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Interpretation of Time-Domain Electromagnetic Soundings in the Randsburg, California, Known Geothermal Resource Area

by

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Interpretation of Time-Domain Electromagnetic Soundings in the Randsburg, California, Known Geothermal Resource Area

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A controlled-source, time-domain electromagnetic (TDEM) sounding survey was conducted in the Randsburg, California, Known Geothermal Resource Area (KGRA) between November 30, 1977, and December 13, 1977. The data were interpreted using layered-earth Davidon-Fletcher-Powell and Marquardt inversion computer programs. The results, which are listed in the appendix, show that the area contains a good conductor at depths ranging from a few hundred to a thousand meters below ground surface.

INTRODUCTION

Eleven TDEM soundings were done in the Randsburg KGRA using a grounded-wire current source and a cryogenic magnetometer. The source wire was 1528 m long, oriented along a direction N55E, and continuously pulsed with a 5-amp current at 5-second intervals (5 seconds positive and 5 seconds negative using the EMT 5000 switcher). The same source was used for all 11 soundings. At each numbered location shown in figure 1, a three-component cryogenic SQUID magnetometer (north axis is parallel to source wire) was used to measure the magnetic fields generated by the wire source. The magnetometer was partially buried and covered with a plastic container to minimize noise due to wind and other vibration. Each component (hx,hy,hz) was digitized and recorded separately on a Gould data logger system at 200 samples/second for about 4 minutes. Natural magnetic noise was very low during the survey period, allowing most of the recording to be done without electronic filtering.

DATA REDUCTION AND INTERPRETATION

Along with the magnetic field recording, an apparent conductivity was estimated at some locations on the basis of the amount of time required for the vertical magnetic field to rise to half of its DC (late-time) value, thalf. The formula is derived from a normalized halfspace response model and is

apparent conductivity = 8.5*thalf/r**2

where apparent conductivity is in mhos/m,
thalf is in seconds, and
r, the source-receiver spacing, is in kilometers.

The following is a partial list of the soundings and their associated apparent conductivities as computed in the field:

sounding	apparent conductivity
1	.094 mhos/m
2	.067 mhos/m
3	.05 mhos/m

5	.15	mhos/m
6	.006	mhos/m

Data reduction first requires that the Gould data-logger tape cartridges be transcribed to 9-track tape (Fitterman and Stearns, 1978) for use on a high-speed digital computer. The data from each component are then stacked and converted to a roughly logarithmically-spaced time series. A 4-minute record usually contains 40 to 50 step responses (one every 5 seconds), or nearly 50,000 data points. The stacking first involves picking the start of a response by searching for characteristically large first differences. The following few data points are then examined to make sure that the large first difference is not the beginning of a spike. The position of the large first difference in the whole data set is also determined to see that it is 5 seconds after the last picked response. A string of 1000 points beginning 10 before the large first difference is then extracted from the data set and stored individually. After the entire data set has been searched, these responses are averaged point by point, or stacked, to determine an average response value and a standard deviation for each time interval. If any data fall more than two standard deviations from the average, those data are rejected and the average and standard deviation, or error, are recalculated. Finally, the stacked response is smoothed with a time-varying filter which emphasizes low frequencies at late times and higher frequencies at early times. The reduced response consists of 49 data points spaced at logarithmically-equal intervals of time.

Interpretation of the reduced, vertical magnetic field TDEM data is done by minimizing the weighted, squared differences between data and layered-earth models. Each data point is weighted with the standard error derived from stacking. A computer inversion program for interpretation has been developed from a similar frequency-domain inversion program (Anderson, 1977) and a TDEM multilayer modelling program (Kauahikaua and Anderson, 1977). For an m-layered model, this computer program determines 2m parameters: m conductivities, (m-1) thicknesses, and a scale factor (denoted fctr). If any of the parameters becomes unreasonably large or small (signalling strong dependence on another parameter or insensitivity to a parameter), the program is rerun with that parameter held constant. For each sounding, the best-fitting layered-model parameters and parameter errors, a parameter correlation matrix, and a data and model plot are included in the appendix.

