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Interpretation of Electromagnetic Extra-Low-Frequency Soundings in the Randsburg, California, Known Geothermal Resource Area

by

Walter L. Anderson

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This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards.

Interpretation of Electromagnetic Extra-Low-Frequency Soundings in the Randsburg, California, Known Geothermal Resource Area

by Walter L. Anderson

An electromagnetic (EM) controlled source survey was made during the period Nov. 30, 1977, to Dec. 13, 1977, in the Randsburg, California, Known Geothermal Resource Area (KGRA). This report summarizes the observed extra-low-frequency (ELF) data and least squares interpretation using a computer program developed by Anderson (1977). The results are given in tabular form along with observed and calculated amplitude and phase plots. In addition, one vertical electrical sounding (VES) was obtained and a graphical solution is included via a Schlumberger inversion program developed by Zohdy (1973).

Five ELF soundings were made using a grounded-wire source having a half-length (L) of 764 meters and located along an azimuth of N 55° E. (see fig. 1). A square receiver loop of approximately 76 meters per side was used at each ELF station. The ELF equipment measures the vertical magnetic field (Hz) at the loop center for a controlled input source frequency range between 1 and 10,000 Hertz. The minimum station separation from the wire source was 552 meters (station WL8), and the maximum separation was 2678 meters (station WL9). The Schlumberger array (denoted as VES-8) was oriented parallel to the wire source across ELF station WL8 and had a maximum potential electrode spacing (AB/2) of 1219 meters (4000 feet).

The observed ELF amplitude and phase soundings were adjusted at each EM station using predetermined equipment calibration curves. Linear-phase drift corrections were applied to the upper frequency decade, except at station WL6--where the sounding ended at 160 Hertz due to equipment failure. Most of the soundings had 10 points per decade, but ended at 2000 Hertz. Repeated observations were averaged and some points were deleted due to obvious erroneous observations. The final observed points are denoted by the symbol "0" in all ELF plots in the appendix. The dotted line indicates the calculated least squares sounding.

The least-squares results were obtained by running an inversion program (Anderson, 1977) using simultaneous amplitude and phase observations at each station. Results for each station are included in the appendix as: (1) least squares amplitude solution with residuals, (2) least squares phase solution with residuals, and (3) layer-solution parameters with statistics regarding the least squares solution.

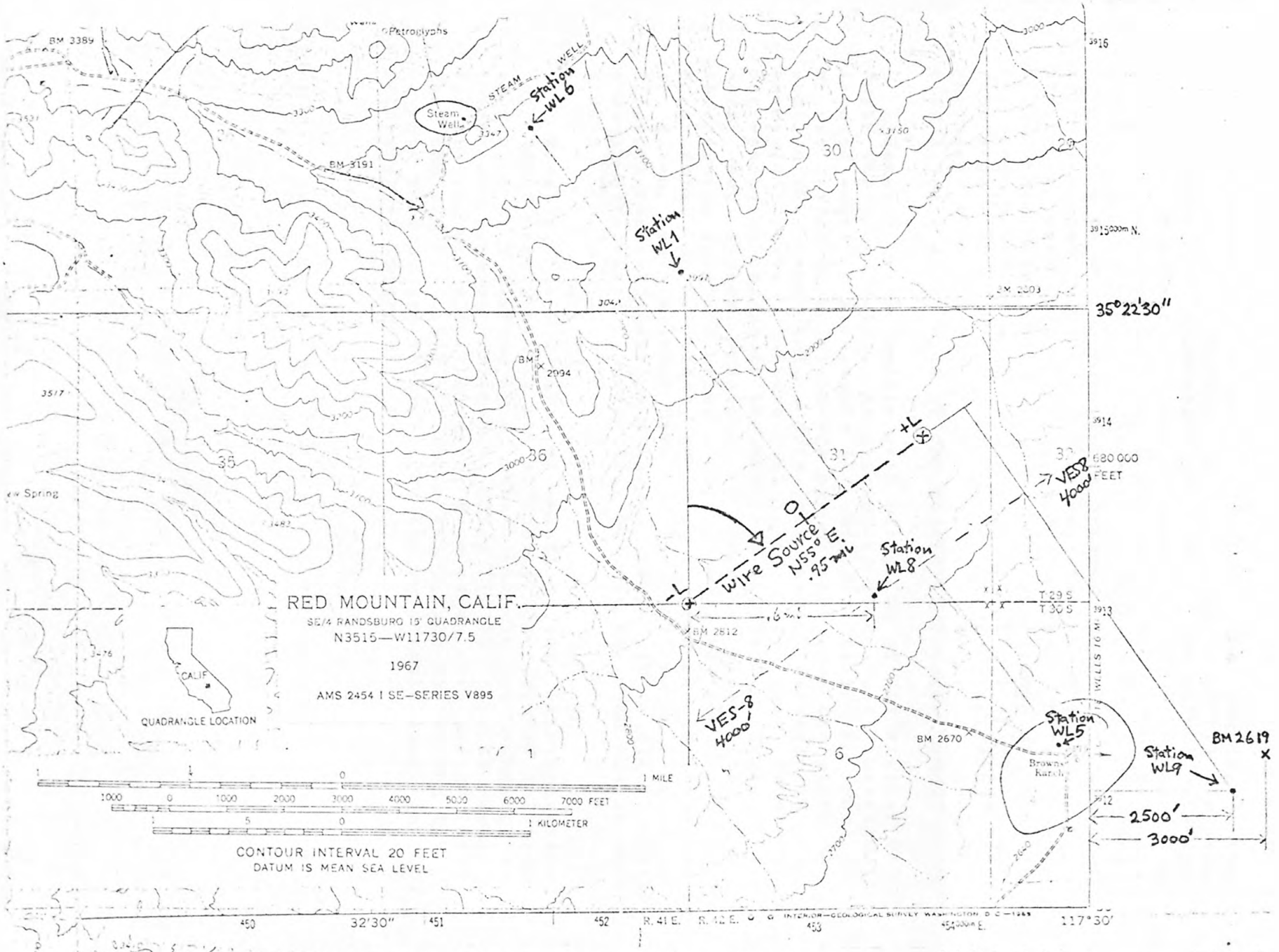


figure 1.-- Wire-source and station locations.

The notation in part (3)--tabulated results in the appendix--follows Anderson (1977), where sigma(i) is the conductivity in mhos/meter of layer i, and thick(i) is the thickness in meters of layer i. Resistivity in ohm-meters and depth from the surface in meters are also given for each layer. The number of layers is denoted in the headings (e.g., run 6C means run C for a 6-layer model). Parameter b(2*mm), mm= number of layers, is an amplitude-shift parameter used in the primary field normalization b(2*mm)/hzp, and has no physical significance in terms of the other model parameters. The parameter statistics are tabulated for additional information regarding the goodness-of-fit for the model selected. Refer to Anderson (1977) for a discussion of the statistical terms used.

Results are complete with exception of ELF station WL6 (near the steam well). An attempt to find a one-dimensional layered model to reasonably fit this data failed to produce a satisfactory solution--as can be seen from the plots for station WL6 (run 5A). Note the sign reversal in the observed phase between 12.5 and 25 Hertz (and the corresponding change in the observed amplitude curve). It does not appear possible to find a theoretical one-dimensional solution using a horizontally layered model for these data. Nevertheless, the last layered result attempted is given, but without statistics (due to a "negative diagonal element" message obtained here). It is likely that a major electrical boundary lies between the wire source and station WL6.

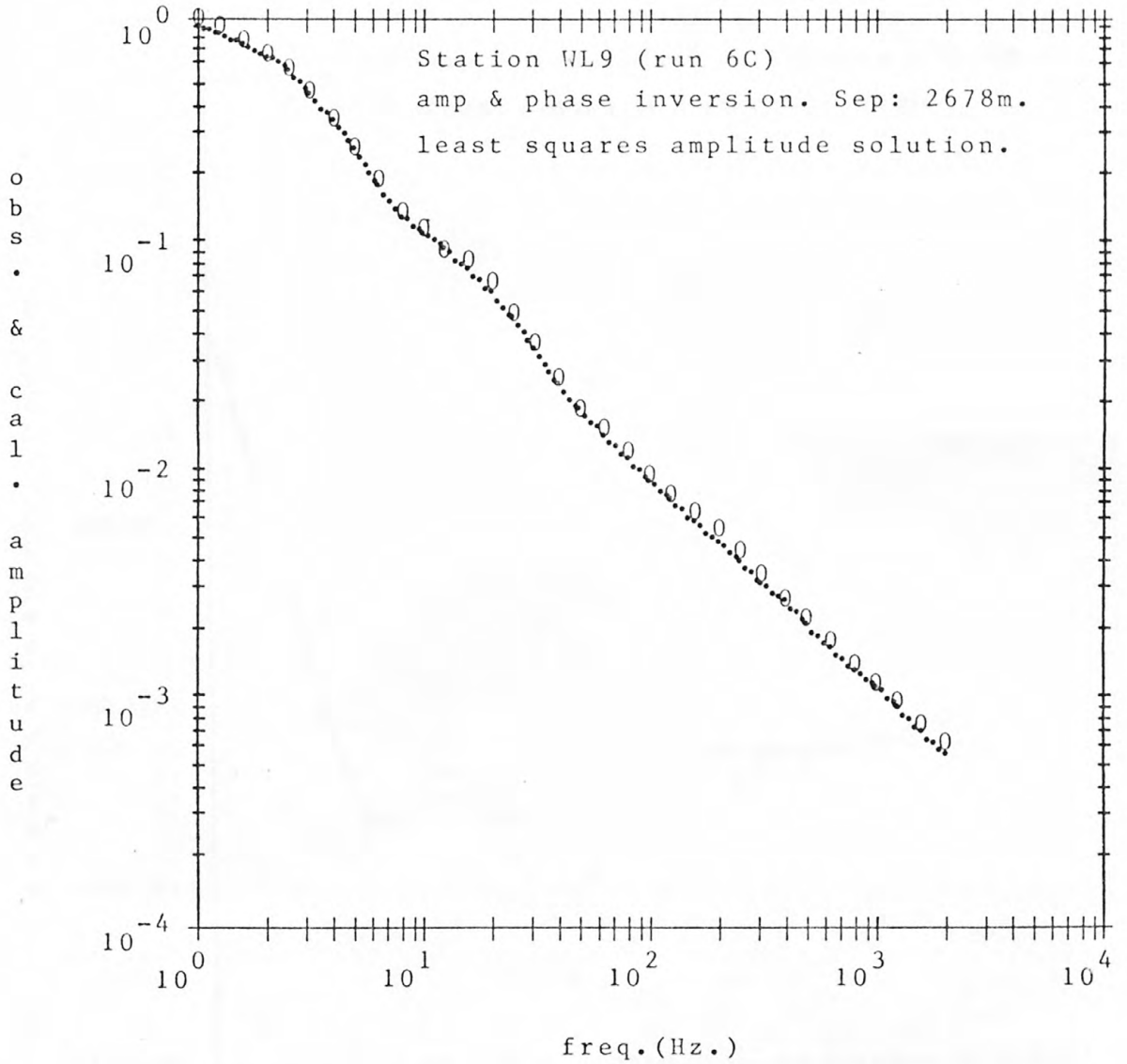
Finally, the Schlumberger sounding and interpretation for VES-8 are given in the appendix. The layered solution is graphically plotted as a direct result of running an inversion program writted by Zohdy (1973). The EM results for station WL8 show a slightly more conductive second layer than the VES results for station VES-8, and the second layer is more shallow and thinner than the comparable layer in the Schlumberger interpretation.

