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IMPROVED DIGITAL FILTERS FOR THE CALCULATION OF SCHLUMBERGER SOUNDING CURVES BY CONVOLUTION

by

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INTRODUCTION

Schlumberger apparent resistivities for a horizontally stratified earth are calculated by taking the Hankel transform of the resistivity transform function. After Ghosh (1971a) demonstrated that the Hankel transform can be computed using digital convolution, many digital filters have been published (Ghosh, 1971b; O'Neill, 1975; Johansen, 1975; Koefoed and Dirks, 1979; Anderson, 1979).

The accuracy of digital convolution is dependent upon the filter sampling rate, the filter length, and the noise in the filter coefficients. Murakami and Uchida (1982) have shown that the reduction of noise in the filter coefficients will result in shorter filters.

A computer subroutine, called APPRES, uses improved filter coefficients calculated using the Murakami and Uchida technique, to calculate Schlumberger apparent resistivities.

PROBLEM DESCRIPTION

The Schlumberger apparent resistivity ρ_a is obtained by

$$\rho_a(r) = r^2 \int_0^\infty T(\lambda) J_1(\lambda r) \lambda d\lambda \qquad (1)$$

where r is AB/2 and $T(\lambda)$ is the resistivity transform.

The resistivity transform for a n-layer horizontally stratified earth is calculated through the recursive formula:

$$T_N = \rho_N \qquad (2a)$$

$$T_{n-1} = \rho_n \frac{1-R}{1+R} \qquad (2b)$$

$$R = \frac{\rho_n - T_n}{\rho_n + T_n} \exp(-2\lambda h_n), \quad n=N-1, N-2, \ldots\ldots, 1 \qquad (2c)$$

$$T(\lambda) = T_1 \tag{2d}$$

where ρ_n and h_n are the resistivity and thickness of the n-th layer, respectively.

The integration in equation(1) is rearranged into the convolution form (Ghosh, 1971a; Johansen, 1975):

$$\rho_a(r) = \sum_J T\left(\frac{e^{y_J}}{r}\right) C_{12}(J) \tag{3}$$

where $C_{12}(J)$ is the sampled value at abscissa y_J of the sinc response $G_{12}(y)$ of the filter function:

$$C_{12}(J) = G_{12}(y_J) \tag{4}$$

where

$$G_{12}(y) = \int_{-\infty}^{\infty} \frac{\sin(\eta-y)}{\eta-y} J_1(e^{\eta}) e^{2\eta} d\eta \tag{5}$$

and D=(ln 10)/NS is the sampling interval with NS being the number of sampling points per log decade. Because of the rapid decay of the filter coefficients, only a finite number of terms are necessary for the summation in equation (3):

$$\rho_a(r) = \sum_{J=1}^{NC} T\left(\frac{\exp(y_J)}{r}\right) C_{12}(J) \tag{6}$$

where NC is the number of filter coefficients.

Substituting $y_J = y_1-(J-1)D$ and $\exp(D)=\exp(\ln 10/NS)=10^{1/NS}=F$, equation (6) is rewritten as:

$$\rho_a(r) = \sum_{J=1}^{NC} T\left(\left(\frac{\exp(y_1)}{r}\right)F^{-(J-1)}\right)C_{12}(J) \qquad (7)$$

Thus the calculation of the apparent resistivity for ND data points requires NDNC estimations of the resistivity transform.

If the apparent resistivity is calculated at logarithmic intervals equal to the filter sampling interval D, a large saving in computation time occurs. Substituting $r=r_1\exp((I-1)D)$ in equation (7) we obtain:

$$\rho_a(r_1)=\sum_{J=1}^{NC} T\left(\left(\frac{\exp(y_1)}{r_1}\right)F^{-(I+J-2)}\right)C_{12}(J) \qquad (8)$$

where the resistivity transform is evaluated only (NC+ND−1) times.

SUBROUTINES

Two sets of digital filter coefficients are given in the Appendix as subroutines YM6 and YM10. These filters were calculated using the noise reduction technique described in Murakami and Uchida (1982). Filter YM6 is 28 coefficients long and is sampled at 6 points per log cycle. Filter YM10 is 70 coefficients long and is sampled at 10 points per log cycle. These subroutines are used to fill a common block (FLTR) with the filter coefficients, starting coordinate, number of coefficients and the filter spacing.