RESULTS

All soundings fit a three-layer model of low-high-low conductivity structure quite closely. The error of the fit was always much less than the measurement error (determined by stacking). Thus, more complicated modelling (four or more layers) was not warranted. Figure 2 is a cross-section displaying the TDEM results alongside ELF frequency sounding results at the same sites (Anderson, 1978). The conductor is shaded in. Agreement is reasonable for soundings 5 and 9 and becomes marginal for soundings 1 and 8. Note that the apparent conductivity determined in the field from the half-time formula agrees very well with the conductivity of the surface layer determined by computer inversion. Figure 3 shows a Schlumberger sounding interpretation (Anderson, 1978) along with TDEM and ELF sounding interpretations at the same location. Note the good agreement between all three proposed models for the general character of the subsurface structure. The interpreted layer conductivities from both TDEM and ELF data are generally greater than those from the Schlumberger data.

Close examination of the parameter correlation matrices and the standard errors shows that the TDEM data are very sensitive to the conductivity-thickness product for the second layer. The magnitude of these products is between 35 and 600 mhos with individual standard errors (of the product) of about 3 to 6 percent. This is of course why the second layer conductivities are unrealistically high and the second layer thicknesses unreasonably thin and why their standard errors are so large. The product alone is determined, not the individual parameters. Many times, the second layer conductance is positively correlated with the first layer thickness, although this trend is not shown by the soundings as a group.

Of the eleven soundings, the data from soundings 3, 7, and 12 were somewhat difficult to interpret. The data from sounding 3 did not stack well due to a bit reading error which caused a profusion of jumps of magnitude 256. Interpretation was not even attempted. The data for sounding 7 were recorded 10 meters away from the source wire (see figure 1). Considerable numerical problems were encountered when TDEM model calculations were attempted for this distance from a 1528-m-long source wire, and infinite wire models were not implemented in the inversion program. Therefore, the source wire was approximated as a dipole and a two-layer model was interpreted (listed in the appendix). The data for sounding 12 were recorded straight off the end of the source wire where the vertical magnetic field was expected to be zero. However, the measured field was surprisingly large - too large to be due to a slight misorientation of the magnetometer. Again, modelling was impossible so the source was taken to be a dipole oriented perpendicular to the source wire and at its center. Exactly how these last two interpretations relate to reality or the other soundings is unknown.

Finally, the vertical magnetic field data were used to estimate the magnitude of the primary magnetic field as is done in the magnetometric method of geophysical surveying (Edwards, 1974). The theoretical primary vertical field is given, for example, by Kauahikaua and Anderson (1977). The following is a list of observed and theoretical primary fields for each sounding plus the magnetometric anomaly, (obs-theoretical)/theoretical, expressed in percent:

sounding	observed, amp/m	theoretical, amp/m	anomaly
1	5.35e-4	4.84e-4	+ 11
2	2.66e-4	2.86e-4	- 7
3	7.28e-5	2.12e-4	- 66
4	2.86e-4	1.30e-3	- 78
5	2.90e-4	3.12e-4	- 7
6	7.71e-5	1.81e-4	- 57
7	9.36e-3	1.91e-2	- 51
8	1.52e-3	1.67e-3	- 9
9	1.81e-4	2.12e-4	- 15
11	8.46e-4	1.31e-4	+546
12	5.87e-4	0	infinite

The anomaly values are contoured in figure 1. The values are generally large, suggesting the existence of lateral inhomogeneities, but the contour pattern is not defined well enough to warrant more quantitative interpretation.

A similar analysis will be possible for the horizontal magnetic field data upon completion of the required computer programs (now in progress). Future TDEM sounding surveys could possibly utilize vertical magnetic field data as well as horizontal magnetic and electric field data. One possible drawback to the use of horizontal fields in sounding work is that they appear to be more contaminated with noise than the vertical fields, requiring more sophisticated stacking and smoothing routines than have been used here.