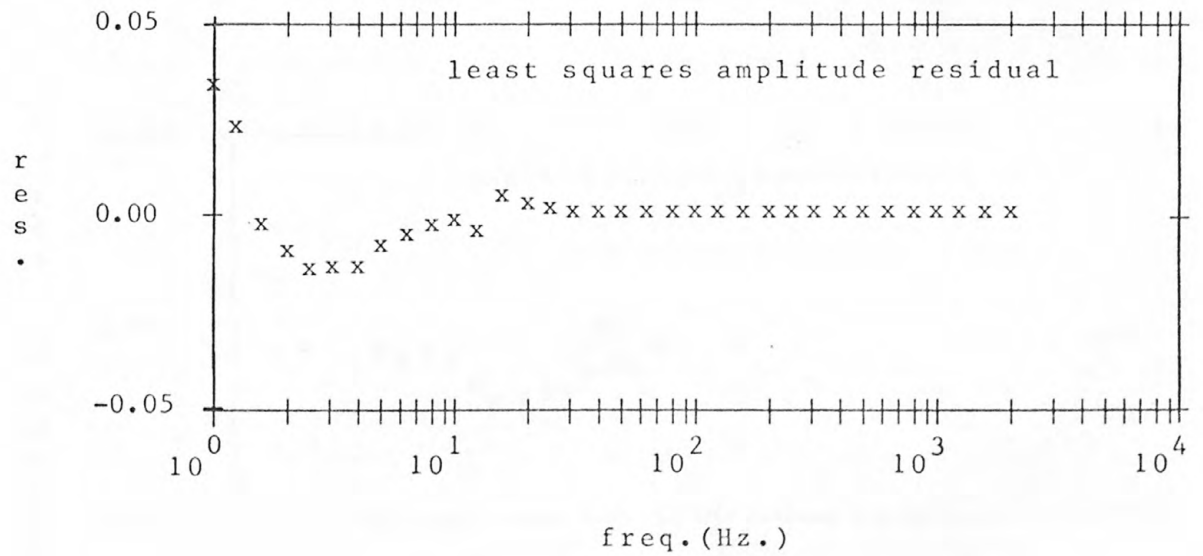
References

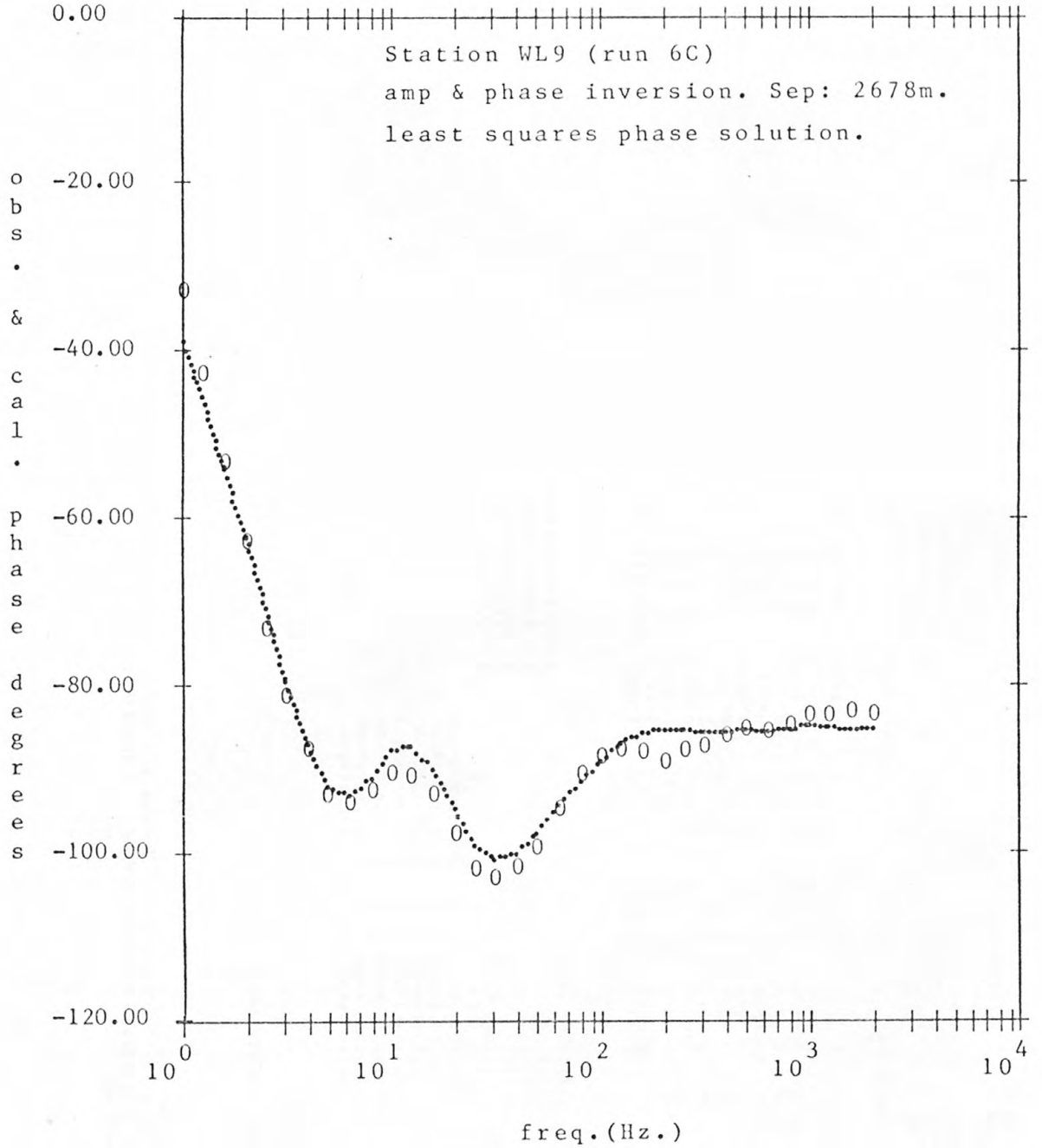
Anderson, W.L., 1977, Marquardt inversion of vertical magnetic field measurements from a grounded wire source: U.S. Geol. Survey Rept. USGS-GD-77-033, 76p, available from U.S. Dept. Commerce Natl. Tech. Inf. Service, Springfield, Va. 22161, as Rept. PB-263-924/AS.

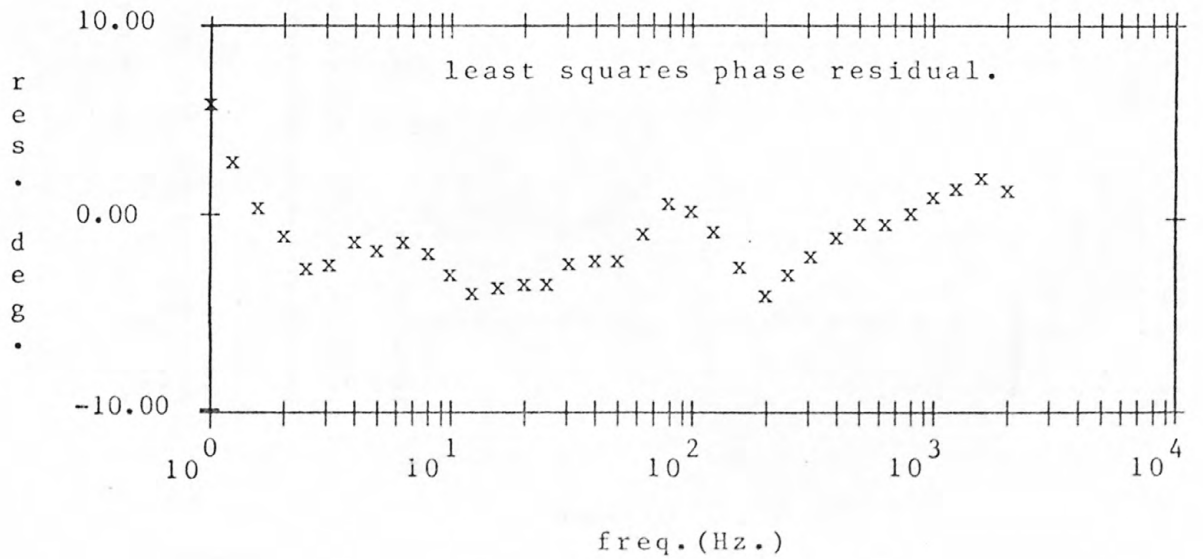
Zohdy, A.A.R., 1973, A computer program for the automatic interpretation of Schlumberger sounding curves over horizontally stratified media: U.S. Geol. Survey Rept. USGS-GD-74-017, 25p, available from U.S. Dept. Commerce Natl. Tech. Inf. Service, Springfield, Va. 22161, as Rept. PB-232-703/AS.

Appendix


Station WL9 (run 6C)
amp & phase inversion. Sep: 2678m.
least squares amplitude solution.
obs. & cal. amplitude
freq.(Hz.)


least squares amplitude residual
res.
freq.(Hz.)


