77 22.17	3.44	1.55
101	93052015	10	42	16.11	1 14.91	77 21.53	7.03	1.93
102	930602gx	20	25	49.16	1 12.98	77 26.01	9.02	2.08
103	9308052q	3	25	15.23	1 12.54	77 21.13	8.3	1.19
104	93102006	11	9	9.05	1 13.11	77 21.53	0.54	1.08
105	93103007	5	32	59.04	1 13.71	77 23.15	2.1	0.27
106	9312010m	4	18	14.65	1 14.91	77 21.65	4.35	1.12

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
107	9312011p	11	9	49.01	1 14.59	77 21.52	4.09	1.08
108	9407271h	16	49	17.11	1 13.43	77 23.55	6.61	0.44
109	9408093i	8	22	20.93	1 13.13	77 21.80	3.58	0.49
110	94081206	1	52	37.45	1 14.66	77 21.43	3.3	1.1
111	9412142u	23	32	7.21	1 13.82	77 22.04	1.53	0.42
112	9412230c	7	13	12.47	1 14.59	77 21.62	6.75	0.99
113	95011102	0	31	0.17	1 12.22	77 23.30	5.55	0.96
114	95021202	1	19	26.44	1 15.05	77 22.04	3.91	0.95
115	95021418	12	9	38.87	1 13.86	77 24.09	1.09	1.37
116	9502234f	22	28	51.94	1 13.56	77 24.62	5.86	0.94
117	9503041i	18	39	25.03	1 14.64	77 21.63	4.17	1.42
118	9503041t	18	49	2.24	1 14.57	77 21.59	4.53	1.37
119	9503041x	18	52	25.56	1 14.59	77 21.40	4.61	1.39
120	9503042w	19	26	16.94	1 14.40	77 21.22	4.89	0.77
121	95030434	19	34	12.96	1 14.76	77 21.52	4.04	1.44
122	9503043g	19	44	54.63	1 15.11	77 21.67	5.39	0.76
123	9503043i	19	47	54.62	1 14.65	77 21.44	5.17	1.1
124	95030502	0	2	16.75	1 14.89	77 21.52	4.57	1.26
125	9503052p	4	2	35.03	1 14.72	77 21.45	4.14	1.46
126	9503056r	12	49	12.32	1 14.70	77 21.38	4.71	0.84
127	9503058s	16	41	55.42	1 14.28	77 21.65	4.36	0.72
128	9503059m	19	25	43.65	1 14.89	77 21.55	4.4	1.12
129	9503059y	20	17	54.88	1 14.33	77 21.50	5.17	0.98
130	9503060u	3	44	8.31	1 14.79	77 21.60	4.62	1.12
131	95030720	10	34	53.34	1 14.72	77 21.70	4.83	0.93
132	95030806	0	23	9.53	1 14.79	77 21.56	4.8	1.21
133	9503083o	16	44	39.98	1 14.93	77 21.79	3.92	1.03
134	95030915	9	33	15.26	1 15.06	77 21.77	4.68	1.34
135	9503094h	23	21	13.12	1 15.64	77 18.73	5.31	0.72
136	9503100t	0	49	11.72	1 15.02	77 21.65	4.48	0.95

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
137	9503100z	0	56	15.96	1 15.37	77 19.55	6.37	0.27
138	95031012	0	58	12.42	1 15.24	77 19.53	7.02	1.63
139	95031013	0	59	46.15	1 15.25	77 20.04	6.46	1.25
140	95031008	0	24	40.53	1 15.53	77 18.83	5.76	1.76
141	9503101e	1	24	47.88	1 14.91	77 21.60	4.54	0.93
142	9503109s	23	36	42.19	1 15.30	77 21.31	5.12	0.78
143	95031091	21	34	54.7	1 15.11	77 21.61	5.17	1.96
144	95031107	1	35	47.57	1 15.45	77 19.08	7.08	0.67
145	9503113r	20	58	54.86	1 15.14	77 19.29	5.81	1.12
146	95031141	22	7	31.95	1 15.86	77 20.35	7.21	1.48
147	95031207	2	55	5.61	1 15.19	77 19.14	4.77	1.12
148	9503121f	11	36	23.67	1 15.44	77 18.90	4.83	0.78
149	9503121i	12	28	9.07	1 15.53	77 20.62	5.92	1
150	9503122s	20	13	55.83	1 15.47	77 19.03	7.84	1.22
151	9503123a	23	15	46.29	1 15.80	77 20.01	6.13	0.91
152	9503130g	4	49	33.17	1 15.84	77 20.42	4.77	0.88
153	9503130j	5	27	42.48	1 15.64	77 18.43	5.73	1.24
154	9503130r	7	15	49.06	1 15.08	77 21.43	5.78	1.45
155	9503130t	7	44	37.08	1 15.43	77 21.50	4.97	1.54
156	9503131x	13	12	37.93	1 15.23	77 19.85	6.29	1.19
157	9503131y	13	13	32.76	1 15.56	77 18.20	5.41	0.99
158	9503140i	5	19	34.53	1 15.67	77 18.70	4.47	0.72
159	9503140r	7	1	42.35	1 15.16	77 19.86	6.09	1.01
160	95031402	1	7	45.72	1 15.57	77 20.97	6.39	1
161	9503142i	19	14	21.45	1 15.54	77 19.76	6.2	1.11
162	9503142k	19	18	21.44	1 15.23	77 20.03	6.7	0.92
163	9503150h	6	3	29.14	1 15.86	77 18.94	4.27	0.99
164	9503150v	8	10	1.31	1 15.59	77 19.19	7.98	1.11
165	95031605	1	35	35.47	1 15.70	77 20.07	6.27	1.05
166	9503162f	21	58	56.02	1 15.43	77 20.47	6.88	1.03