Subroutine APPRES, given in the Appendix, computes the Schlumberger apparent resistivity over a horizontally stratified earth. Subroutine APPRES is called in a user program by the FORTRAN statement:

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CALL APPRES(RES,THK,NL,AB,RHOA,ND,MODE)
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where the parameters are:

RES(NL)	:	RESISTIVITY OF EACH LAYER (input)
THK(NL-1)	:	THICKNESS OF EACH LAYER (input)
NL	:	NUMBER OF LAYERS OF EARTH MODEL (input)
AB(ND)	:	AB/2 (input)
RHOA(ND)	:	CALCULATED APPARENT RESISTIVITY (output)
ND	:	NUMBER OF DATA POINTS (input)
MODE	:	CALCULATION OPTION (see below)

If MODE is set to a negative integer, the apparent resistivities are calculated using equation 7 at abscissas given in array AB. If MODE is set to a positive integer, the apparent resistivities are evaluated using equation 8 at ND logarithmically equidistant points starting at AB(1).

Before the subroutine APPRES is called, the user should make a choice between filter YM6 or YM10. By putting either of the statements CALL YM6 or CALL YM10 in the main program somewhere before calling APPRES, the filter constants are stored in a named common block (FLTR).

In order to illustrate the usage of subroutines APPRES, YM6, and YM10, a driver program that compares the performance of the YM6 and YM10 filters with that of two widely used filters published by O'Neill (1975) and Johansen (1975) is provided in the APPENDIX. The filter coefficients and parameters for the O'Neill and Johansen filters are not presented here, but can be obtained from the respective publications.

FILTER ACCURACY

Tables 1 through 6 show the results obtained for different resistivity models using the driver program given in the Appendix. Values are generated using the O'Neill, YM6, Johansen, and YM10 filters. Anderson (1979) has shown that the Johansen filter is accurate for resistivity contrasts of greater than 10,000 to 1.

The filter ONEILL consists of 20 coefficients with a sampling distance of (ln10)/6 (O'Neill, 1975), and the filter JOHANS consists of 141 coefficients with a sampling distance of (ln10)/10.

Tables 1 through 6 also include the ratio of apparent resistivities calculated using the ONEILL, YM6 and JOHANS filters with respect to those calculated using the YM10 filter. The maximum resistivity contrast used in this report is 10,000 to 1. The JOHANS and YM10 filters give the same results throughout Tables 1 to 6, demonstrating that the YM10 filter is accurate for resistivity contrasts up to 10,000 to 1. Thus the YM10 filter, in spite of its size, can be used for almost all practical applications.

Table 1 shows the results of a of two layer model with a resistivity ratio of 1,000 to 1. The ONEILL filter gives a maximum error of about 24%, and the YM6 filter gives a maximum error of only 3.3%. For a resistivity ratio of 10,000 to 1, table 2 shows that the YM6 filter gives a maximum error of about 20% at the foot of the very steep downhill branch. Thus care must be taken when using the YM6 filter when the apparent resistivity curve will include a long, steep downhill branch.

Table 3 shows the results for a resistive subsurface with a contrast of 1 to 10,000. For this model all of the filters give satisfactory results. This is because, for horizontal layering, the apparent resistivity curve can not rise steeper than 45 degrees. Note that the JOHANS filter shows a little error at the beginning of the ascending branch. This is due to a noisy oscillation in JOHANS filter.

Tables 4 through 6 show the results for more complicated layering. These Tables confirm that YM6 filter gives satisfactory results except for a conductive subsurface that produces a long, steep downhill branch. Thus we conclude that YM6 filter can be used for most practical applications.