Station WL9 (run 6C)
amp & phase inversion. Sep: 2678m.
least squares phase solution.
obs. & cal. phase degrees
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
10^0
10^1
10^2
10^3
10^4
freq.(Hz.)


least squares phase residual.
res. deg.
10.00
0.00
-10.00
10^0
10^1
10^2
10^3
10^4
freq.(Hz.)

```
m a r q h z p --      Station WL9 (run 6C)
iob = 5          mm =  6          x0= 0.10363e+04 y0= 0.24689e+04 l= 0.76428e+03
method = 0       nz = 12          nw = 12          ier = 2          mev =   300
eps=0.10000e-03 ep=0.10000e-02  neps =   10      nfin =    1
```

receiver-transmitter separation (rho) = 0.26776e+04

primary field (hzp x 4pi) = 0.19431e-03

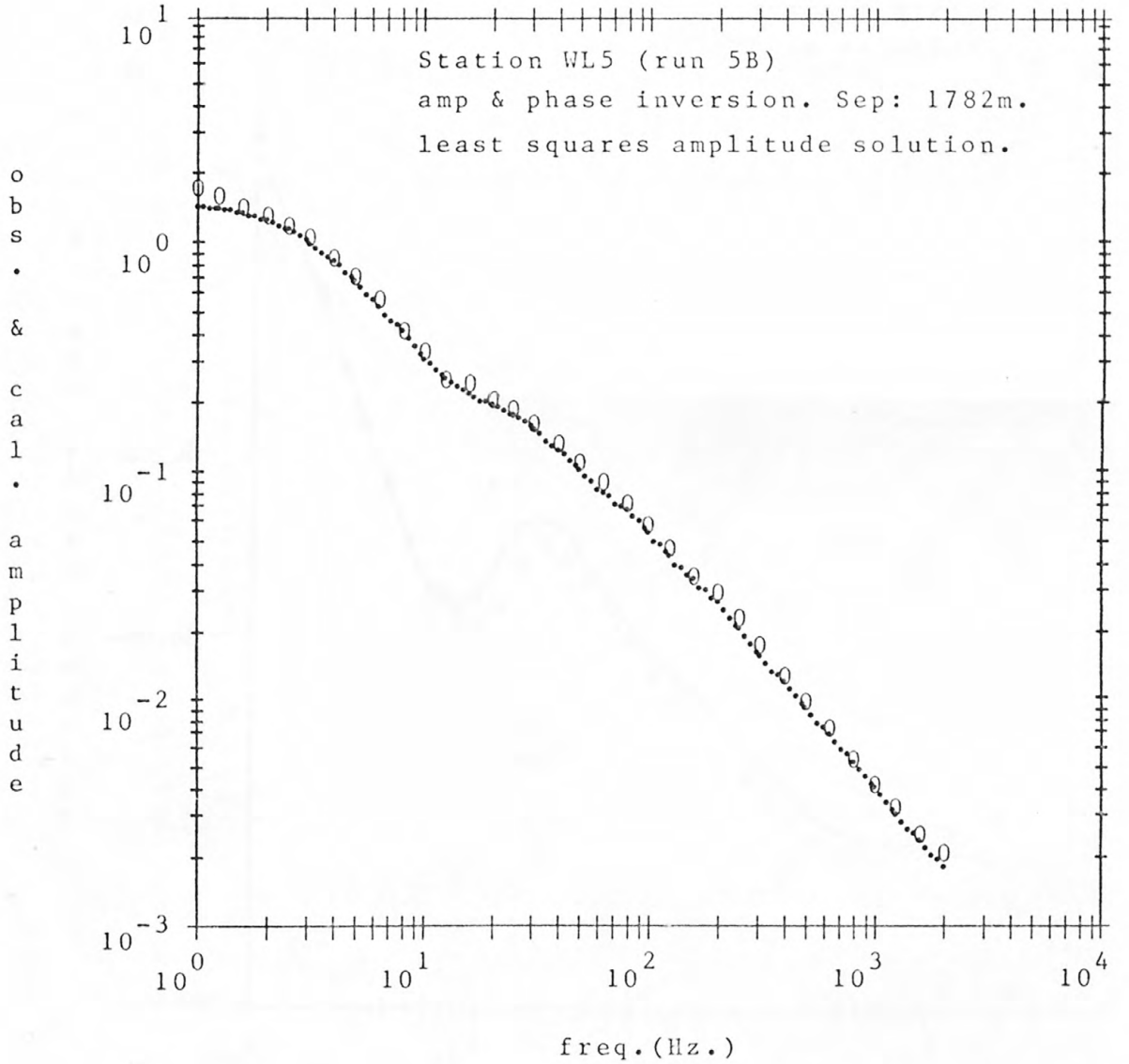
parameter order--		final unscaled parameters--		resistivity		depth
1	sigma(1)	1	0.10585287e+00	1	0.94470748e+01	
2	sigma(2)	2	0.13882226e+00	2	0.72034556e+01	
3	sigma(3)	3	0.61153927e-01	3	0.16352180e+02	
4	sigma(4)	4	0.14533378e-01	4	0.68807127e+02	
5	sigma(5)	5	0.60273774e+00	5	0.16590964e+01	
6	sigma(6)	6	0.88818935e-02	6	0.11258860e+03	
7	thick(1)	7	0.19521724e+02			1 0.19521724e+02
8	thick(2)	8	0.16910931e+03			2 0.18863103e+03
9	thick(3)	9	0.93224852e+02			3 0.28185588e+03
10	thick(4)	10	0.16232356e+03			4 0.44417944e+03
11	thick(5)	11	0.12770419e+03			5 0.57188363e+03
12	b(12)	12	0.11912844e+01			

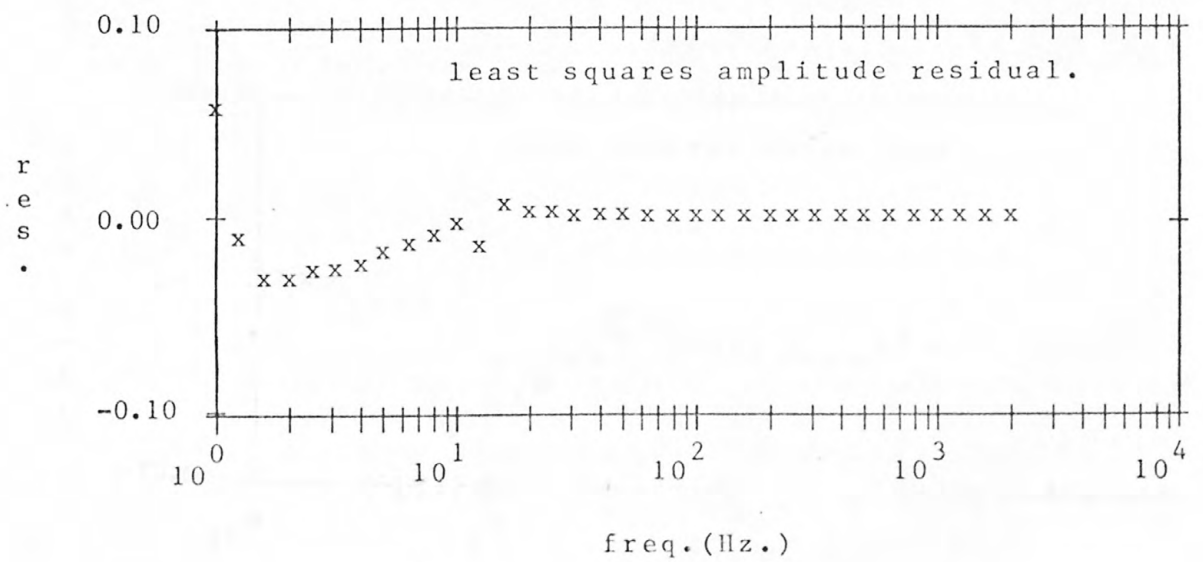
parameter correlation matrix

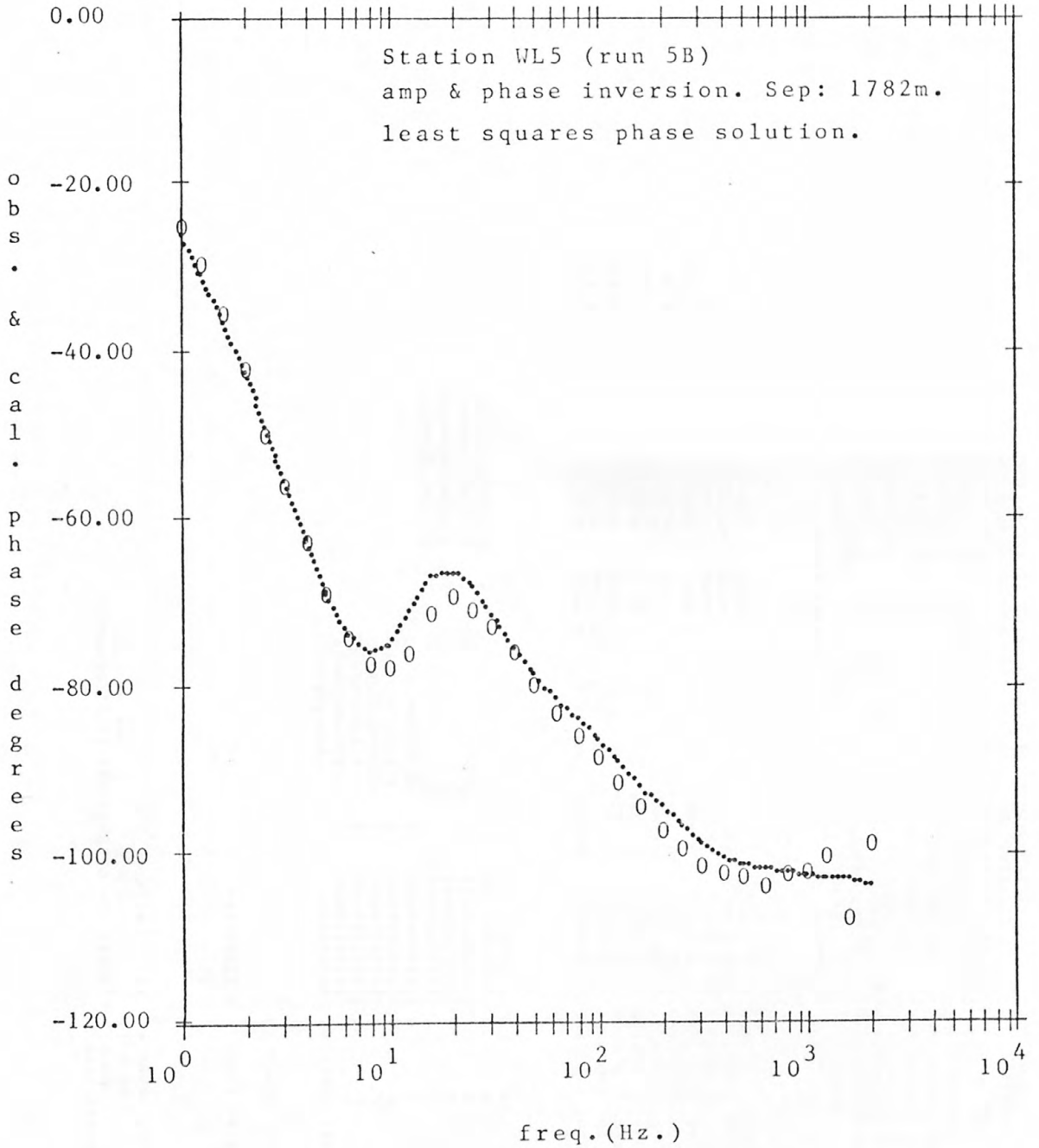
1	1.0000	0.8837	0.0985	0.2491	0.6890	0.7989	0.2091	-0.0921	-0.1784	0.1939	-0.5827	0.0587
2	0.8836	1.0000	0.2042	0.3278	0.7302	0.8255	0.1673	-0.2047	-0.2674	0.2833	-0.6384	0.0621
3	0.0980	0.2040	1.0000	0.9519	0.6514	-0.1041	0.3933	-0.9970	-0.9816	0.9808	-0.7699	-0.0053
4	0.2488	0.3278	0.9527	1.0000	0.8080	0.0798	0.3045	-0.9299	-0.9927	0.9935	-0.9015	0.0091
5	0.6889	0.7304	0.6524	0.8085	1.0000	0.6072	0.1522	-0.6233	-0.7484	0.7587	-0.9832	0.0476
6	0.7990	0.8258	-0.1034	0.0805	0.6077	1.0000	-0.2288	0.1226	0.0029	0.0121	-0.4765	0.0735
7	0.2087	0.1670	0.3926	0.3034	0.1512	-0.2291	1.0000	-0.4258	-0.3359	0.3380	-0.1987	-0.0193
8	-0.0916	-0.2044	-0.9968	-0.9290	-0.6221	0.1233	-0.4265	1.0000	0.9652	-0.9648	0.7408	0.0069
9	-0.1780	-0.2674	-0.9821	-0.9924	-0.7478	0.0036	-0.3368	0.9659	1.0000	-0.9998	0.8543	-0.0027
10	0.1935	0.2832	0.9813	0.9932	0.7580	0.0114	0.3390	-0.9655	-0.9998	1.0000	-0.8620	0.0038
11	-0.5825	-0.6385	-0.7709	-0.9019	-0.9831	-0.4759	-0.1998	0.7420	0.8549	-0.8627	1.0000	-0.0381
12	0.0587	0.0622	-0.0052	0.0091	0.0476	0.0735	-0.0193	0.0069	-0.0027	0.0038	-0.0381	1.0000