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
167	95031623	19	8	8.27	1 15.94	77 20.64	6.33	0.99
168	9503170x	12	25	52.6	1 15.59	77 18.58	5.53	0.99
169	9503170z	12	33	50.9	1 15.34	77 19.00	4.94	1.13
170	95031704	2	32	6.24	1 15.56	77 18.82	5.79	0.98
171	9503171m	18	10	30.86	1 15.63	77 18.64	4.86	0.82
172	9503172b	21	9	52.38	1 15.05	77 19.06	5.45	1.08
173	9503172q	23	55	10.81	1 15.18	77 19.02	5.73	0.91
174	9503180d	6	54	8.54	1 15.25	77 19.21	5.76	1.09
175	95031801	1	32	41.94	1 15.42	77 19.09	5.31	0.89
176	9503191a	16	58	35.7	1 15.32	77 19.14	4.82	0.85
177	9503191p	18	55	54.3	1 15.61	77 18.40	5.15	0.9
178	95032004	14	50	51.41	1 15.12	77 19.08	5.16	0.91
179	95032020	21	0	22.34	1 15.59	77 18.30	5.15	1.11
180	95032024	21	58	31.39	1 15.77	77 19.43	6.31	1.11
181	9503211b	16	52	23.01	1 15.63	77 19.32	5.03	1.22
182	9503220x	7	31	18.76	1 15.71	77 19.12	5.2	1.16
183	95032217	9	18	22.06	1 15.69	77 20.85	6.52	1.11
184	95040106	4	6	49.13	1 15.70	77 18.70	5.41	1.17
185	9504030t	15	5	34.49	1 15.74	77 21.27	5.91	0.69
186	95040410	5	57	8.4	1 15.35	77 19.09	7.35	0.98
187	95040501	0	41	39.16	1 15.70	77 18.92	6.34	0.8
188	9504057e	22	20	22.46	1 15.30	77 19.12	5.39	0.61
189	95040605	4	5	2.93	1 15.44	77 19.69	6.22	0.64
190	9504140b	3	20	26.82	1 13.43	77 22.01	2.62	1.23
191	95041406	3	16	25.33	1 13.43	77 22.01	2.74	0.95
192	9504140n	4	32	35.63	1 13.40	77 21.99	2.42	1.14
193	95041701	0	2	9.86	1 14.08	77 21.22	5.97	1.02
194	95041702	0	8	10.22	1 14.50	77 20.94	5.88	1.28
195	9504181r	16	12	31.09	1 15.56	77 18.69	5.08	1.04
196	9505030u	11	35	31.24	1 15.56	77 17.36	7.77	1.34

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
197	95050304	2	40	42.41	1 15.68	77 19.09	7.85	0.9
198	95050502	0	49	12.91	1 14.96	77 19.61	6.88	1.05
199	95050603	3	5	48.77	1 15.75	77 20.04	6.79	1.73
200	9505070e	15	19	0.03	1 15.34	77 19.83	6.64	0.88
201	9505150x	23	38	15.54	1 15.29	77 21.80	5.68	1.38
202	9505191i	17	15	35.94	1 15.78	77 19.58	6.29	0.77
203	95052111	16	59	51.38	1 14.61	77 21.58	6.58	0.79
204	95052613	23	33	6.87	1 14.52	77 20.50	7.64	1.24
205	9505280t	19	13	35.16	1 15.67	77 19.46	6.26	0.97
206	9506020k	11	22	50.62	1 15.01	77 18.81	5.48	0.92
207	95060207	10	2	16.48	1 14.76	77 18.76	6.36	0.84
208	95060210	15	47	42.83	1 15.08	77 18.55	5.29	0.99
209	9506040d	10	42	15.57	1 15.26	77 21.60	5.06	1.68
210	9506080b	9	22	49.04	1 14.93	77 19.58	6.07	1.27
211	95060807	5	36	57.6	1 15.52	77 19.56	6.72	1.27
212	9506100e	16	0	54.29	1 15.66	77 19.19	7.09	0.84
213	95061203	4	51	35.76	1 15.86	77 20.05	6.87	0.78
214	95061405	3	21	14.86	1 15.18	77 20.83	6.41	0.88
215	95061607	16	9	53.76	1 15.73	77 20.12	7.02	1.14
216	95061704	4	3	43.81	1 15.83	77 20.20	6.91	1.17
217	95062108	7	32	3.77	1 14.06	77 23.54	3.25	0.86
218	9506300k	23	0	21.06	1 15.59	77 18.71	4.52	0.78
219	9507051o	18	8	27.71	1 14.90	77 19.00	5.61	1
220	95070516	13	21	30.41	1 14.75	77 20.10	5.68	1.1
221	9507060n	14	10	5.14	1 14.81	77 19.14	5.93	0.71
222	9507070h	6	32	50.95	1 14.90	77 18.92	6.06	1.03
223	95070702	2	42	19.56	1 15.00	77 18.95	5.97	1.15
224	95071814	12	0	3.28	1 14.22	77 19.75	6.3	1.22
225	95072503	1	2	12.6	1 15.44	77 20.29	6.93	1.26
226	95072905	1	30	14.42	1 15.91	77 19.82	6.93	1.02

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
227	95073021	3	30	20.86	1 14.02	77 20.60	5.86	1.48
228	9507311h	21	44	38.36	1 15.71	77 18.30	7.94	0.98
229	9508080k	23	56	57.5	1 15.38	77 19.40	5.15	1.4
230	9508092p	20	7	45.58	1 16.15	77 19.22	7.01	1.37
231	95081104	2	5	54.25	1 15.79	77 20.16	5.98	1.09
232	9508162u	12	11	25.34	1 15.62	77 18.99	5.28	1.27
233	95081717	20	56	18.59	1 15.91	77 19.90	6.97	0.96
234	9508281t	21	7	55.86	1 15.65	77 20.25	5.74	1.41
235	9509032o	3	32	35.19	1 15.78	77 21.63	5.79	0.85
236	9510120y	10	48	42.22	1 15.24	77 21.98	6.03	1.22
237	9510167f	7	54	45.37	1 14.70	77 21.41	5.52	1.79
238	9510190s	8	36	5.18	1 15.06	77 21.79	4.38	1.61
239	9511171g	17	58	25.23	1 15.64	77 20.05	6.26	
240	9511240h	10	2	49.59	1 14.12	77 19.58	6.49	1.29
241	9512050y	14	15	22.27	1 15.82	77 19.82	6.71	1.56
242	95120511	14	35	2.29	1 15.78	77 19.48	6.73	1.08
243	95120615	14	8	1.54	1 15.85	77 19.94	6.7	1.37
244	9601120j	8	7	41.86	1 15.46	77 20.15	4.09	0.48
245	96011307	4	54	23.06	1 16.49	77 19.18	6.07	0.56
246	9601151h	17	28	33.68	1 16.02	77 19.52	6.23	1.22
247	96011515	14	57	23.42	1 15.96	77 18.98	4.88	0.89
248	9601310v	16	57	14.46	1 15.84	77 19.40	6.28	0.55
249	9602051v	11	49	50.85	1 15.41	77 19.32	4.68	0.56
250	9602160z	9	15	36.48	1 13.90	77 20.22	7.48	1.26
251	96041608	14	59	57.66	1 16.26	77 19.55	4.76	0.76
252	9605080t	16	4	20.04	1 15.88	77 19.66	5.95	0.96
253	9605130e	16	14	22.26	1 16.16	77 19.60	5.37	0.89
254	9605300b	9	29	26.89	1 13.98	77 20.01	6.49	1.32
255	96060205	4	48	36.26	1 13.45	77 24.41	3.74	0.59
256	96080307	1	38	33.01	1 15.48	77 18.72	6.03	0.2