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TABLE 1

LAYER	RESISTIVITY	THICKNESS	DEPTH
1	1000.00	1.000	1.000
2	1.00		

AB/2	ONEILL	RATIO	YM6	RATIO	JOHANSEN	RATIO	YM10
1.0	843.78	1.000	843.65	1.000	843.59	1.000	843.59
1.5	635.21	1.000	635.01	1.000	635.01	1.000	635.01
2.0	428.59	1.000	428.32	1.000	428.39	1.000	428.39
2.5	267.99	1.001	267.77	1.000	267.79	1.000	267.79
3.0	159.10	1.001	159.00	1.001	158.90	1.000	158.90
4.0	51.04	1.004	51.11	1.005	50.85	1.000	50.85
5.0	15.62	1.012	15.63	1.012	15.44	1.000	15.44
6.0	5.17	1.037	5.06	1.013	4.99	1.000	4.99
7.0	2.29	1.093	2.08	0.994	2.09	1.000	2.09
8.0	1.51	1.148	1.27	0.967	1.31	1.000	1.31
10.0	1.24	1.181	1.03	0.978	1.05	0.999	1.05
15.0	1.22	1.206	1.03	1.014	1.01	0.999	1.01
20.0	1.22	1.209	1.00	0.994	1.01	1.000	1.01
25.0	1.22	1.215	1.01	1.001	1.00	1.000	1.01
30.0	1.23	1.223	1.01	1.006	1.00	1.000	1.00
40.0	1.23	1.229	1.00	1.001	1.00	1.000	1.00
50.0	1.23	1.233	1.00	1.001	1.00	1.000	1.00
60.0	1.24	1.236	1.00	1.003	1.00	1.000	1.00
70.0	1.24	1.238	1.00	1.003	1.00	1.000	1.00
80.0	1.24	1.239	1.00	1.002	1.00	1.000	1.00
100.0	1.24	1.237	1.00	1.001	1.00	1.000	1.00
150.0	1.22	1.220	1.00	1.002	1.00	1.000	1.00
200.0	1.19	1.193	1.00	1.002	1.00	1.000	1.00
250.0	1.17	1.166	1.00	1.002	1.00	1.000	1.00
300.0	1.14	1.144	1.00	1.002	1.00	1.000	1.00
400.0	1.11	1.112	1.00	1.002	1.00	1.000	1.00
500.0	1.09	1.091	1.00	1.002	1.00	1.000	1.00
600.0	1.08	1.076	1.00	1.002	1.00	1.000	1.00
700.0	1.07	1.066	1.00	1.002	1.00	1.000	1.00
800.0	1.06	1.058	1.00	1.002	1.00	1.000	1.00
1000.0	1.05	1.046	1.00	1.002	1.00	1.000	1.00

TABLE 2

LAYER	RESISTIVITY	THICKNESS	DEPTH
1	10000.00	1.000	1.000
2	1.00		

AB/2	ONEILL	RATIO	YM6	RATIO	JOHANSEN	RATIO	YM10
1.0	8435.29	1.000	8434.02	1.000	8433.41	1.000	8433.41
1.5	6346.51	1.000	6344.46	1.000	6344.50	1.000	6344.50
2.0	4277.48	1.000	4274.71	1.000	4275.50	1.000	4275.49
2.5	2669.67	1.001	2667.45	1.000	2667.70	1.000	2667.69
3.0	1579.87	1.001	1578.92	1.001	1577.94	1.000	1577.93
4.0	499.19	1.004	499.89	1.005	497.34	1.000	497.35
5.0	145.58	1.012	145.71	1.013	143.80	1.000	143.80
6.0	41.67	1.046	40.49	1.017	39.81	1.000	39.82
7.0	13.12	1.175	11.03	0.988	11.17	1.000	11.17
8.0	5.56	1.540	3.18	0.879	3.61	0.998	3.61
10.0	3.10	2.596	0.96	0.804	1.18	0.988	1.19
15.0	3.10	3.079	1.14	1.137	1.00	0.992	1.01
20.0	3.12	3.074	0.95	0.940	1.01	0.997	1.02
25.0	3.17	3.146	1.02	1.010	1.01	0.996	1.01
30.0	3.24	3.226	1.06	1.060	1.00	0.998	1.00
40.0	3.30	3.304	1.01	1.008	1.00	1.004	1.00
50.0	3.33	3.333	1.01	1.007	1.00	1.001	1.00
60.0	3.37	3.358	1.03	1.028	1.00	1.000	1.00
70.0	3.39	3.379	1.03	1.028	1.00	0.998	1.00
80.0	3.40	3.391	1.02	1.018	1.00	1.002	1.00
100.0	3.38	3.374	1.01	1.013	1.00	1.000	1.00
150.0	3.20	3.194	1.02	1.021	1.00	0.999	1.00
200.0	2.93	2.931	1.02	1.018	1.00	1.001	1.00
250.0	2.66	2.660	1.02	1.018	1.00	0.999	1.00
300.0	2.44	2.445	1.02	1.019	1.00	1.000	1.00
400.0	2.12	2.117	1.02	1.015	1.00	0.998	1.00
500.0	1.91	1.912	1.02	1.018	1.00	1.001	1.00
600.0	1.77	1.762	1.02	1.016	1.00	0.998	1.00
700.0	1.66	1.662	1.02	1.019	1.00	1.001	1.00
800.0	1.58	1.580	1.02	1.018	1.00	1.002	1.00
1000.0	1.46	1.463	1.02	1.015	1.00	0.999	1.00