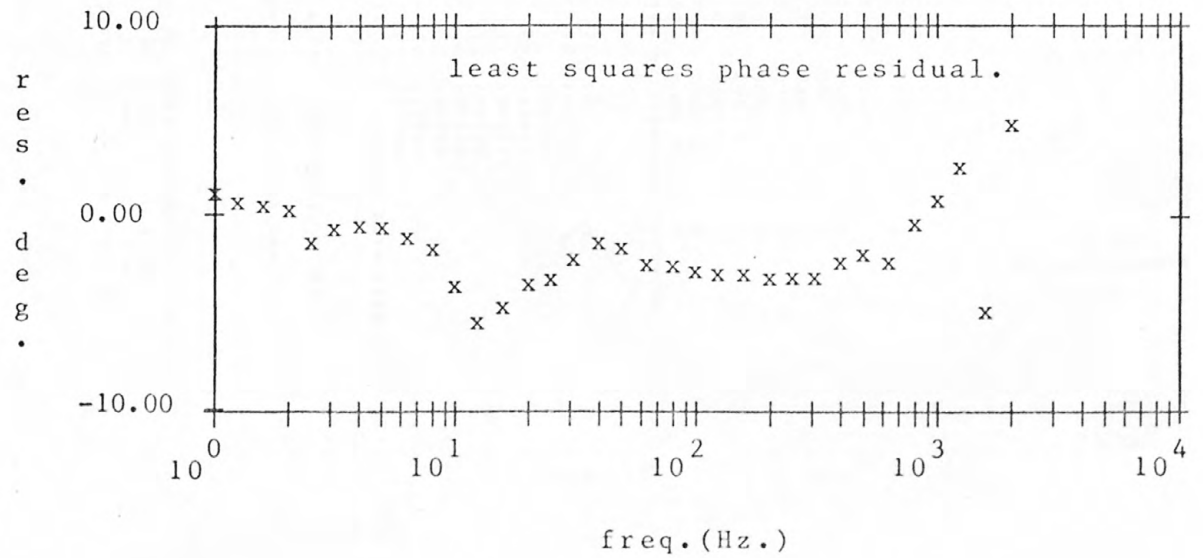
parameter	std error	one - parameter lower	one - parameter upper	support plane lower	support plane upper
1	0.76477848e-02	0.90557301e-01	0.12114844e+00	0.52867464e-01	0.15883828e+00
2	0.99739871e-02	0.11887429e+00	0.15877024e+00	0.69720452e-01	0.20792407e+00
3	0.41608604e+01	-0.82605668e+01	0.83828746e+01	-0.28766132e+02	0.28888440e+02
4	0.58679514e+01	-0.11721370e+02	0.11750436e+02	-0.40639826e+02	0.40668892e+02
5	0.63120580e+01	-0.12021378e+02	0.13226854e+02	-0.43128483e+02	0.44333958e+02
6	0.84918533e-01	-0.16095517e+00	0.17871896e+00	-0.57945096e+00	0.59721474e+00
7	0.69083109e+01	0.57051017e+01	0.33338345e+02	-0.28340458e+02	0.67383904e+02
8	0.13759451e+04	-0.25827809e+04	0.29209995e+04	-0.93637179e+04	0.97019364e+04
9	0.14273512e+05	-0.28453800e+05	0.28640249e+05	-0.98796569e+05	0.98983019e+05
10	0.17116899e+05	-0.34071476e+05	0.34396122e+05	-0.11842703e+06	0.11875168e+06
11	0.21812961e+04	-0.42348881e+04	0.44902964e+04	-0.14934759e+05	0.15240167e+05
12	0.14794219e+01	-0.17675593e+01	0.41501282e+01	-0.90584509e+01	0.11441020e+02

phi	s e
0.2029e100e+03	0.1903863[illegible]e+01


Station WL5 (run 5B)
amp & phase inversion. Sep: 1782m.
least squares amplitude solution.
obs. & cal. amplitude
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
freq.(Hz.)


least squares amplitude residual.
res.
0.10
0.00
-0.10
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
freq.(Hz.)


Station WL5 (run 5B)
amp & phase inversion. Sep: 1782m.
least squares phase solution.
obs. & cal. phase degrees
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
10^0
10^1
10^2
10^3
10^4
freq.(Hz.)


least squares phase residual.
res. deg.
10.00
0.00
-10.00
10^0
10^1
10^2
10^3
10^4
freq.(Hz.)

```
m a r q h z p --      Station WL5 (run 5B)
iob = 5          mm =  5          x0= 0.33833e+03 y0= 0.17496e+04 l= 0.76428e+03
method = 0       nz = 12          nw = 12         ier = 2         mev =   300
eps=0.10000e-03 ep=0.10000e-03  neps =   10      nfin =    1
```

receiver-transmitter separation (rho) = 0.17820e+04

primary field (hzp x 4pi) = 0.43996e-03

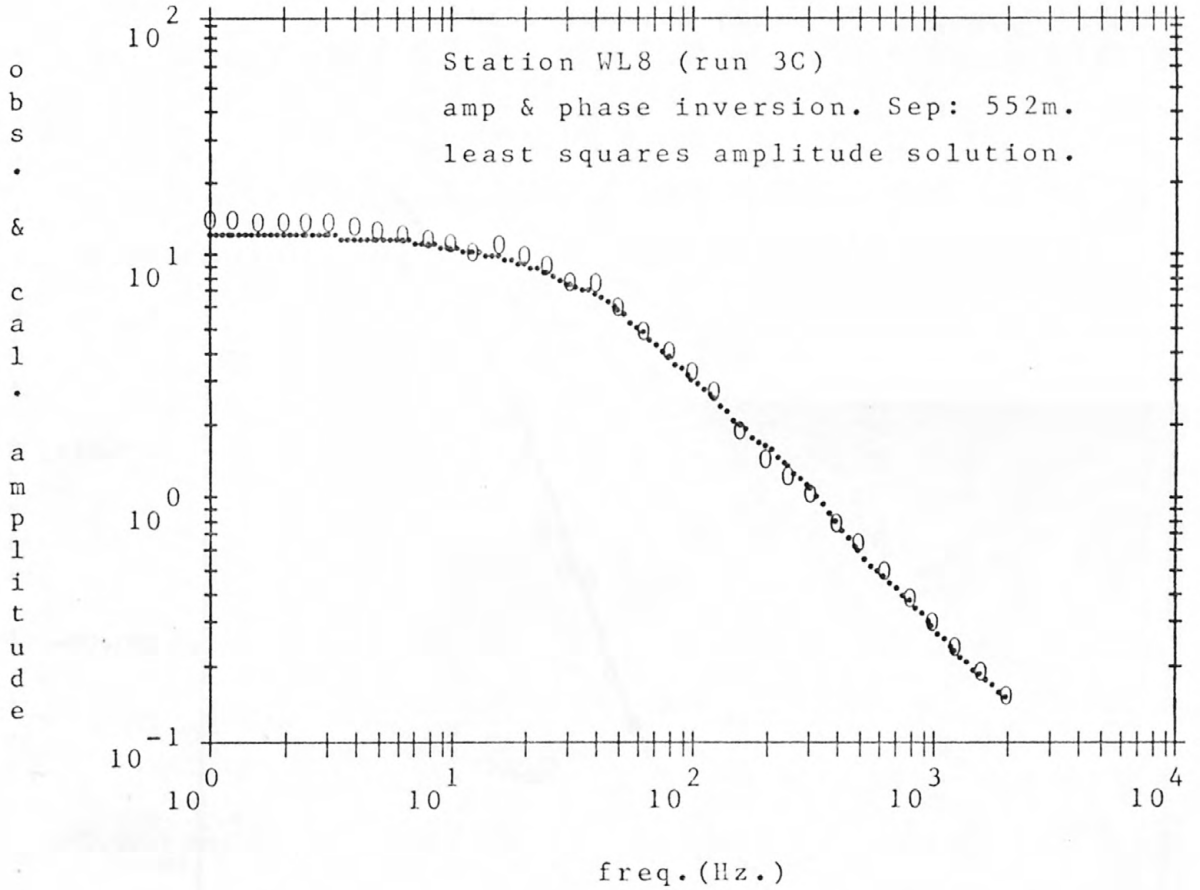
parameter order--		final unscaled parameters--		resistivity		depth
1	sigma(1)	1	0.15250871e+00	1 0.65570025e+01		
2	sigma(2)	2	0.71752139e-01	2 0.13936867e+02		
3	sigma(3)	3	0.18352892e+00	3 0.54487326e+01		
4	sigma(4)	4	0.37389911e+00	4 0.26745183e+01		
5	sigma(5)	5	0.52278094e-01	5 0.19128471e+02		
6	thick(1)	6	0.10565331e+02		1	0.10565331e+02
7	thick(2)	7	0.14224763e+03		2	0.15281296e+03
8	thick(3)	8	0.17487457e+03		3	0.32768753e+03
9	thick(4)	9	0.12744464e+03		4	0.45513217e+03
10	b(10)	10	0.18049097e+01			