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
257	96081908	8	18	13.95	1 16.03	77 19.86	7.36	0.72
258	9608260d	10	18	13.78	1 16.60	77 19.89	7.54	0.63
259	9609011q	9	53	25.29	1 15.90	77 18.93	5.73	1.11
260	9609100d	5	9	15.4	1 14.46	77 23.50	7.3	0.73
261	96100909	10	32	15.13	1 16.04	77 19.72	6.22	0.86
262	9610110f	9	23	52.18	1 14.98	77 20.58	5.49	0.53
263	9610110l	11	33	45.4	1 15.00	77 20.30	5.44	0.82
264	9610110o	12	58	37.01	1 14.99	77 20.73	5.05	1
265	9610110w	14	13	47.34	1 15.04	77 20.28	5.11	0.77
266	96101119	18	6	53.94	1 14.92	77 20.90	5.56	1.1
267	9610121q	14	19	20.04	1 16.08	77 20.10	6.23	0.6
268	96102412	16	8	51.23	1 15.46	77 19.18	4.52	0.54
269	9610280d	3	46	32.65	1 16.35	77 18.75	6.26	0.98
270	96102816	19	37	37.17	1 16.55	77 20.87	9.72	0.58
271	96103107	5	4	19.67	1 15.81	77 18.88	5.33	0.92
272	9611080s	14	1	5.38	1 16.49	77 21.50	4.47	1.39
273	9611081e	18	59	19.85	1 16.49	77 21.25	5.35	1.55
274	96111804	3	8	21.82	1 16.04	77 19.41	6.58	1.06
275	9701120k	4	14	36.24	1 15.86	77 20.45	6.32	0.56
276	9701120m	4	15	58.15	1 15.51	77 19.53	4.24	0.3
277	9701120o	4	16	54.2	1 16.01	77 20.05	5	0.59
278	9701120p	4	18	6.12	1 15.91	77 19.86	4.17	0.19
279	9701130c	7	19	12.8	1 15.56	77 19.45	3.51	0.47
280	97011814	23	41	11.16	1 13.57	77 21.77	3.31	0.44
281	97012315	9	10	29.88	1 15.69	77 19.52	4.53	0.62
282	97020201	1	18	52.36	1 14.94	77 20.84	5.8	0.33
283	97021401	0	23	38.43	1 15.50	77 19.77	5.74	0.72
284	97022214	17	1	38.43	1 16.44	77 21.49	4.32	0.96
285	9703020f	9	47	33.51	1 16.12	77 19.74	6.04	1.6
286	9703051s	18	36	17.66	1 16.50	77 21.49	4.53	0.71

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
287	9703051u	18	47	20.5	1 16.44	77 21.50	4.05	0.99
288	97030607	3	35	20.26	1 15.77	77 20.04	4.97	0.78
289	9703085k	17	16	33.56	1 16.39	77 21.50	4.41	1
290	97031910	20	52	52.68	1 15.74	77 20.53	4.85	0.12
291	9703220a	4	41	10.77	1 15.93	77 17.22	7.81	0.72
292	97032213	15	19	10.89	1 16.14	77 21.52	3.9	1.09
293	9704040m	14	0	15.32	1 15.64	77 21.11	4.01	0.6
294	9704041b	22	10	38.71	1 15.55	77 21.24	3.77	0.52
295	9704140r	11	58	35.85	1 15.90	77 19.00	4.94	0.76
296	97041500	0	27	56.06	1 16.19	77 20.35	6.56	0.98
297	9704171f	14	4	17.35	1 16.12	77 19.80	7.89	0.92
298	97041818	16	35	35.94	1 16.30	77 21.48	4.65	0.71
299	97042112	13	58	54.9	1 15.52	77 19.39	4.01	0.59
300	9704290n	16	21	46.33	1 16.39	77 21.35	4.78	1.28
301	9704300z	22	45	18.55	1 15.90	77 19.98	5.39	1.11
302	97051126	20	17	30.31	1 15.89	77 19.36	5.48	0.87
303	9705197t	18	29	47.13	1 14.90	77 21.05	5	0.66
304	9705215h	18	26	48.84	1 16.19	77 18.87	7.72	0.93
305	9705221s	12	24	21.83	1 16.45	77 21.34	5.13	0.83
306	9705221z	16	56	45.56	1 16.50	77 21.37	4.66	1.03
307	9705260c	10	42	3.64	1 16.42	77 21.49	4.37	0.85
308	97060300	0	3	43.92	1 14.58	77 20.97	5.67	0.91
309	9706170l	16	16	0.47	1 16.43	77 21.29	4.67	0.93
310	9706220t	13	51	58.77	1 16.46	77 21.48	4.83	0.76
311	9706260g	12	31	33.38	1 16.60	77 21.13	6.43	0.96
312	970718im	16	20	28.54	1 16.37	77 21.64	5.26	1.36
313	9708215i	16	27	31.44	1 16.10	77 21.41	3.84	1.1
314	97091214	15	46	44.68	1 16.28	77 20.98	5.83	1.3
315	9709130a	7	32	32.41	1 16.20	77 21.11	2.9	0.76
316	97092000	0	23	11.71	1 12.83	77 24.00	3.59	0.75