REFERENCES

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

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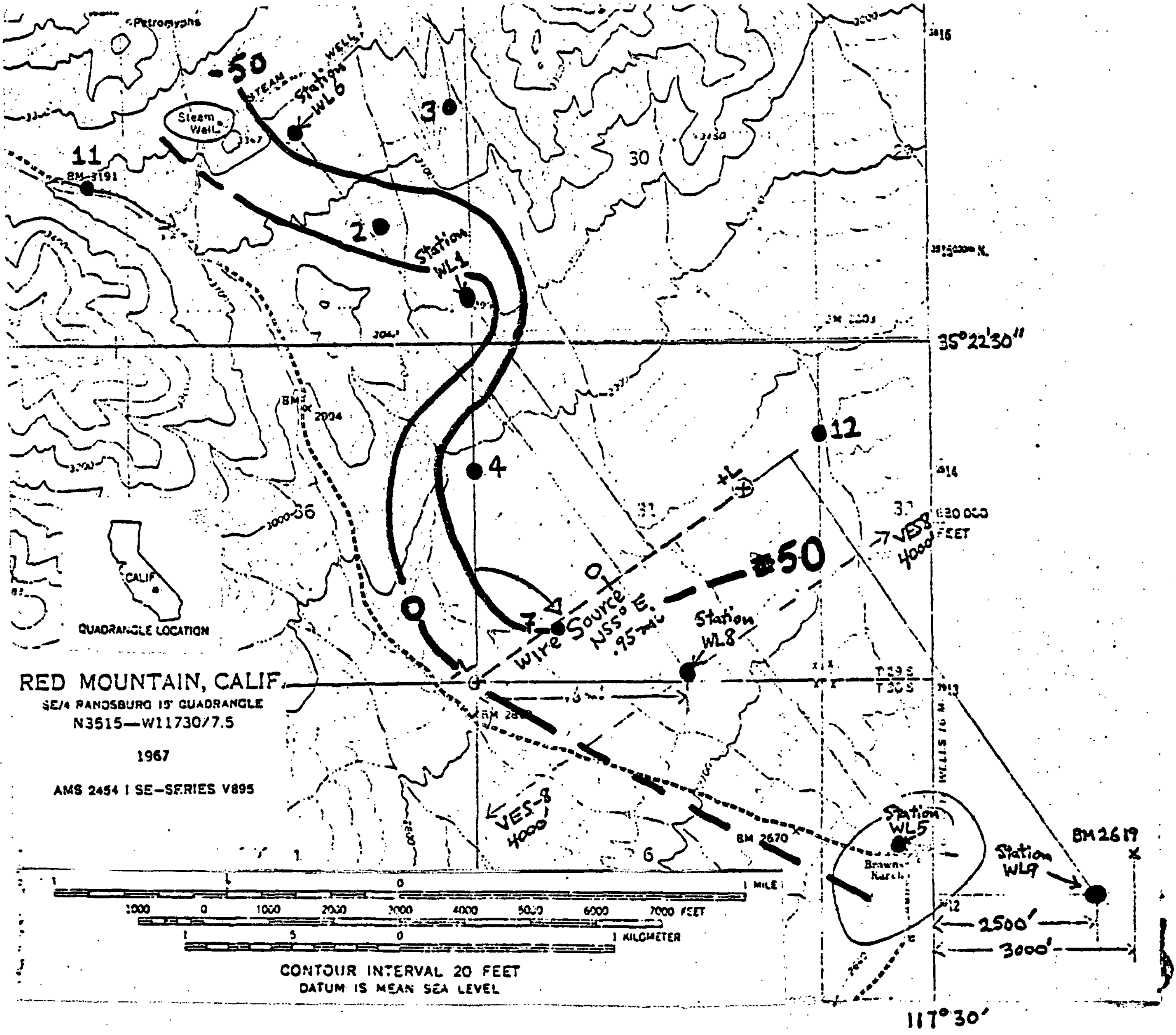

Figure 1. Map of the southwestern section of the Randsburg, California KGRA showing locations of the source wire and 11 TDEM magnetometer sites. Magnetometric anomaly values (percent anomalous field values) are contoured at an interval of 50 percent.