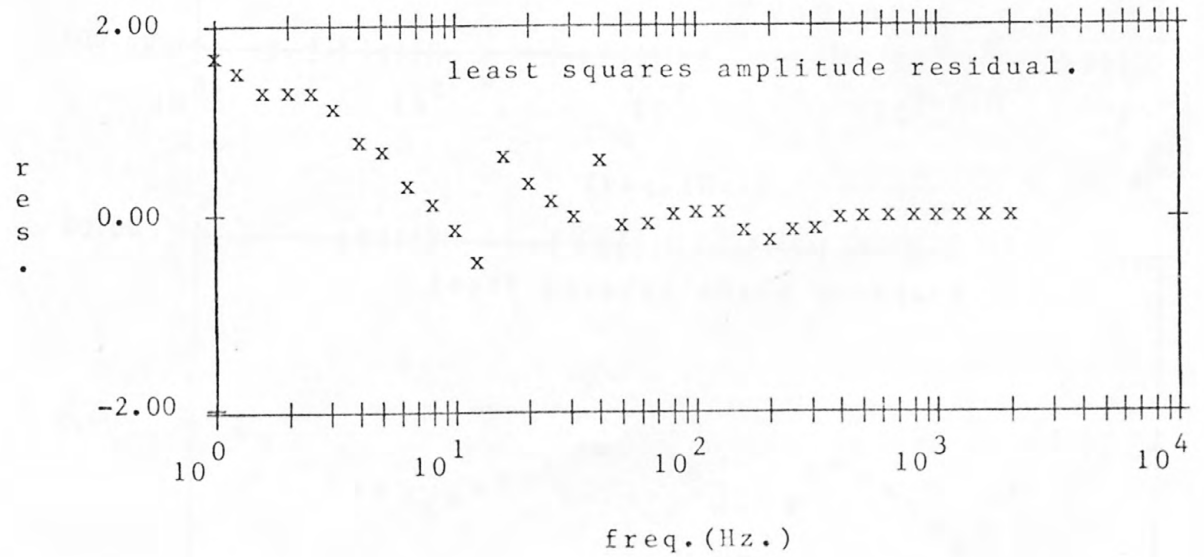
parameter correlation matrix

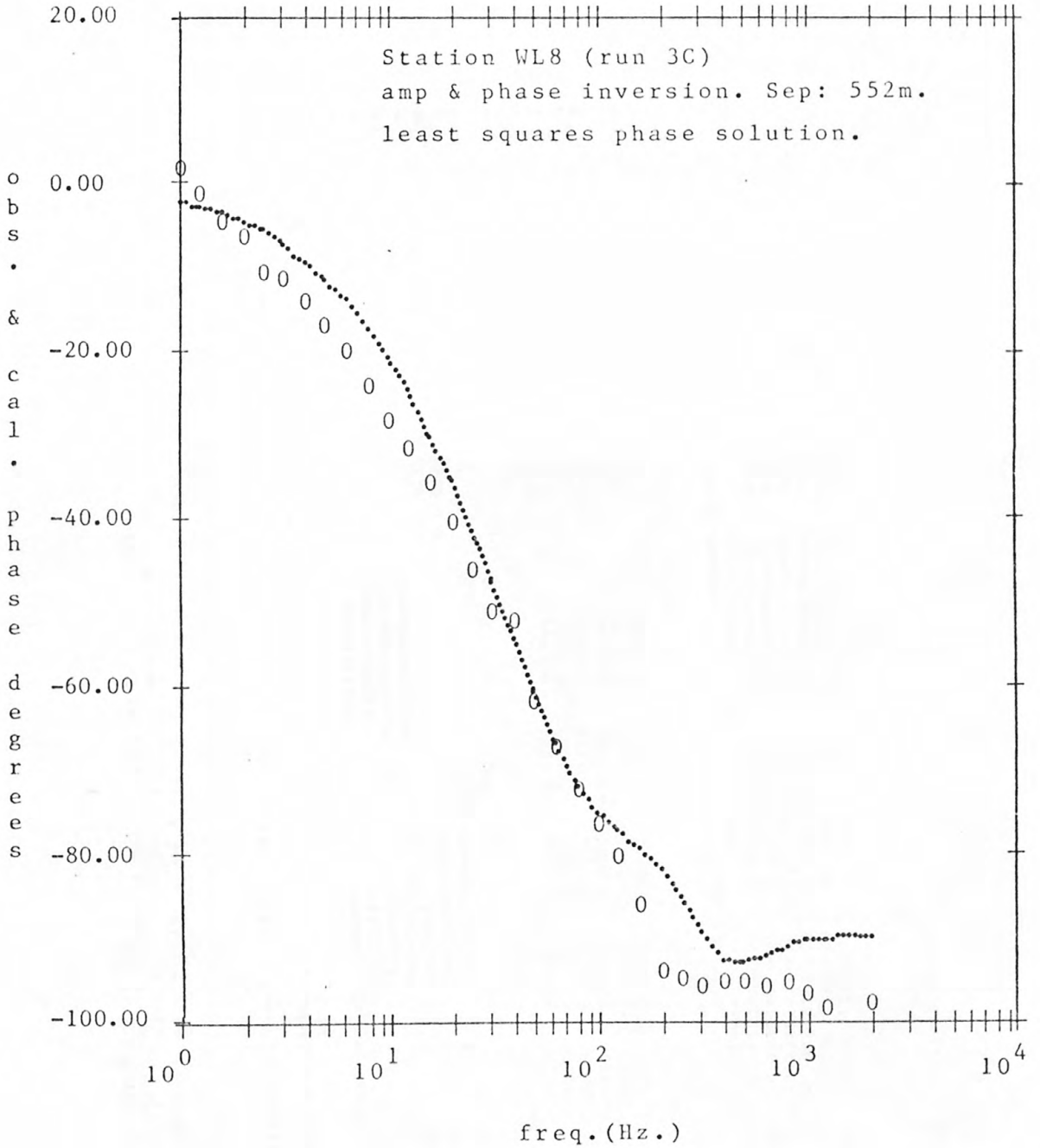
1	1.0000	0.8280	0.5754	0.4848	0.6538	-0.9629	0.6818	0.3393	-0.5164	0.0203
2	0.8280	1.0000	0.6493	0.5626	0.7660	-0.7659	0.6546	0.4281	-0.5924	0.0346
3	0.5754	0.6493	1.0000	0.8289	0.5534	-0.5645	0.9080	0.8341	-0.8494	0.0196
4	0.4848	0.5626	0.8289	1.0000	0.6895	-0.4389	0.6533	0.9744	-0.9985	0.0273
5	0.6538	0.7660	0.5534	0.6895	1.0000	-0.5286	0.4091	0.5393	-0.7118	0.0510
6	-0.9629	-0.7659	-0.5645	-0.4389	-0.5286	1.0000	-0.7361	-0.3142	0.4694	-0.0110
7	0.6818	0.6546	0.9080	0.6533	0.4091	-0.7361	1.0000	0.6380	-0.6793	0.0063
8	0.3393	0.4281	0.8341	0.9744	0.5393	-0.3142	0.6380	1.0000	-0.9687	0.0199
9	-0.5164	-0.5924	-0.8494	-0.9985	-0.7118	0.4694	-0.6793	-0.9687	1.0000	-0.0282
10	0.0203	0.0346	0.0196	0.0273	0.0510	-0.0110	0.0063	0.0199	-0.0282	1.0000

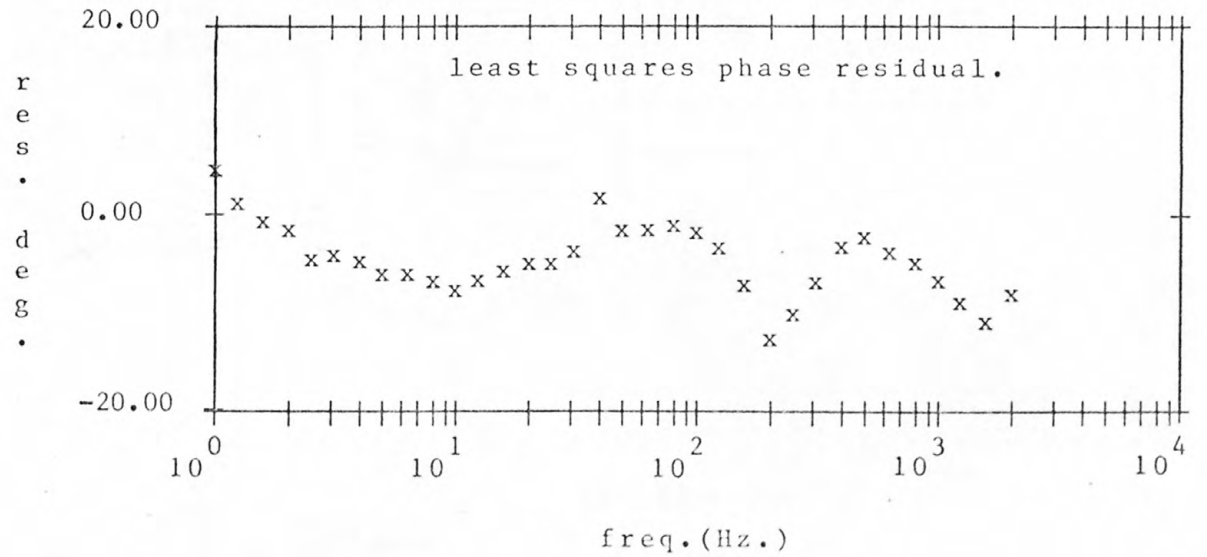
parameter	std error	one - parameter lower	one - parameter upper	support plane lower	support plane upper
1	0.25299812e-01	0.10190909e+00	0.20310833e+00	-0.75013470e-02	0.31251877e+00
2	0.50146597e-02	0.61722820e-01	0.81781458e-01	0.40036647e-01	0.10346763e+00
3	0.53624628e-01	0.76279662e-01	0.29077817e+00	-0.15562301e+00	0.52268083e+00
4	0.10580792e+01	-0.17422593e+01	0.24900575e+01	-0.63179812e+01	0.70657794e+01
5	0.54488972e-01	-0.56699849e-01	0.16125604e+00	-0.29234042e+00	0.39689661e+00
6	0.49385332e+01	0.68826485e+00	0.20442398e+02	-0.20668695e+02	0.41799358e+02
7	0.27170168e+02	0.87907295e+02	0.19658797e+03	-0.29591599e+02	0.31408686e+03
8	0.25922413e+03	-0.34357368e+03	0.69332283e+03	-0.14646028e+04	0.18143519e+04
9	0.60761997e+03	-0.10877953e+04	0.13426846e+04	-0.37154815e+04	0.39703707e+04
10	0.20621456e+01	-0.23193815e+01	0.59292009e+01	-0.11237244e+02	0.14847064e+02

phi	s e
0.27815471e+03	0.21899249e+01


Station WL8 (run 3C)
amp & phase inversion. Sep: 552m.
least squares amplitude solution.
obs. & cal. amplitude
freq.(Hz.)


least squares amplitude residual.
res.
freq.(Hz.)