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
317	971226by	14	50	23.09	1 16.35	77 21.58	4.37	1.06
318	9712260f	0	40	59.47	1 15.64	77 19.84	5.04	0.85
319	9712261y	4	24	19.56	1 14.02	77 23.30	1.51	0.4
320	9801201o	15	18	52.38	1 16.41	77 21.65	4.74	0.97
321	9801271m	14	40	59.48	1 16.06	77 21.31	4.07	0.97
322	98012723	17	11	38.08	1 15.87	77 19.94	5.56	0.79
323	9802031a	10	19	5.13	1 16.30	77 21.63	4.11	0.92
324	98020406	2	13	15.67	1 15.53	77 20.36	5.7	0.91
325	9802181m	11	52	19.53	1 15.51	77 20.35	4.71	0.17
326	98021906	4	25	45.54	1 14.08	77 20.89	5.08	0.62
327	98021927	13	58	14.05	1 13.10	77 23.12	1.97	0.66
328	9802220d	11	8	34.47	1 13.76	77 21.80	2.46	0.18
329	9802230t	10	22	26.47	1 15.48	77 19.50	5.8	0.31
330	9802231m	18	18	16.56	1 13.05	77 21.78	0.95	1.08
331	9802231w	22	47	31.74	1 15.31	77 21.15	5.13	0.21
332	98030101	0	39	24.79	1 15.33	77 20.59	4.9	0.33
333	9803040u	7	22	2.56	1 14.99	77 20.26	5.08	0.41
334	98030610	9	31	8.92	1 15.43	77 17.82	8.06	0.83
335	98031810	8	16	7.16	1 13.23	77 20.67	5.12	0.46
336	9804090e	4	56	18.63	1 15.57	77 18.58	9.75	1.07
337	9804145q	22	4	57.32	1 14.10	77 21.15	3.45	0.43
338	98042908	8	34	5.08	1 15.90	77 19.85	6.63	0.59
339	98052509	6	5	1.15	1 15.77	77 19.55	8.35	1.45
340	98052555	17	19	14.44	1 14.86	77 21.30	5.6	0.28
341	98052708	4	12	55.77	1 14.58	77 21.25	6.01	0.6
342	98052968	15	39	6.52	1 16.38	77 21.49	4.39	0.86
343	9806020o	11	25	0.02	1 13.06	77 21.71	1.36	0.18
344	9806111j	16	51	3.57	1 14.60	77 20.32	6.8	0.41
345	9806267m	19	22	21.1	1 17.06	77 18.60	9.02	0.37
346	98071300	1	25	42.47	1 15.74	77 20.53	4.87	0.73

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
347	980716a6	22	51	39.17	1 13.34	77 21.60	4.02	0.87
348	980722dm	15	42	31.17	1 15.64	77 19.87	6.01	0.12
349	980722dn	15	42	56.99	1 15.63	77 19.26	5.01	0.53
350	98072332	14	22	14.91	1 15.79	77 19.97	5.47	0.75
351	9807254m	15	52	55.51	1 15.41	77 20.29	5.04	0.67
352	9808100e	5	20	34.22	1 13.92	77 21.24	4.39	0.18
353	9808155v	14	49	40.29	1 16.44	77 21.57	4.39	1.12
354	98081669	17	44	34	1 16.10	77 18.80	6.44	1.02
355	9808210e	1	57	10.92	1 11.94	77 21.16	4.1	0.51
356	98082350	11	5	59.96	1 14.89	77 20.48	3.57	0.55
357	9808270j	4	14	53.18	1 13.31	77 21.94	0.51	0.4
358	9903124s	19	38	36.76	1 15.45	77 19.61	5.67	0.39
359	9903220l	13	3	12.3	1 12.80	77 21.88	5.81	0.2
360	9903265q	15	18	43.27	1 14.25	77 23.46	4.41	0.26
361	9903295r	22	37	17.79	1 15.18	77 19.20	5.84	0.28
362	99042529	23	35	39.58	1 16.24	77 18.41	7.25	1.06
363	9905040e	9	19	30.05	1 13.14	77 24.91	6.09	0.55
364	9905089i	16	19	49.5	1 15.79	77 17.16	6.58	0.37
365	9905230s	11	17	30.49	1 15.82	77 19.25	4.75	0.79
366	99061400	2	7	19.43	1 16.61	77 19.62	6.54	1.21
367	99062600	0	4	53.19	1 15.76	77 19.96	5.73	0.27
368	99062664	16	53	16.77	1 15.35	77 19.59	5.18	0.96
369	9906290e	2	37	22.16	1 15.32	77 17.62	7.32	0.52
370	9907124z	15	39	44.7	1 16.57	77 19.59	9.14	1.01
371	99071608	6	30	19.68	1 16.49	77 19.95	7.65	1.24
372	9912026n	16	11	46.71	1 15.80	77 19.52	7.03	1.27
373	9912080m	8	43	6.03	1 17.51	77 19.88	7.26	0.75
374	99121002	2	8	31.09	1 15.43	77 19.55	6.02	1.28
375	9912292d	14	9	58.08	1 13.44	77 21.61	2.08	0.92
376	10636	21	16	46.25	1 15.87	77 19.87	7.91	1.54