TABLE 3

LAYER	RESISTIVITY	THICKNESS	DEPTH
1	1.00	1.000	1.000
2	10000.00		

AB/2	ONEILL	RATIO	YM6	RATIO	JOHANSEN	RATIO	YM10
1.0	1.22	0.999	1.23	1.000	1.23	1.002	1.23
1.5	1.58	0.999	1.58	1.000	1.58	1.000	1.58
2.0	2.02	0.999	2.02	1.000	2.02	0.999	2.02
2.5	2.50	0.999	2.51	1.000	2.50	0.999	2.51
3.0	3.00	0.999	3.00	1.000	3.00	1.000	3.00
4.0	3.99	0.999	4.00	1.000	4.00	1.000	4.00
5.0	4.99	0.999	5.00	1.000	4.99	1.000	5.00
6.0	5.99	0.999	5.99	1.000	6.00	1.000	6.00
7.0	6.99	0.999	6.99	1.000	7.00	1.000	6.99
8.0	7.98	0.999	7.99	1.000	7.99	1.000	7.99
10.0	9.98	0.999	9.99	1.000	9.99	1.000	9.99
15.0	14.96	0.999	14.97	1.000	14.98	1.000	14.98
20.0	19.93	0.999	19.95	1.000	19.96	1.000	19.96
25.0	24.90	0.999	24.93	1.000	24.94	1.000	24.94
30.0	29.87	0.999	29.90	1.000	29.91	1.000	29.91
40.0	39.79	0.999	39.83	1.000	39.84	1.000	39.84
50.0	49.69	0.999	49.74	1.000	49.75	1.000	49.75
60.0	59.57	0.999	59.63	1.000	59.65	1.000	59.64
70.0	69.43	0.999	69.50	1.000	69.52	1.000	69.51
80.0	79.27	0.999	79.36	1.000	79.37	1.000	79.37
100.0	98.91	0.999	99.01	1.000	99.03	1.000	99.02
150.0	147.66	0.999	147.81	1.000	147.83	1.000	147.83
200.0	195.97	0.999	196.15	1.000	196.18	1.000	196.18
250.0	243.84	0.999	244.05	1.000	244.09	1.000	244.08
300.0	291.28	0.999	291.52	1.000	291.56	1.000	291.55
400.0	384.89	0.999	385.19	1.000	385.24	1.000	385.23
500.0	476.88	0.999	477.23	1.000	477.28	1.000	477.27
600.0	567.30	0.999	567.69	1.000	567.75	1.000	567.74
700.0	656.20	0.999	656.64	1.000	656.70	1.000	656.69
800.0	743.63	0.999	744.11	1.000	744.17	1.000	744.17
1000.0	914.28	0.999	914.84	1.000	914.92	1.000	914.90