Station WL8 (run 3C)
amp & phase inversion. Sep: 552m.
least squares phase solution.
obs. & cal. phase degrees
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
10^0
10^1
10^2
10^3
10^4
freq.(Hz.)


least squares phase residual.
res. deg.
20.00
0.00
-20.00
10^0
10^1
10^2
10^3
10^4
freq.(Hz.)

```
m a r q h z p --      Station WL8 (run 3C)
iob = 5          mm =  3          x0= 0.60960e+02 y0= 0.54864e+03 l= 0.76428e+03
method = 0       nz = 12          nw = 12         ier = 4         mev =   300
eps=0.10000e-06 ep=0.10000e-02  neps =   10      nfin =    1
```

receiver-transmitter separation (rho) = 0.55202e+03

primary field (hzp x 4pi) = 0.29550e-02

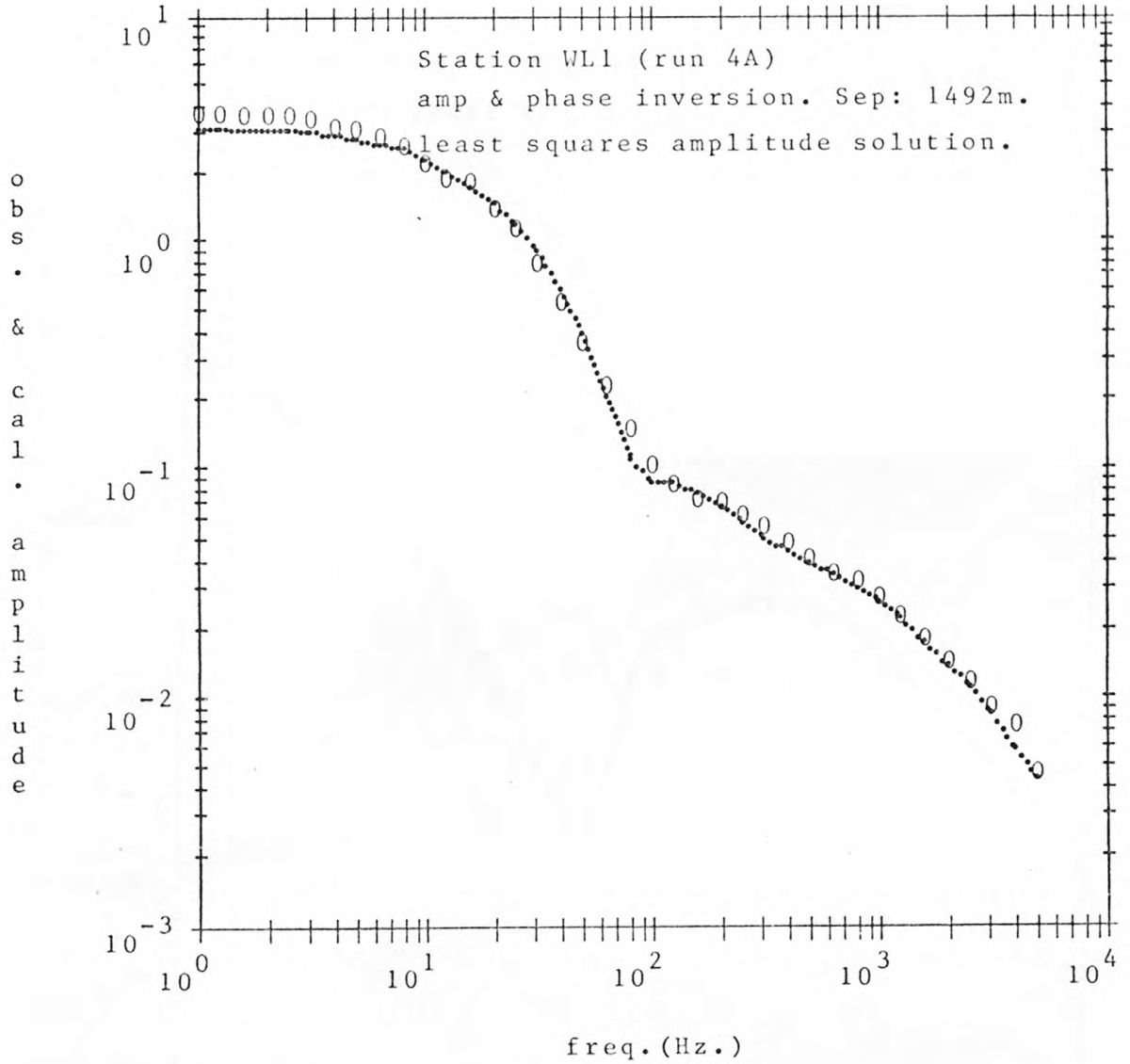
parameter order--			final unscaled parameters--			resistivity		depth
1	sigma(1)	1	0.79592713e-01	1	0.12563964e+02			
2	sigma(2)	2	0.23913920e+00	2	0.41816649e+01			
3	sigma(3)	3	0.47324802e-03	3	0.21130569e+04			
4	thick(1)	4	0.15338561e+03			1	0.15338561e+03	
5	thick(2)	5	0.63199394e+02			2	0.21658501e+03	
6	b(6)	6	0.12105653e+02					

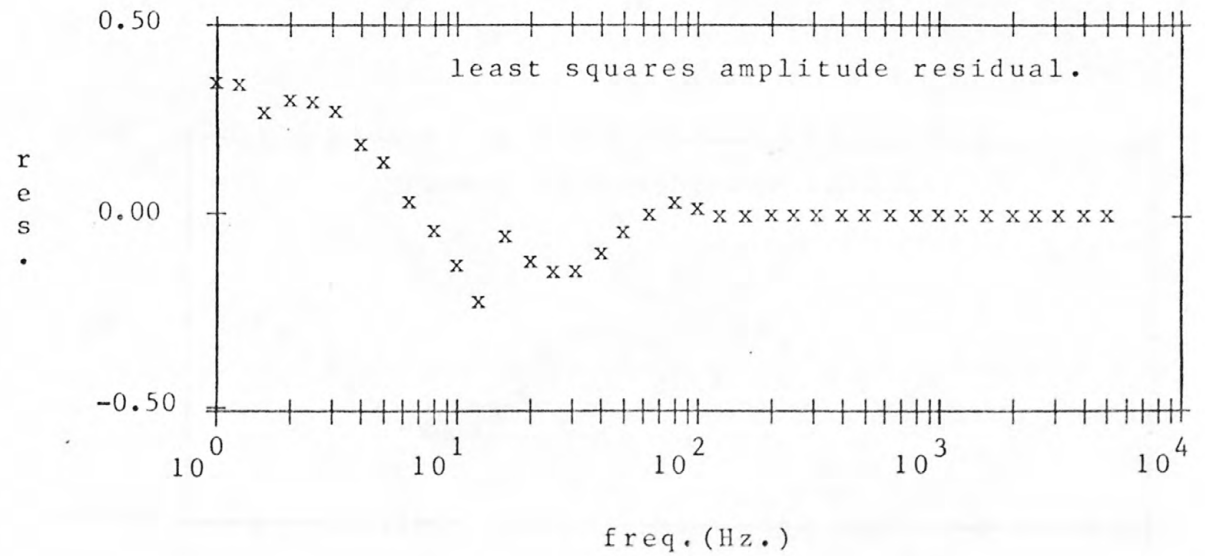
parameter correlation matrix

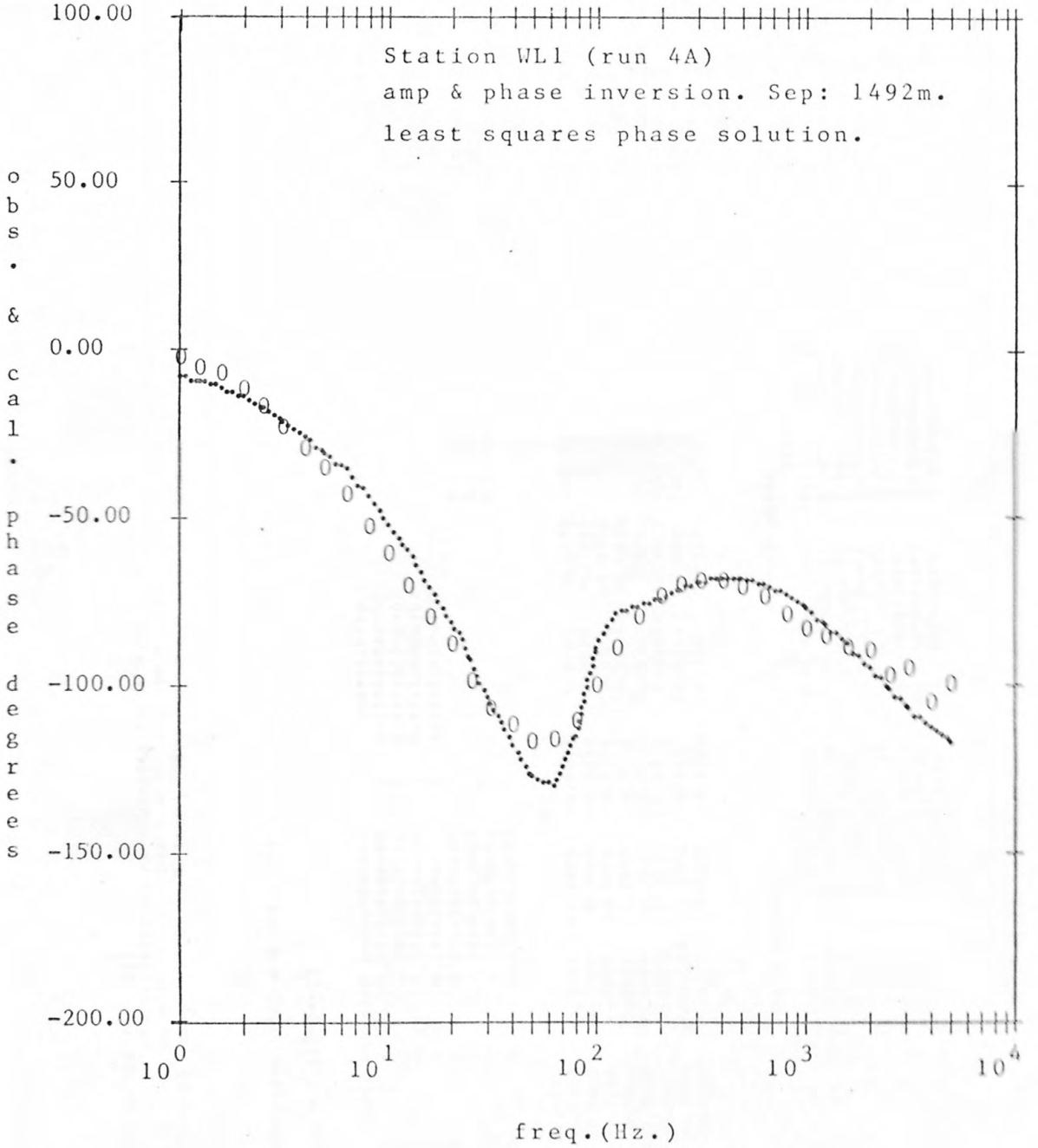
1	1.0000	0.1030	0.5681	0.1194	-0.1894	0.1964
2	0.1030	1.0000	0.0892	0.9898	-0.9845	-0.0503
3	0.5681	0.0892	1.0000	0.1173	-0.2599	0.2622
4	0.1194	0.9898	0.1173	1.0000	-0.9808	-0.0434
5	-0.1894	-0.9845	-0.2599	-0.9808	1.0000	0.0059
6	0.1964	-0.0503	0.2622	-0.0434	0.0059	1.0000