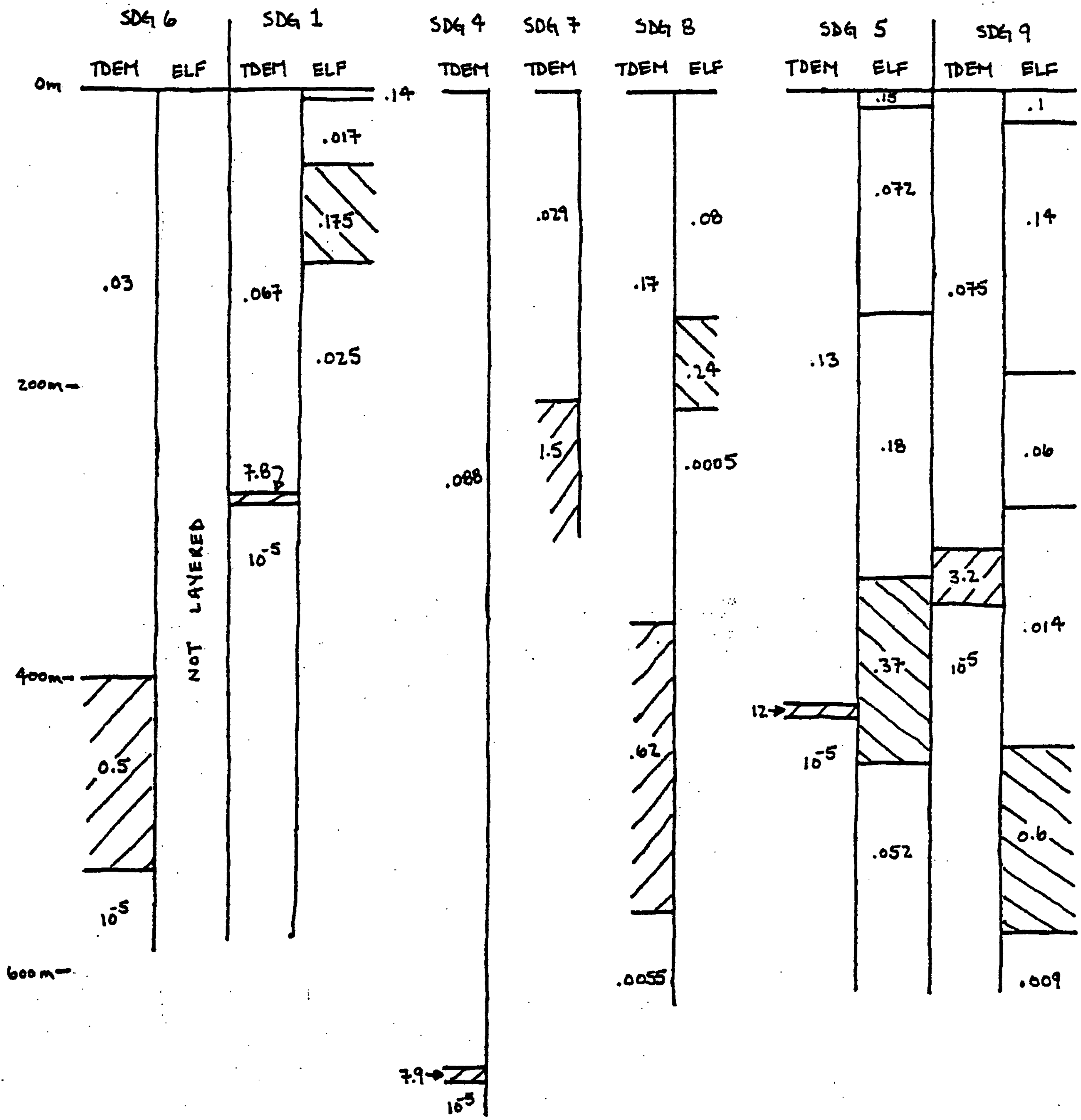

Figure 2. Cross-section perpendicular to the wire source in Figure 1 showing both TDEM and ELF sounding interpretation. Horizontal distances are not to scale.