TABLE 4

LAYER	RESISTIVITY	THICKNESS	DEPTH
1	1000.00	1.000	1.000
2	1.00	9.000	10.000
3	1000.00		

AB/2	ONEILL	RATIO	YM6	RATIO	JOHANSEN	RATIO	YM10
1.0	843.78	1.000	843.65	1.000	843.59	1.000	843.59
1.5	635.22	1.000	635.01	1.000	635.02	1.000	635.02
2.0	428.60	1.000	428.32	1.000	428.40	1.000	428.40
2.5	268.00	1.001	267.78	1.000	267.80	1.000	267.80
3.0	159.11	1.001	159.01	1.001	158.91	1.000	158.91
4.0	51.06	1.004	51.13	1.005	50.88	1.000	50.88
5.0	15.66	1.011	15.68	1.012	15.48	1.000	15.48
6.0	5.25	1.036	5.13	1.013	5.06	1.000	5.07
7.0	2.40	1.088	2.19	0.994	2.21	1.000	2.21
8.0	1.67	1.131	1.43	0.970	1.48	1.000	1.48
10.0	1.53	1.141	1.31	0.982	1.34	0.999	1.34
15.0	1.93	1.120	1.74	1.008	1.72	1.000	1.73
20.0	2.44	1.093	2.23	0.997	2.23	1.000	2.23
25.0	2.99	1.077	2.77	1.000	2.77	1.000	2.77
30.0	3.54	1.066	3.33	1.002	3.32	1.000	3.32
40.0	4.65	1.051	4.42	1.000	4.42	1.000	4.42
50.0	5.75	1.041	5.52	1.000	5.52	1.000	5.52
60.0	6.85	1.034	6.62	1.000	6.62	1.000	6.62
70.0	7.95	1.030	7.72	1.000	7.72	1.000	7.72
80.0	9.04	1.026	8.81	1.000	8.81	1.000	8.81
100.0	11.21	1.020	10.99	1.000	10.99	1.000	10.99
150.0	16.60	1.012	16.40	1.000	16.40	1.000	16.40
200.0	21.92	1.008	21.75	1.000	21.75	1.000	21.75
250.0	27.19	1.005	27.05	1.000	27.05	1.000	27.05
300.0	32.41	1.004	32.29	1.000	32.29	1.000	32.29
400.0	42.71	1.002	42.63	1.000	42.63	1.000	42.63
500.0	52.82	1.001	52.76	1.000	52.77	1.000	52.77
600.0	62.74	1.000	62.71	1.000	62.72	1.000	62.71
700.0	72.49	1.000	72.47	1.000	72.48	1.000	72.48
800.0	82.07	1.000	82.06	1.000	82.07	1.000	82.07
1000.0	100.71	1.000	100.73	1.000	100.73	1.000	100.73

TABLE 5

LAYER	RESISTIVITY	THICKNESS	DEPTH
1	10000.00	1.000	1.000
2	100.00	49.000	50.000
3	1.00		

AB/2	ONEILL	RATIO	YM6	RATIO	JOHANSEN	RATIO	YM10
1.0	8462.59	1.000	8461.33	1.000	8460.73	1.000	8460.73
1.5	6408.15	1.000	6406.13	1.000	6406.17	1.000	6406.16
2.0	4369.82	1.000	4367.09	1.000	4367.85	1.000	4367.84
2.5	2781.84	1.001	2779.65	1.000	2779.88	1.000	2779.88
3.0	1701.50	1.001	1700.55	1.001	1699.59	1.000	1699.58
4.0	621.87	1.003	622.53	1.004	620.03	1.000	620.04
5.0	261.96	1.007	262.07	1.007	260.19	1.000	260.19
6.0	152.39	1.012	151.25	1.005	150.55	1.000	150.56
7.0	120.09	1.016	118.05	0.999	118.16	1.000	118.16
8.0	110.20	1.018	107.86	0.996	108.26	1.000	108.27
10.0	105.26	1.018	103.15	0.998	103.36	1.000	103.37
15.0	102.85	1.021	100.92	1.001	100.77	1.000	100.78
20.0	101.47	1.021	99.32	0.999	99.37	1.000	99.37
25.0	100.00	1.022	97.85	1.000	97.84	1.000	97.84
30.0	98.18	1.023	96.01	1.001	95.95	1.000	95.95
40.0	93.11	1.025	90.84	1.000	90.83	1.000	90.82
50.0	86.33	1.028	84.02	1.000	84.01	1.000	84.00
60.0	78.31	1.031	75.98	1.000	75.95	1.000	75.95
70.0	69.62	1.035	67.27	1.000	67.24	1.000	67.24
80.0	60.84	1.041	58.47	1.000	58.45	1.000	58.45
100.0	44.62	1.056	42.25	1.000	42.25	1.000	42.25
150.0	18.20	1.137	16.04	1.002	16.00	1.000	16.00
200.0	7.67	1.337	5.78	1.007	5.74	1.000	5.74
250.0	4.09	1.688	2.46	1.015	2.42	1.000	2.42
300.0	2.90	2.008	1.47	1.017	1.44	1.000	1.44
400.0	2.21	2.052	1.09	1.010	1.08	0.998	1.08
500.0	1.96	1.897	1.05	1.016	1.03	1.001	1.03
600.0	1.81	1.763	1.04	1.017	1.02	0.998	1.02
700.0	1.70	1.670	1.04	1.020	1.02	1.001	1.01
800.0	1.61	1.593	1.03	1.019	1.01	1.002	1.01
1000.0	1.49	1.480	1.02	1.014	1.01	0.999	1.01