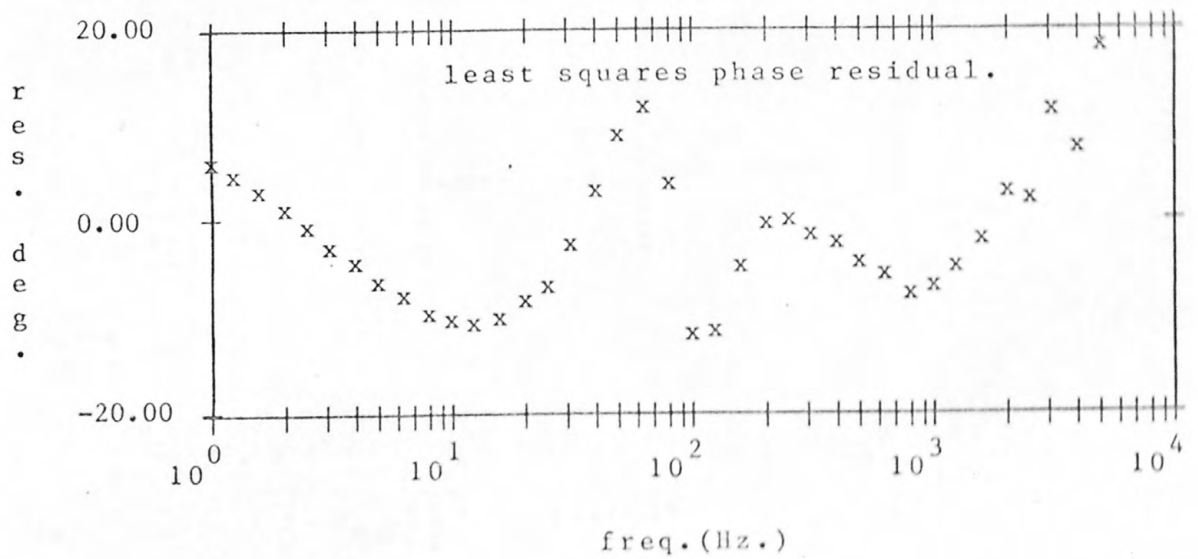
parameter	std error	one - parameter lower	one - parameter upper	support plane lower	support plane upper
1	0.50198418e-02	0.69553029e-01	0.89632397e-01	0.55000611e-01	0.10418481e+00
2	0.84091785e+00	-0.14426965e+01	0.19209749e+01	-0.38805001e+01	0.43587785e+01
3	0.66150308e-01	-0.13182737e+00	0.13277386e+00	-0.32359575e+00	0.32454224e+00
4	0.96348168e+02	-0.39310722e+02	0.34608195e+03	-0.31862209e+03	0.62539331e+03
5	0.28565458e+03	-0.50810976e+03	0.63450854e+03	-0.13362165e+04	0.14626153e+04
6	0.15438482e+02	-0.18771310e+02	0.42982616e+02	-0.63527151e+02	0.87738457e+02

phi	s e
0.13243998e+04	0.46218274e+01


Station WL1 (run 4A)
amp & phase inversion. Sep: 1492m.
least squares amplitude solution.
obs. & cal. amplitude
freq.(Hz.)


least squares amplitude residual.
res.
freq.(Hz.)


Station WL1 (run 4A)
amp & phase inversion. Sep: 1492m.
least squares phase solution.
obs. & cal. phase degrees
100.00
50.00
0.00
-50.00
-100.00
-150.00
-200.00
10^0
10^1
10^2
10^3
10^4
freq.(Hz.)


least squares phase residual.
res. deg.
20.00
0.00
-20.00
10^0
10^1
10^2
10^3
10^4
freq.(Hz.)

```
m a r q h z p --      Station WL1 (run 4A)
iob = 5          mm =  4          x0= 0.27432e+03 y0= 0.14661e+04 l= 0.76428e+03
method = 0       nz = 12          nw = 12          ier = 4          mev =   300
eps=0.10000e-04 ep=0.10000e-02  neps =   10      nfin =    1
```

receiver-transmitter separation (rho) = 0.14915e+04

primary field (hzp x 4pi) = 0.61048e-03

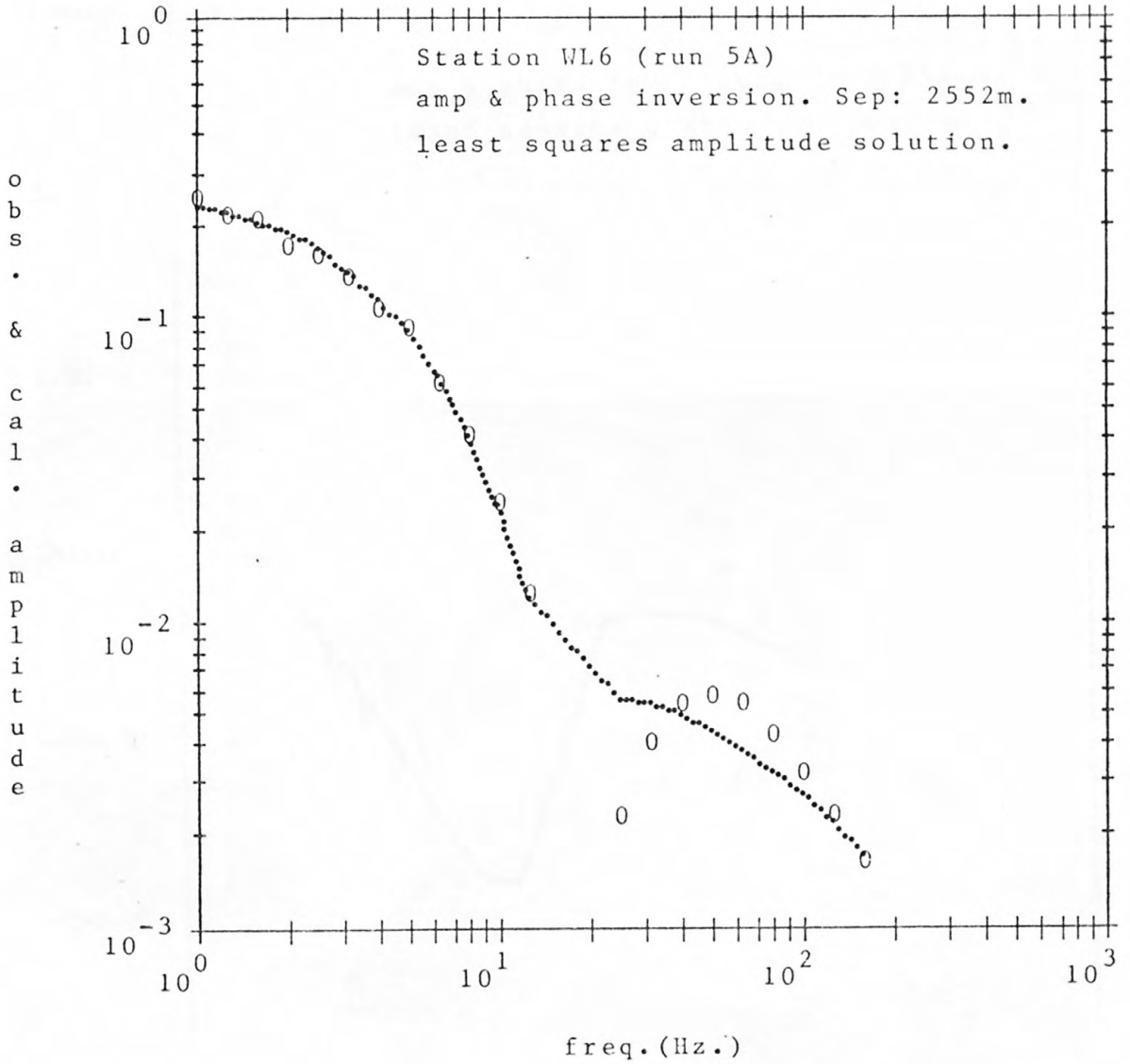
parameter order--		final unscaled parameters--		resistivity		depth
1	sigma(1)	1	0.13522614e+00	1 0.73950198e+01		
2	sigma(2)	2	0.16737642e-01	2 0.59745573e+02		
3	sigma(3)	3	0.17495424e+00	3 0.57157802e+01		
4.	sigma(4)	4	0.24842586e-01	4 0.40253458e+02		
5	thick(1)	5	0.57259259e+01		1	0.57259259e+01
6	thick(2)	6	0.45796286e+02		2	0.51522212e+02
7	thick(3)	7	0.65589869e+02		3	0.11711208e+03
8	b(8)	8	0.33584951e+01			