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
377	0001200d	3	39	56.05	1 16.62	77 24.05	3.86	0.97
378	12064	23	17	40.39	1 15.98	77 19.48	7.99	0.77
379	22703	2	21	8.08	1 13.44	77 21.56	2.16	1.06
380	00022811	8	28	58.14	1 13.27	77 21.74	0.8	0.92
381	30409	5	40	8.09	1 16.13	77 19.48	7.96	0.83
382	31312	7	45	23.85	1 13.44	77 21.92	1.17	0.29
383	000406ch	23	41	31.81	1 15.27	77 19.74	8.18	1.76
384	41010	4	44	58.79	1 16.47	77 19.95	6.56	0.75
385	0004105v	23	48	58.18	1 12.98	77 23.18	2.44	0.41
386	41910	5	38	16.2	1 15.85	77 18.36	6.08	0.97
387	0004205y	12	28	21.21	1 15.41	77 17.20	7.96	1.4
388	0004207l	21	12	32.92	1 12.13	77 20.38	4.94	0.44
389	0005011d	12	1	27.06	1 16.25	77 19.82	5.24	0.56
390	0006040g	0	51	12.26	1 15.87	77 17.20	8.41	0.94
391	0006177b	21	7	5.56	1 16.72	77 19.09	8.11	1.18
392	000630g4	19	38	43.31	1 16.21	77 20.60	6.01	0.68
393	72202	3	3	31.18	1 15.77	77 19.36	6.14	0.33
394	0007313o	15	59	5.85	1 15.25	77 17.73	7.49	0.81
395	0008023z	15	18	44.3	1 15.45	77 17.59	7.65	1.34
396	000804cd	21	14	14.18	1 16.60	77 18.24	8.16	0.73
397	0008055b	19	57	30.16	1 15.39	77 19.40	9.3	0.98
398	0008233j	22	32	16.1	1 15.92	77 19.97	5.35	1.21
399	010620a4	21	20	52.23	1 15.32	77 19.56	5.48	0.38
400	0105110u	5	8	35.44	1 16.41	77 20.98	6.71	0.96
401	0105144s	20	49	43.72	1 17.67	77 19.48	7.74	0.69
402	0106018k	18	20	56.83	1 16.34	77 20.09	6.48	0.85
403	010612es	22	54	11.25	1 16.33	77 20.19	5.1	0.48
404	1061660	19	4	5.17	1 16.26	77 19.92	7.7	0.76
405	0106194v	14	19	4.25	1 14.83	77 19.63	7.61	1.15
406	1062000	0	40	32.07	1 14.63	77 19.40	6.34	1.03

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
407	1062011	8	10	54.12	1 15.35	77 17.81	6.91	0.82
408	1050124	7	54	12.25	1 16.24	77 20.06	5.5	0.84
409	1093008	4	18	56.9	1 16.33	77 20.66	4.53	0.5
410	01071351	22	23	58.53	1 16.38	77 18.63	5.46	1.1
411	010820ac	13	15	4.03	1 16.18	77 20.27	5.72	1.01
412	010820ae	13	16	5.07	1 15.97	77 20.19	6.74	1.01
413	0108220h	2	2	45.86	1 16.22	77 18.09	6.05	0.79
414	0108220n	2	44	33.22	1 16.34	77 18.42	5.86	0.6
415	0109031h	11	43	39.2	1 15.39	77 17.02	8.13	0.86
416	1091105	3	58	6.63	1 16.85	77 18.39	7.8	0.83
417	0109110b	4	59	52.41	1 16.75	77 18.25	7.82	0.78
418	0107135e	21	27	22.48	1 16.67	77 18.87	5.73	1.1
419	0110121k	16	11	44.06	1 16.29	77 20.73	4.56	0.78
420	1100915	9	23	10.31	1 16.26	77 20.95	4.97	1.06
421	1100121	16	11	43.89	1 16.44	77 20.67	5.28	0.72
422	1101404	2	54	33.92	1 12.90	77 22.98	4.98	0.17
423	011031ap	20	6	22.49	1 15.25	77 24.14	8.17	0.9
424	0111083p	11	6	49.79	1 12.71	77 23.34	4.24	0.11
425	1111605	2	49	40.08	1 16.68	77 19.83	6.05	1.77
426	0111173k	18	48	53.01	1 16.69	77 18.98	8.76	1.28
427	011202io	21	28	38.14	1 15.76	77 18.52	7.65	0.93
428	1121110	9	38	34.27	1 13.90	77 20.85	5.95	0.09
429	0112182h	20	48	9.43	1 14.83	77 19.34	6.04	0.95
430	0112201v	23	7	7.23	1 16.47	77 20.58	4.8	0.89
431	0203140r	19	11	54.23	1 13.13	77 20.75	5.92	0.1
432	0204080a	5	8	14.6	1 13.39	77 21.56	0.78	0.74
433	0204083g	15	41	50.2	1 15.11	77 19.57	5.36	0.67
434	2041705	5	32	14.59	1 13.69	77 21.67	2.38	0.74
435	2041900	2	54	54.01	1 13.72	77 21.38	3.27	0.16
436	0206101y	9	56	18.8	1 13.13	77 21.84	4.13	-0.03

N	Code	Origin Time			Latitude	Longitude	Depth	Mag.
	yymmddx	H	M	S	Deg. Min.	Deg. Min.	km	
437	2061026	10	14	23.02	1 13.41	77 22.08	1.41	0.22
438	2061031	11	59	25.86	1 13.28	77 22.15	2.65	0.1
439	0206103a	12	21	12.49	1 13.34	77 22.07	2.29	-0.13