TABLE 6

LAYER	RESISTIVITY	THICKNESS	DEPTH
1	10000.00	1.000	1.000
2	30.00	9.000	10.000
3	300.00	20.000	30.000
4	1.00		

AB/2	ONEILL	RATIO	YM6	RATIO	JOHANSEN	RATIO	YM10
1.0	8443.34	1.000	8442.07	1.000	8441.47	1.000	8441.47
1.5	6364.68	1.000	6362.65	1.000	6362.69	1.000	6362.68
2.0	4304.73	1.000	4301.97	1.000	4302.75	1.000	4302.74
2.5	2702.80	1.001	2700.58	1.000	2700.83	1.000	2700.82
3.0	1615.85	1.001	1614.90	1.001	1613.92	1.000	1613.92
4.0	535.73	1.003	536.43	1.005	533.89	1.000	533.90
5.0	180.72	1.010	180.85	1.011	178.95	1.000	178.95
6.0	75.81	1.025	74.65	1.009	73.96	1.000	73.97
7.0	47.02	1.043	44.96	0.997	45.08	1.000	45.08
8.0	39.85	1.051	37.48	0.989	37.91	1.000	37.91
10.0	39.33	1.050	37.21	0.994	37.43	1.000	37.45
15.0	47.45	1.046	45.52	1.003	45.37	1.000	45.38
20.0	56.82	1.038	54.67	0.999	54.72	1.000	54.73
25.0	65.53	1.034	63.39	1.000	63.37	1.000	63.38
30.0	72.95	1.031	70.78	1.001	70.72	1.000	70.72
40.0	83.48	1.028	81.19	1.000	81.19	1.000	81.19
50.0	88.95	1.027	86.63	1.000	86.62	1.000	86.62
60.0	90.42	1.027	88.08	1.000	88.06	1.000	88.06
70.0	88.88	1.028	86.53	1.000	86.50	1.000	86.50
80.0	85.22	1.029	82.84	1.000	82.83	1.000	82.83
100.0	74.26	1.033	71.89	1.000	71.89	1.000	71.89
150.0	43.84	1.053	41.66	1.000	41.64	1.000	41.64
200.0	22.89	1.092	20.99	1.001	20.96	1.000	20.96
250.0	11.69	1.166	10.07	1.004	10.03	1.000	10.03
300.0	6.34	1.295	4.94	1.009	4.89	1.000	4.89
400.0	2.82	1.659	1.73	1.015	1.70	0.999	1.70
500.0	2.06	1.796	1.16	1.014	1.15	1.001	1.15
600.0	1.82	1.727	1.07	1.011	1.05	0.999	1.05
700.0	1.69	1.645	1.05	1.016	1.03	1.001	1.03
800.0	1.60	1.571	1.04	1.018	1.02	1.001	1.02
1000.0	1.48	1.461	1.03	1.016	1.01	0.999	1.01