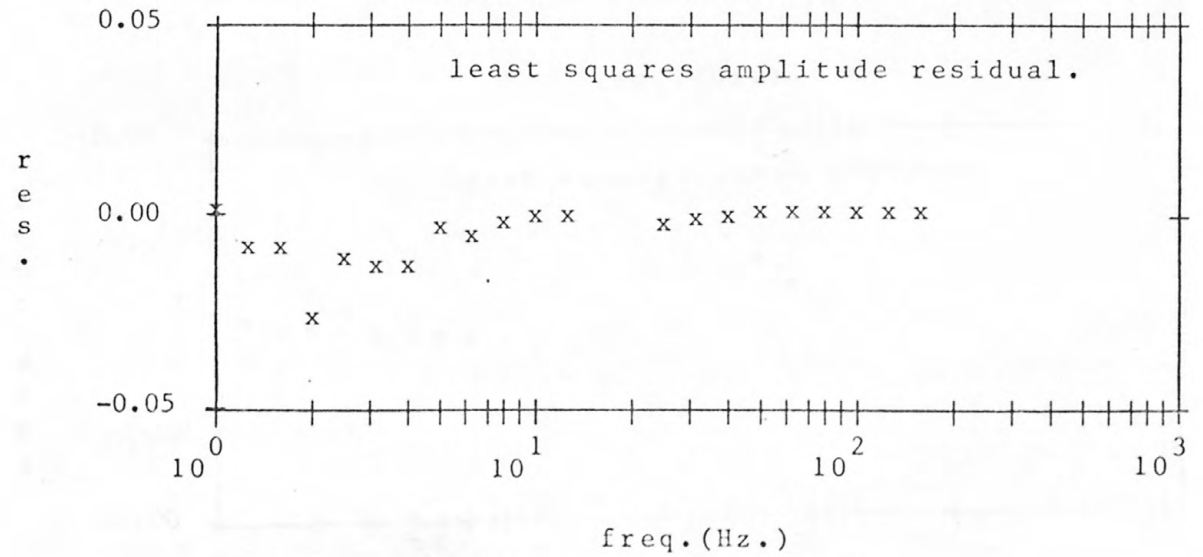
parameter correlation matrix

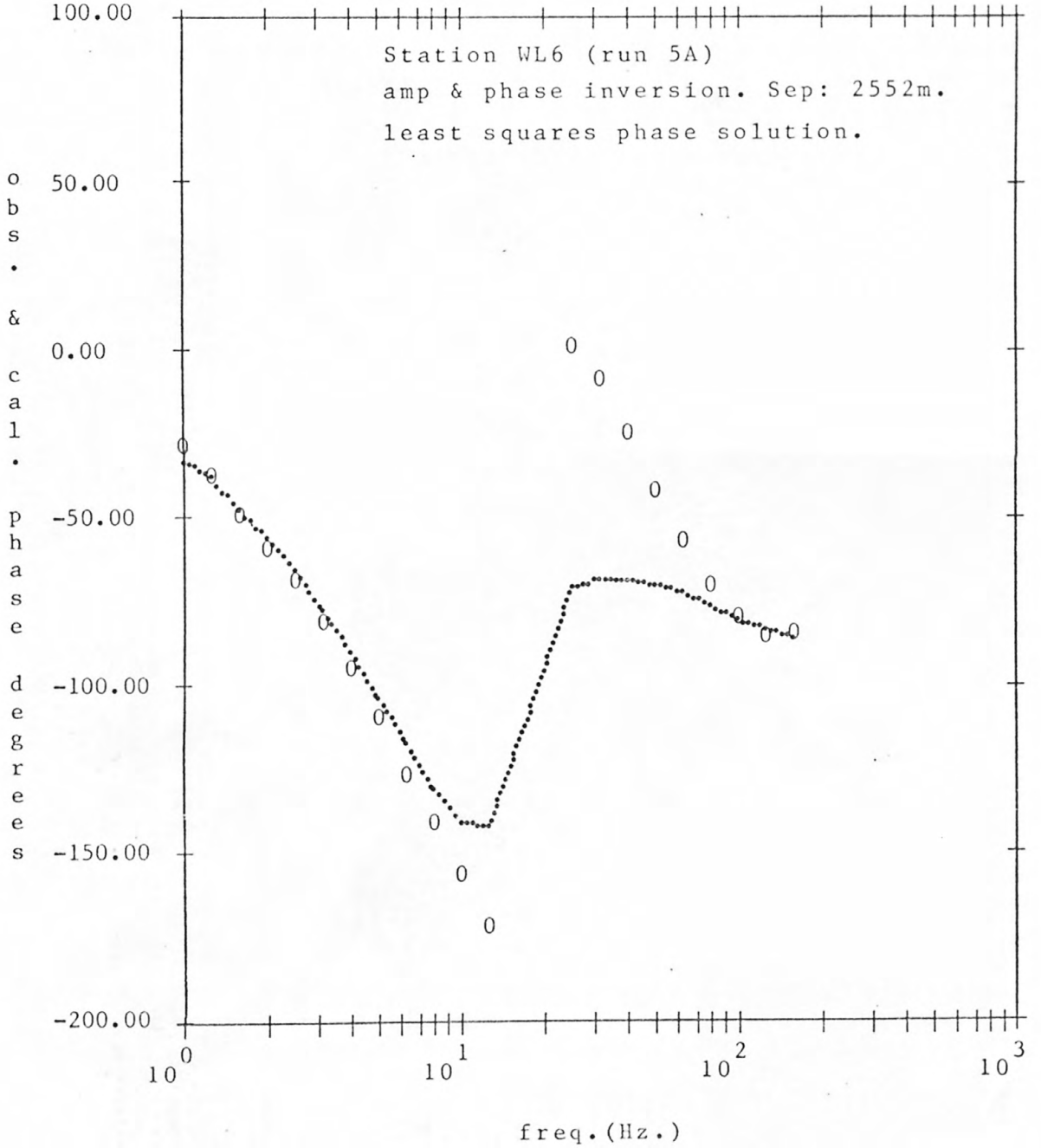
1	1.0000	0.1085	-0.0661	-0.8001	-0.4058	0.1747	0.1655	-0.0307
2	0.1085	1.0000	0.7744	0.0824	-0.9256	0.9507	-0.7784	0.0017
3	-0.0661	0.7744	1.0000	0.3774	-0.6203	0.8348	-0.9836	0.0127
4	-0.8001	0.0824	0.3774	1.0000	0.2215	0.0279	-0.4898	0.0369
5	-0.4058	-0.9256	-0.6203	0.2215	1.0000	-0.9200	0.5991	0.0102
6	0.1747	0.9507	0.8348	0.0279	-0.9200	1.0000	-0.8214	-0.0011
7	0.1655	-0.7784	-0.9836	-0.4898	0.5991	-0.8214	1.0000	-0.0161
8	-0.0307	0.0017	0.0127	0.0369	0.0102	-0.0011	-0.0161	1.0000

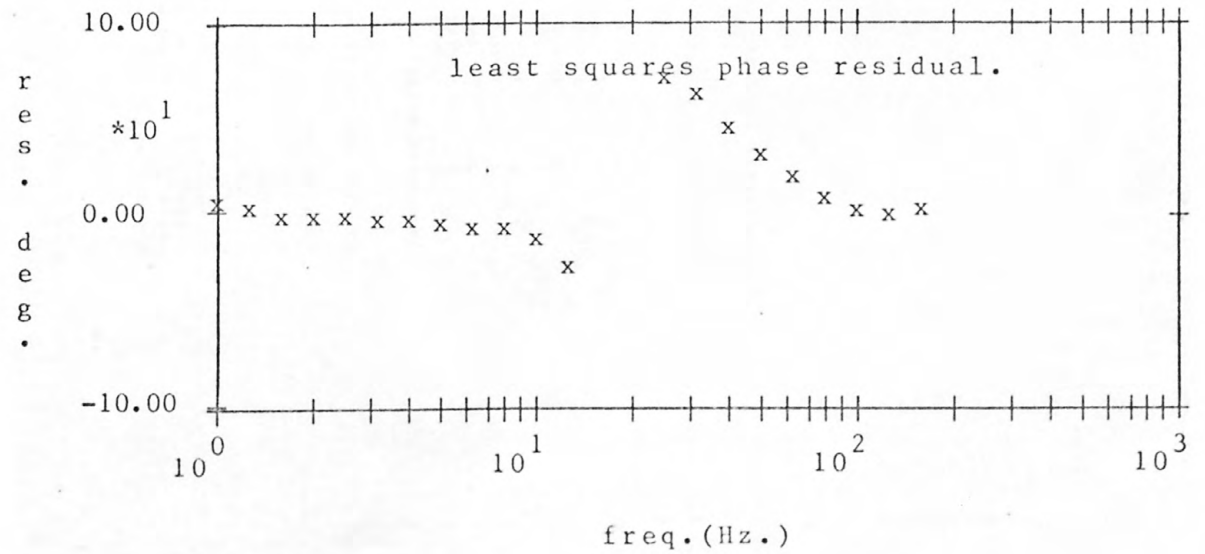
parameter	std error	one - parameter lower	one - parameter upper	support plane lower	support plane upper
1	0.10804862e-01	0.11361642e+00	0.15683587e+00	0.74104611e-01	0.19634767e+00
2	0.19986172e-01	-0.23234702e-01	0.56709986e-01	-0.96321221e-01	0.12979650e+00
3	0.58060471e-01	0.58833301e-01	0.29107518e+00	-0.15348538e+00	0.50339387e+00
4	0.55682565e-02	0.13706073e-01	0.35979099e-01	-0.66562293e-02	0.56341401e-01
5	0.26891732e+01	0.34757948e+00	0.11104272e+02	-0.94863350e+01	0.20938187e+02
6	0.14613333e+02	0.16569619e+02	0.75022952e+02	-0.36869212e+02	0.12846178e+03
7	0.31260975e+02	0.30679193e+01	0.12811182e+03	-0.11124891e+03	0.24242865e+03
8	0.59938721e+01	-0.86292492e+01	0.15346239e+02	-0.30547966e+02	0.37264956e+02

phi	s e
0.20529624e+04	0.54945995e+01


Station WL6 (run 5A)
amp & phase inversion. Sep: 2552m.
least squares amplitude solution.
obs. & cal. amplitude
10^0
10^{-1}
10^{-2}
10^{-3}
10^0
10^1
10^2
10^3
freq.(Hz.)


least squares amplitude residual.
res.
0.05
0.00
-0.05
10^0
10^1
10^2
10^3
freq.(Hz.)


Station WL6 (run 5A)
amp & phase inversion. Sep: 2552m.
least squares phase solution.
obs. & cal. phase degrees
100.00
50.00
0.00
-50.00
-100.00
-150.00
-200.00
10^0
10^1
10^2
10^3
freq.(Hz.)


least squares phase residual.
res. deg.
$*10^1$
10.00
0.00
-10.00
10^0
10^1
10^2
10^3
freq.(Hz.)

```
m a r q h z p --      Station WL6 (run 5A)
iob = 5          mm =  5          x0= 0.79250e+02 y0= 0.25512e+04 l= 0.76428e+03
method = 0       nz = 12          nw = 12          ier = 2          mev =    300
eps=0.10000e-07 ep=0.10000e-02  neps =    10      nfin =     1


receiver-transmitter separation (rho) = 0.25524e+04

primary field (hzp x 4pi) = 0.22470e-03


parameter order--          final unscaled parameters--          resistivity          depth
      1       sigma(  1)        1       0.12649309e+00    1    0.79055703e+01
      2       sigma(  2)        2       0.57746017e+00    2    0.17317212e+01
      3       sigma(  3)        3       0.77522431e+00    3    0.12899492e+01
      4       sigma(  4)        4       0.13742714e+01    4    0.72765832e+00
      5       sigma(  5)        5       0.14184692e-01    5    0.70498534e+02
      6       thick(  1)        6       0.15540674e+03                         1    0.15540674e+03
      7       thick(  2)        7       0.52196850e+02                         2    0.20760359e+03
      8       thick(  3)        8       0.54857416e+01                         3    0.21308933e+03
      9       thick(  4)        9       0.54283565e+01                         4    0.21851768e+03
     10            b( 10)       10       0.27168555e+00


negative diagonal element
```