APPENDIX C. PROGRAM CODE

The C++ code written for solving the coda waves' envelopes inversion problem by means of the Back-Projection algorithm is attached. A free version of Borland C++ (BuilderX [3]) and a commercial compiler as Microsoft Visual C++ [4] was used to assure a high compatibility. The program reads data from text files. How data is organized is easily deduced by reading the program.

```
/***************************************************************************\
*                                                                           *
*                         BACKPROJECTION ALGORITHM                          *
*                                                                           *
\***************************************************************************/

 #define PIMITJ 1.57079632679489661923l322
 #define PI 3.141592654


 #include <stdlib.h>
 #include <string.h>
 #include <stdio.h>
 #include <math.h>
 #include <malloc.h>
 #include <time.h>
 #include <dos.h>
 #include "nrutil2.h"
 #include "fresnel.h"

void main(void)
{

 FILE *fp, *fp2;
 FILE *fp1,*fp3;
 char buffer[10];
 int i, j, k, ns, nt, t, n, m, s,count=0, ii, jj, kk, radi, int_ssx, int_ssy, ch;
 int int_x, int_y, *nr,nrr;
 int ndat,num, num1,num2,rec,cuenta_elipses;
 unsigned char **IMA;
 float **res,*b;
 long int nx,ny,nz;
 double cx1,cy1,cx2,cy2,dt,cz,vmax=0.0,vmin=0.0, vmed=0.0,alea;
 double *sx,*sy,*sz,*ex,*ey,*ez,*time,dato, *vec, *a, *af;
 double x, y, z, ssx, ssy,ssz,correccio_alsada;
 double lx, ly, unitat_x, unitat_y, unitat_z, escala_y, escala_y2, escala_z, escala_z2;
 double velocitat1, velocitat2,temps,distancia1,distancia2,distancia,tempo;
 double tini;
 double semi_a,semi_b,exc, r, L, area, valor_mig, factor_elipse, cont;


 /****************************************************
  *****    DEFINITION OF IMPORTANT VARIABLES      ****
  ****************************************************

    (cx1,cy1)                origin coordinates
    (cx2,cy2)                end coordinates
    cz                       maximum depth
    nx                       number of blocks direction x
    ny                       number of blocks direction y
    nz                       number of blocks direction z
    ns                       number of seismografs
    nt                       number of events
    t                        maximum number of time intervals
    dt                       time interval

    (sx[],sy[],sz[])         coordinates of seismograms

    (ex[],ey[],ez[])         coordinates of events

    nr[]                     number of residues for each event
    vec[]                    residues of one event
    a[]                      result of inversion

    vmax                     maximum of a[]
    vmin                     minimum of a[]
    vmed                     average of a[]

    unitat_x                 longitutude of a block in x direction
    unitat_y                 longitutude of a block in y direction
    unitat_z                 longitutude of a block in z direction
```

```
  cuenta_elipses           number of residues of a certain block

*********************************************************************/

printf("/*********************************************************/\n");
printf("/*                                                       */\n");
printf("/*               BACKPROJECTION IN ACTION                */\n");
printf("/*                                                       */\n");
printf("/*                      Version 2.0                      */\n");
printf("/*                                                       */\n");
printf("/*                 Observatori de l'Ebre                 */\n");
printf("/*                                                       */\n");
printf("/*                  By: Eduard Carcol%c                   */\n",130);
printf("/*                                                       */\n");
printf("/*********************************************************/\n");

printf("\n\n\t Press any key to continue....\n\n");
getchar();

printf("\n\n\tVELOCITY MODEL:\n\n");

printf("\n\t z = 4.2    v = %.2f ",velocity1(4.2));
printf("\n\t z = 3.2    v = %.2f ",velocity1(3.2));
printf("\n\t z = 2.2    v = %.2f ",velocity1(2.2));
printf("\n\t z = 1.0    v = %.2f ",velocity1(1.0));
printf("\n\t z = 0.2    v = %.2f ",velocity1(0.2));
printf("\n\t z = -2.0   v = %.2f ",velocity1(-2.0));
printf("\n\t z = -3.8   v = %.2f ",velocity1(-3.8));
printf("\n\t z = -10    v = %.2f ",velocity1(-10.0));
printf("\n\t z = -21.8  v = %.2f ",velocity1(-21.8));
printf("\n\t z = -30    v = %.2f ",velocity1(-30));
printf("\n\t z = -39.8  v = %.2f ",velocity1(-39.8));
printf("\n\t z = -50.0  v = %.2f ",velocity1(-50.0));

printf("\n\n\n\n\n\tPress any key to continue....\n\n");
getchar();

/**** open and read data ****/

fp=fopen("datos.dat","r");

fscanf(fp,"%lf",&cx1);fscanf(fp,"%lf",&cy1);
fscanf(fp,"%lf",&cx2);fscanf(fp,"%lf",&cy2);
fscanf(fp,"%lf",&cz);

fscanf(fp,"%li",&nx); fscanf(fp,"%li",&ny); fscanf(fp,"%li",&nz);

fscanf(fp,"%i",&ns);

fscanf(fp,"%i",&nt);

fscanf(fp,"%i",&t);

fscanf(fp,"%lf",&dt);

/**** memory allocation ****/

sx =(double *) dvector (ns);
sy =(double *) dvector (ns);
sz =(double *) dvector (ns);
ex =(double *) dvector (nt);
ey =(double *) dvector (nt);
ez =(double *) dvector (nt);