APPENDIX

```
C     PROGRAM FOR THE COMPARISON OF THE O'NEILL,YM6, JOHANSEN,
C     AND YM10 DIGITAL FILTERS
      DIMENSION RES(50),THK(50),RC(50),RD(50),RE(50),RF(50)
      DIMENSION AB(50),DEP(50)
      DATA (AB(I),I=1,31)/1.,1.5,2.,2.5,3.,4.,5.,6.,7.,8.,10.,15.,
     *20.,25.,30.,40.,50.,60.,70.,80.,100.,150.,200.,250.,
     *300.,400.,500.,600.,700.,800.,1000./
      ND=31
C     INPUT LAYER PARAMETERS
      WRITE(6,10)
10    FORMAT(' ENTER NUMBER OF LAYERS'$)
      READ(5,*)NL
      NL1=NL-1
      WRITE(6,20)NL
20    FORMAT(' ENTER',I3,' LAYER RESISTIVITIES')
      READ(5,*)(RES(I),I=1,NL)
      WRITE(6,30)NL1
30    FORMAT(' ENTER',I3,' LAYER THICKNESS'S)
      READ(5,*)(THK(I),I=1,NL1)
C     CALCULATE DEPTHS
      DEP(1)=THK(1)
      DO 140 I=2,NL1
140   DEP(I)=DEP(I-1)+THK(I)
      WRITE(6,150)
150   FORMAT(1H1//' LAYER   RESISTIVITY   THICKNESS',
     *7X,'DEPTH'/)
      WRITE(6,160)(I,RES(I),THK(I),DEP(I),I=1,NL1)
      WRITE(6,160)NL,RES(NL)
160   FORMAT(1X,I5,F14.2,2F12.3)
      MODE=-2
C
C     SPECIFY FILTER, THEN CALL APPRES
C
      CALL ONEILL
      CALL APPRES(RES,THK,NL,AB,RC,ND,MODE)
      CALL YM6
      CALL APPRES(RES,THK,NL,AB,RD,ND,MODE)
      CALL JOHANS
      CALL APPRES(RES,THK,NL,AB,RE,ND,MODE)
      CALL YM10
      CALL APPRES(RES,THK,NL,AB,RF,ND,MODE)
C
C     PRINT RESULTS
C     RATIO IS WITH RESPECT TO
C     THE RESULTS OF YM10
C
      WRITE(6,170)
170   FORMAT(/'   AB/2      ONEILL  RATIO',8X,'YM6  RATIO',
     *'   JOHANSEN  RATIO',7X',YM10')
      DO 175 I=1,ND
      RATC=RC(I)/RF(I)
      RATD=RD(I)/RF(I)
      RATE=RE(I)/RF(I)
175   WRITE(6,180)AB(I),RC(I),RATC,RD(I),RATD,RE(I),RATE,RF(I)
180     FORMAT(F7.1,3(F11.2,F7.3),F11.2)
      STOP
      END
```

```
      SUBROUTINE APPRES(RES,THK,NL,AB,RHOA,ND,MODE)
C
C     CALCULATES THE SCHLUMBERGER APPARENT RESISTIVITY
C     FOR A LAYERED EARTH
C
C     NL           : NUMBER OF LAYERS
C     RES          : LAYER RESISTIVITIES
C     THK          : LAYER THICKNESS'S
C     ND           : NUMBER OF RESISTIVITIES TO CALCULATE
C     AB           : AB/2 SPACINGS OF CALCULATED POINTS
C     RHOA         : CALCULATED APPARENT RESISTIVITIES
C     MODE         : CALCLATION MODE
C                      .LE.0 SPECIFIED AB'S
C                      .GT.0 AB'S CALC. AT FILTER SPACING STARTING AT AB(1)
C
      DIMENSION RES(1),THK(1),AB(1),RHOA(1),T(200)
C
C      FILTER PARAMETERS IN COMMON
C
C      NC : NUMBER OF COEFFICIENTS
C      F  : FILTER SPACING
C      Y1 : ABSCISSA OF FC(1)
C      FC : FILTER COEFFICIENTS
C
C      THE COMMON IS SETUP FOR UP TO 141 FILTER COEFICIENTS
C
      COMMON/FLTR/NC,F,Y1,FC(141)
      DOUBLE PRECISION TT,R,T,RR
      NL1=NL-1
      IF(MODE.LE.0) GOTO 100
C
C     EQUALLY SPACED
C
      X=EXP(Y1)/AB(1)
      NT=ND-1+NC
C
C     CALC. KERNEL
C
      DO 10 L=1,NT
      TT=RES(NL)
      DO 9 K=1,NL1
      I=NL-K
      R=(RES(I)-TT)/(RES(I)+TT)*EXP(-2.*THK(I)*X)
9     TT=RES(I)*(1.-R)/(1.+R)
      T(L)=TT
10    X=X/F
C
C      CONVOLVE
C
      DO 12 I=1,ND
      RR=0.
      DO 11 J=1,NC
11    RR=RR+FC(J)*T(J+I-1)
12    RHOA(I)=RR
      RETURN
C
C     SPECIFIED ABSCISSA
C
100   DO 110 I=1,ND
      RR=0.
      X=EXP(Y1)/AB(I)
```

```
      DO 120 J=1,NC
      TT=RES(NL)
C
C     CALC. KERNEL
C
      DO 130 K=1,NL1
      L=NL-K
      R=(RES(L)-TT)/(RES(L)+TT)*EXP(-2.*THK(L)*X)
130   TT=RES(L)*(1.-R)/(1.+R)
      X=X/F
120   RR=RR+FC(J)*TT
110   RHOA(I)=RR
      RETURN
      END
```

```
      SUBROUTINE YM6
      COMMON/FLTR/NC,F,Y1,FC(141)
      DIMENSION A(28)
C
C      FILTER PARAMETERS ARE STORED IN COMMON  (FLTR)
C
C      NC : NUMBER OF FILTER COEFFICIENTS
C      F  : FILTERSPACING
C      Y1 : ABSCISSA OF FC(1)
C      FC : FILTER COEFFICIENTS
C
C      THE COMMON IS SET UP FOR UP TO 141 COEFFICIENTS
C
      NC=28
      DATA (A(I),I=1,28)/
     * .86463368E-4,-.36875438E-3,+.92111524E-3,-.18772686E-2,
     * .35343506E-2,-.64612278E-2,+.11691267E-1,-.21088677E-1,
     *+.38045092E-1,-.68913866E-1,+.12666755E-0,-.24355470E-0,
     *+.52117305E-0,-.12644217E+1,+.27992503E+1,-.34853734E+1,
     *+.41912647E+0,+.11950174E+1,+.61073260E-0,+.24298434E-0,
     *+.82207576E-1,+.27770876E-1,+.87075202E-2,+.28615354E-2,
     *+.88399812E-3,+.28020133E-3,+.10060054E-3,+.34147278E-4/
      DO 10 I=1,28
10    FC(I)=A(I)
      F=10.**(1./6.)
      Y1=7.4222404
      RETURN
      END
```

```
      SUBROUTINE YM10
      COMMON/FLTR/NC,F,Y1,FC(141)
      DIMENSION A(70)
C
C      FILTER PARAMETERS ARE STORED IN COMMON  (FLTR)
C
C      NC : NUMBER OF FILTER COEFFICIENTS
C      F  : FILTERSPACING
C      Y1 : ABSCISSA OF FC(1)
C      FC : FILTER COEFFICIENTS
C
C      THE COMMON IS SET UP FOR UP TO 141 COEFFICIENTS
C
      DATA (A(I),I=1,70)/
     *-.22247786E-4,+.51184989E-4,-.66575186E-4,+.86592875E-4,
     *-.11262944E-3,+.14649463E-3,-.19054233E-3,+.24783420E-3,
     *-.32235248E-3,+.41927675E-3,-.54534402E-3,+.70931693E-3,
     *-.92259288E-3,+.11999962E-2,-.15608086E-2,+.20301093E-2,
     *-.26405183E-2,+.34344639E-2,-.44671314E-2,+.58102992E-2,
     *-.75573279E-2,+.98296496E-2,-.12785208E-1,+.16629439E-1,
     *-.21629544E-1,+.28133073e-1,-.36592072e-1,+.47594515e-1,
     *-.61905179E-1,+.80518827E-1,-.10472943E+0,+.13622036E+0,
     *-.17718202E+0,+.23046613E+0,-.29978969E+0,+.39001009E+0,
     *-.50751079E+0,+.66077997E+0,-.86135847E+0,+.11254667E+1,
     *-.14762271E+1,+.19413057E+1,-.25117825E+1,+.29397638E+1,
     *-.22862253E+1,-.71362115E+0,+.41491251E+1,-.23169602E+1,
     *-.16867419E+1,-.32170199E+0,+.68963453E+0,+.69150854E+0,
     *+.54204064E+0,+.32222510E+0,+.19033795E+0,+.99724447E-1,
     *+.54063095E-1,+.27109364E-1,+.14239291E-1,+.70240599E-2,
     *+.36435998E-2,+.17863940E-2,+.92183691E-3,+.45100602E-3,
     *+.23218367E-3,+.11353351E-3,+.58376418E-4,+.28547132E-4,
     *+.14666868E-4,+.14501929E-4/
      DO 10 I=1,70
10    FC(I)=A(I)
      NC=70
      F=10**.1
      Y1=12.664218
      RETURN
      END
```