a = (double  *)dvector(nx*ny*nz);
b = (float  *)dvector(nx);
af = (double  *)dvector(nx*ny*nz);
res = (float **) hfmatrix(0, nt*ns ,0,t);
vec = (double *) dvector(t);
time =(double *) dvector (ns*nt);
IMA = (unsigned char  **)hcmatrix(0,ny,0,nx);
nr = (int *) ivector(0,ns*nt);
```

```
 if(sx == NULL || sy == NULL || sz == NULL
  || ex == NULL || ey == NULL || ez == NULL
  || time == NULL || a == NULL || vec == NULL || res == NULL || IMA == NULL
  || af == NULL || nr == NULL)
 {printf("oooooh!!!!!");exit(0);}

 /**** reading coordinates of stations ****/

 for(i=0;i<ns;i++){
  fscanf(fp,"%lf",&dato);sy[i]=dato;
  fscanf(fp,"%lf",&dato);sx[i]=dato;
  fscanf(fp,"%lf",&dato);sz[i]=dato;

 }

 /**** reading coordinates of events ****/

 for(i=0;i<nt;i++){
  fscanf(fp,"%lf",&dato);ex[i]=dato;
  fscanf(fp,"%lf",&dato);ey[i]=dato;
  fscanf(fp,"%lf",&dato);ez[i]=dato;
 }

 fclose(fp);


/**** screen output of data ****/

 printf("\ncx1 = %lf;",cx1);
 printf("   cy1 = %lf",  cy1);
 printf("\ncx2 = %lf;",cx2);
 printf("   cy2 = %lf",  cy2);
 printf("\ncz = %lf; ",cz);
 printf("\nnx = %li;",nx);
 printf("   ny = %li ; ",ny);
 printf("nz = %li; ",nz);
 printf("\nns = %i;",ns);
 printf("   nt = %i",nt);
 printf("\nt = %i;",t);
 printf("   dt = %lf",dt);

 printf("\n\n") ;

 for(i=0;i<ns;i++){
    printf("\rsx = %lf; sy = %lf; sz = %lf",sx[i],sy[i],sz[i]);
 }

 printf("\n\n");

 for(i=0;i<nt;i++){
    printf("\rex = %lf; ey = %lf; ez = %lf",ex[i],ey[i],ez[i]);
 }

 printf("\n");


/**** opening file of residues ****/

 fp=fopen("residual.dat","r");

 /**** reading number of events ****/

 fscanf(fp,"%i",&ndat);
 printf("\n ndat = %i",ndat);

 /**** reading residues ****/

 rec = 4;
 for(i=0;i<nt;i++){
  for(j=1;j<(ns+1);j++){

    fscanf(fp,"%i",&num);
```

```
    fscanf(fp,"%i",&num2);
    fscanf(fp,"%i",&nrr);
    fscanf(fp,"%lf",&tini);

    for(k=0;k<nrr;k++) {fscanf(fp,"%lf",&dato); vec[k]=dato; }

    count=count+1;

    if(count>ndat) break;

    if(num > rec && j!=1) i++;

    if(num2 != j ) {
       j=num2;

       time[(j-1)+i*ns]=tini;
       nr[(j-1)+i*ns] = nrr;
       for(k=0;k<nrr;k++) res[(j-1)+i*ns][k]=vec[k];
    }
    else {
      time[(j-1)+i*ns]=tini;
      nr[(j-1)+i*ns] = nrr;
      for(k=0;k<nrr;k++) res[(j-1)+i*ns][k]=vec[k]; }
        printf("\rSisme = %d; Sismog. = %d; T_Ini = %.1lf;  N_Sismes = %d; N_Sismog. =
            %d"
        ,num,num2,tini, i,j);
        rec = num;
      }
 }

 fclose(fp);

 /**** computation starts *****/

 printf("\n\n\nCalculating...\n\n");

 /**** definitions and conversions ****/

  cx1 = cx1*111.0;  cx2 = cx2*111.0;   cy1 = cy1*111.0;   cy2 = cy2*111.0;
  lx = cx2-cx1; ly = cy2-cy1;

  /**** adimensional lengths ****/

  unitat_x = lx/nx;
  unitat_y = ly/ny;
  unitat_z = cz/nz;

  escala_y = unitat_y/unitat_x;
  escala_z = unitat_z/unitat_x;

  escala_y2= escala_y*escala_y;
  escala_z2= escala_z*escala_z;

  /**** screen output of units of length ****/

  printf("\nunitat_x = %lf; ",unitat_x); printf("unitat_y = %lf; ",unitat_y);
  printf("unitat_z = %lf\n",unitat_z);
  printf("\nescala_y = %lf; ",escala_y); printf("escala_z = %lf; ",escala_z);
  printf("\n\n");


/************************* INVERSION *******************************************/
/************************  n number of events         ************************/
/************************  m number of time intervals ************************/
/************************  i corresponds to x         ************************/
/************************  j corresponds to y         ************************/
/************************  k corresponds to z         ************************/

/**** output to file resultat.txt in text format ****/

 fp = fopen("resultat.txt","w");
 fprintf(fp,"%li\n", nx*ny*nz );
```

```
printf("\n");
fprintf(fp,"\n");


/* definition of a parameter that indicates the minimum depth of the computation */

correccio_alsada = 4.5/unitat_z;

//correccio_alsada = 0.0;

for(k=0;k<nz;k++){ printf("seccio %i\r",k);

if(k==0){
  correccio_alsada = 4.5/unitat_z;
} else {
    correccio_alsada = 5.0/unitat_z;
}

 for(j=0;j<ny;j++){
   for(i=0;i<nx;i++){

   a[i+j*nx+k*ny*nx]=0.0;
       cont =0;
   cuenta_elipses = 0;

   for (n=0;n<nt;n++){

       x   = ex[n]*111.0; y   = ey[n]*111.0; z = ez[n];

       velocitat2 =
            velocity2((-1.0)*(k-correccio_alsada+0.5)*unitat_z,z)/unitat_x;

       x = (x-cx1)/unitat_x;
       y = (y-cy1)/unitat_y;
       z = z /unitat_z;

       for(s=0;s<ns;s++){

       if(time[n*ns+s]<0.1) continue;

           ssx = sx[s]*111.0; ssy = sy[s]*111.0; ssz = sz[s];

               velocitat1 = velocity2((-1.0)
                            *(k-correccio_alsada+0.5)*unitat_z,ssz)/unitat_x;

           ssx = (ssx-cx1)/unitat_x;
           ssy = (ssy-cy1)/unitat_y;
           ssz = (ssz)/unitat_z;

           /**** distance HYPOCENTER-STATION ****/

           r = sqrt( pow(x-ssx,2)
              +escala_y2*pow(y-ssy,2)
              +escala_z2*pow(z-ssz,2));

           /**** distance HIPOCENTER-BLOCK (i,j) ****/

           distancia2 = sqrt( pow(x-(i+0.5),2)
                  + escala_y2*pow(y-(j+0.5),2)
                  + escala_z2*pow(z-(-1.0)*(k-correccio_alsada+0.5),2));

           /**** distance STATION-BLOCK (i,j) ****/

           distancia1 = sqrt( pow(ssx-(i+0.5),2)
                  + escala_y2*pow(ssy-(j+0.5),2)
                  + escala_z2*pow(ssz-(-1.0)*(k-correccio_alsada+0.5),2));

           /**** parameters ****/

           L = distancia1 + distancia2;
           exc = r/L;semi_b = L/2.0;
           semi_a = sqrt(pow(semi_b,2)-pow((r/2.0),2));
```

```
            area = 2.0*PI*semi_a*semi_a + 2.0*PI*(semi_a*semi_b/exc)*asin(exc);
            valor_mig = (4.0*PI/(L*r))*log((L+r)/(L-r));
            valor_mig = valor_mig/area;
            factor_elipse = (pow(1.0/(distancia1*distancia2),2)/valor_mig);

            /**** time corresponding to event n of station s ****/

            tempo = distancia1 / velocitat1  + distancia2/velocitat2;

            /**** number tof the residue to needed for average ****/

            m = ceil(  (tempo-(time[n*ns+s]+dt/2.0))/dt  );
            t = nr[n*ns+s];

            /**** average ****/

            if(m>=1 && m<t){
              temps = time[n*ns+s]+dt/2.0+m*dt;
              a[i+j*nx+k*ny*nx] = a[i+j*nx+k*ny*nx]
                 +(factor_elipse)*(   res[n*ns+s][m]*(temps-tempo)
                   + res[n*ns+s][m-1]* ( tempo-(temps-dt) ))/dt;
              cont = cont + factor_elipse;
              cuenta_elipses++;
            }
        }
      }

      if (cont != 0) a[i+j*nx+k*ny*nx] = a[i+j*nx+k*ny*nx]/(cont*1.0);
      else a[i+j*nx+k*ny*nx]=1.0;

      /**** Counting residues instead of inversion ****/

      // if(cont < 10) a[i+j*nx+k*ny*nx] = 0.0;
         // a[i+j*nx+k*ny*nx]=cuenta_elipses;

      }
    }
}

 /**** statistics of inversion ****/

 for(k=0;k<nz;k++){
  for(j=0;j<ny;j++){
      for(i=0;i<nx;i++){
       vmed = vmed + a[i+j*nx+k*ny*nx]/(nx*ny*nz*1.0);
         if(vmax<a[i+j*nx+k*ny*nx]) vmax=a[i+j*nx+k*ny*nx];
             if(vmin>a[i+j*nx+k*ny*nx]) vmin=a[i+j*nx+k*ny*nx];
      }
   }
  }

 /**** output to text file ****/

 for(k=0;k<nz;k++){
   for(j=0;j<ny;j++){
        for(i=0;i<nx;i++){
             fprintf(fp,"%lf\n ",a[i+j*nx+k*ny*nx]);
      }
   }
 }
 fprintf(fp,"\n");
 fclose(fp);

 /*****************************************************************/

 /**** Output to binary file ****/

 fp3 = fopen("resultat.raw","wb");

 for(k=0;k<nz;k++){
   for(j=0;j<ny;j++){
      for(i=0;i<nx;i++){
```

```
                 b[i] = a[i+j*nx+k*ny*nx];
         }
         fwrite(b,sizeof(float),nx,fp3);
    }
  }
  fclose(fp3);

  /**** Files for Surfer ****/
  /**** horitzontal sections ****/

  printf("\n");
  for(n=0;n<nz;n++){

   sprintf(buffer, "secc%i.dat", n);
   printf("%s\r",buffer);
   fp=fopen(buffer,"w");

   for(i=0;i<nx;i++){
      for(j=0;j<ny;j++){
      fprintf(fp,"%lf %lf %f\n",
        (cx1 + ((cx2-cx1)/nx)*i + ((cx2-cx1)/nx)/2.0)/111.0,
        (cy1+((cy2-cy1)/ny)*j+((cy2-cy1)/ny)/2.0)/111.0,
        a[i+j*nx+n*ny*nx]-1.0);
      }
   }

   fclose(fp);

  }

  /**** Vertical sections ****/

  printf("\n");
  for(j=0;j<ny;j++){

   sprintf(buffer, "tall%i.dat", j);
   printf("%s\r",buffer);
   fp=fopen(buffer,"w");

   for(i=0;i<nx;i++){
      for(n=0;n<nz;n++){
      fprintf(fp,"%lf %lf %f\n",
        (cx1+((cx2-cx1)/nx)*i+((cx2-cx1)/nx)/2.0)/111.0,
        (n*cz/nz + 0.5*cz/nz),
        a[i+j*nx+n*ny*nx]-1.0);
      }
   }

   fclose(fp);

  }

  printf("\n vmax = %lf, vmin = %lf, vmed = %lf", vmax, vmin, vmed);

  fp=fopen("resultat.txt","a");
  fprintf(fp,"\n vmax = %lf, vmin = %lf, vmed = %lf", vmax, vmin, vmed);
  fclose (fp);

 /**** conversion inversion to .RAW image (for Photoshop) ****/

  for(k=0;k<nz;k++){
   for(j=0;j<ny;j++){
     for(i=0;i<nx;i++){
            af[i+j*nx+k*ny*nx] = a[(nx-1-i)+(ny-1-j)*nx+k*ny*nx];
     }
   }
  }

  for(k=0;k<nz;k++){
   for(j=0;j<ny;j++){
     for(i=0;i<nx;i++){
            a[i+j*nx+k*ny*nx] = af[i+j*nx+k*ny*nx];
```

```
    }
  }
 }

 /**** Horizontal seccions ****/

 printf("\n");
 for(n=0;n<nz;n++){

  sprintf(buffer, "secc%i.raw", n);
  printf("%s\r",buffer);
  fp=fopen(buffer,"wb+");

  for(i=0;i<nx;i++){
     for(j=0;j<ny;j++){
     IMA[j][i]=255.0*(a[i+j*nx+n*nx*ny]-vmin)/(vmax-vmin);
     }
  }

  for ( i=0; i<ny; i++ ) fwrite((void*)IMA[i], 1, nx, fp);
  fclose(fp);
 }


/**** vertical sections ****/

 printf("\n");
 for(j=0;j<ny;j++){

  sprintf(buffer, "tall%i.raw", j);
  printf("%s\r",buffer);
  fp=fopen(buffer,"wb+");

  for(i=0;i<nx;i++){
     for(n=0;n<nz;n++){
     IMA[n][i]=255.0*(a[i+j*nx+n*nx*ny]-vmin)/(vmax-vmin);
     }
  }
  for ( i=0; i<nz; i++ ) fwrite((void*)IMA[i], 1, nx, fp);


  fclose(fp);
 }
/**********************************************/


}

/**** computes average of two velocities ****/

double velocity2 (double z1,double z2){

 return((velocity1(z1)+velocity1(z2))/2.0);

}

/***** velocity at a certain depth (by interpolating) ****/

double velocity1 (double z){

 if( z>=4.2 )
 return (1.966);

 else if( z<4.2 && z>= 2.2 )
 return ( ((1.966-2.079)/2.0)*z + 1.966 - ((1.966-2.079)/2.0)*4.2 );

 else if( z<2.2 && z>=0.2 )
 return( ((2.079-2.247)/2.0)*z + 2.079 - ((2.079-2.247)/2.0)*2.2 );

 else if( z<0.2 && z>=(-3.8))
 return( ((2.247-3.371)/4.0)*z + 2.247 - ((2.247-3.371)/4.0)*0.2 );
```

```
else if( z<(-3.8) && z>=(-21.8))
return( ((3.371-3.820)/18.0)*z+ 3.371 - ((3.371-3.820)/18.0)*(-3.8) );

else if(z<(-21.8) && z>=(-39.8))
return( ((3.820-4.494)/18.0)*z+ 3.820 - ((3.820-4.494)/18.0)*(-21.8) );

else if(z<(-39.8))
return(4.494);

}
```

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