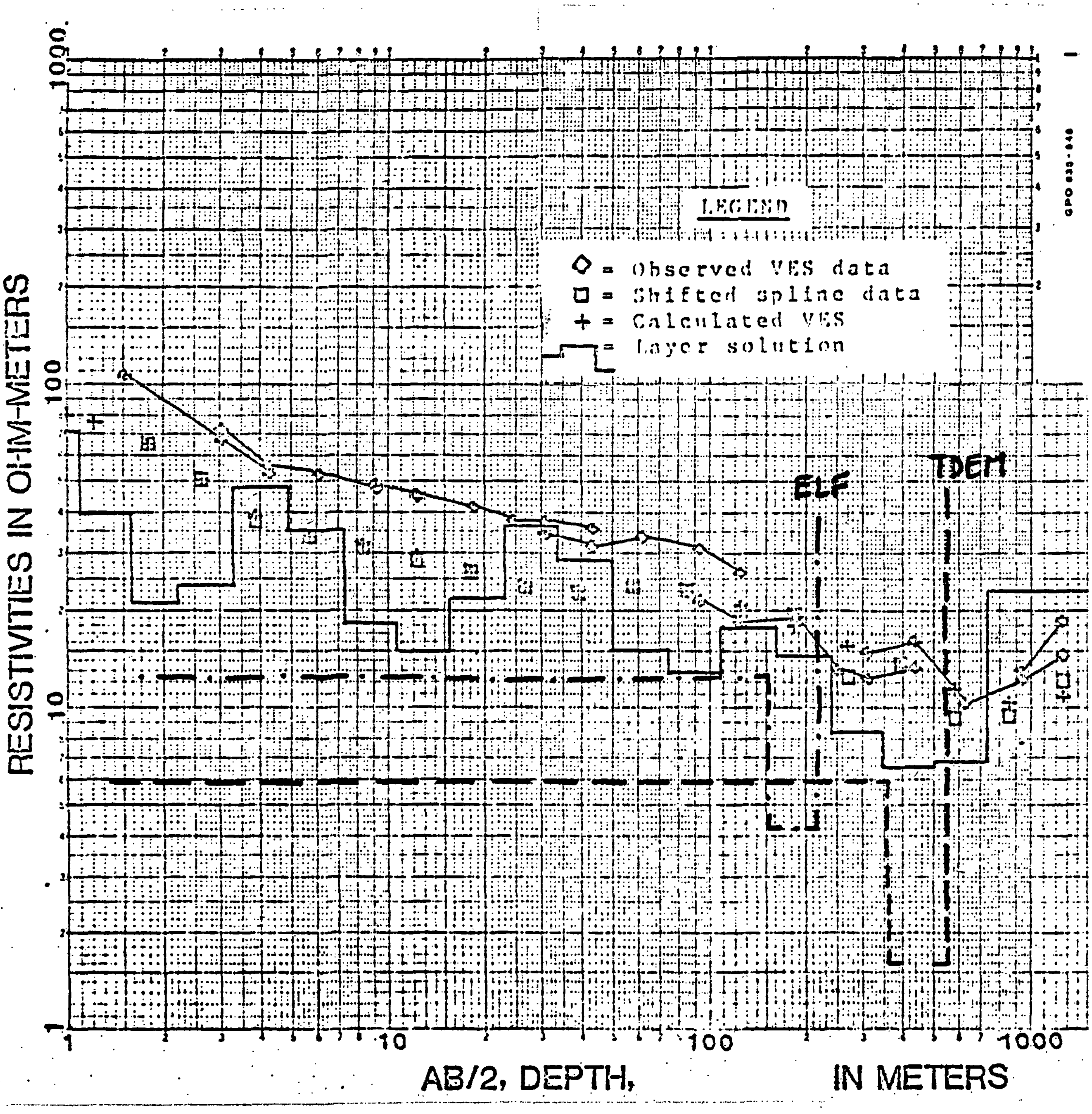

Figure 3. VES-8 Schlumberger sounding and interpretation (modified from Anderson, 1978). Shown also are the interpretations at TDEM and ELF sounding 8 for comparison.

APPENDIX

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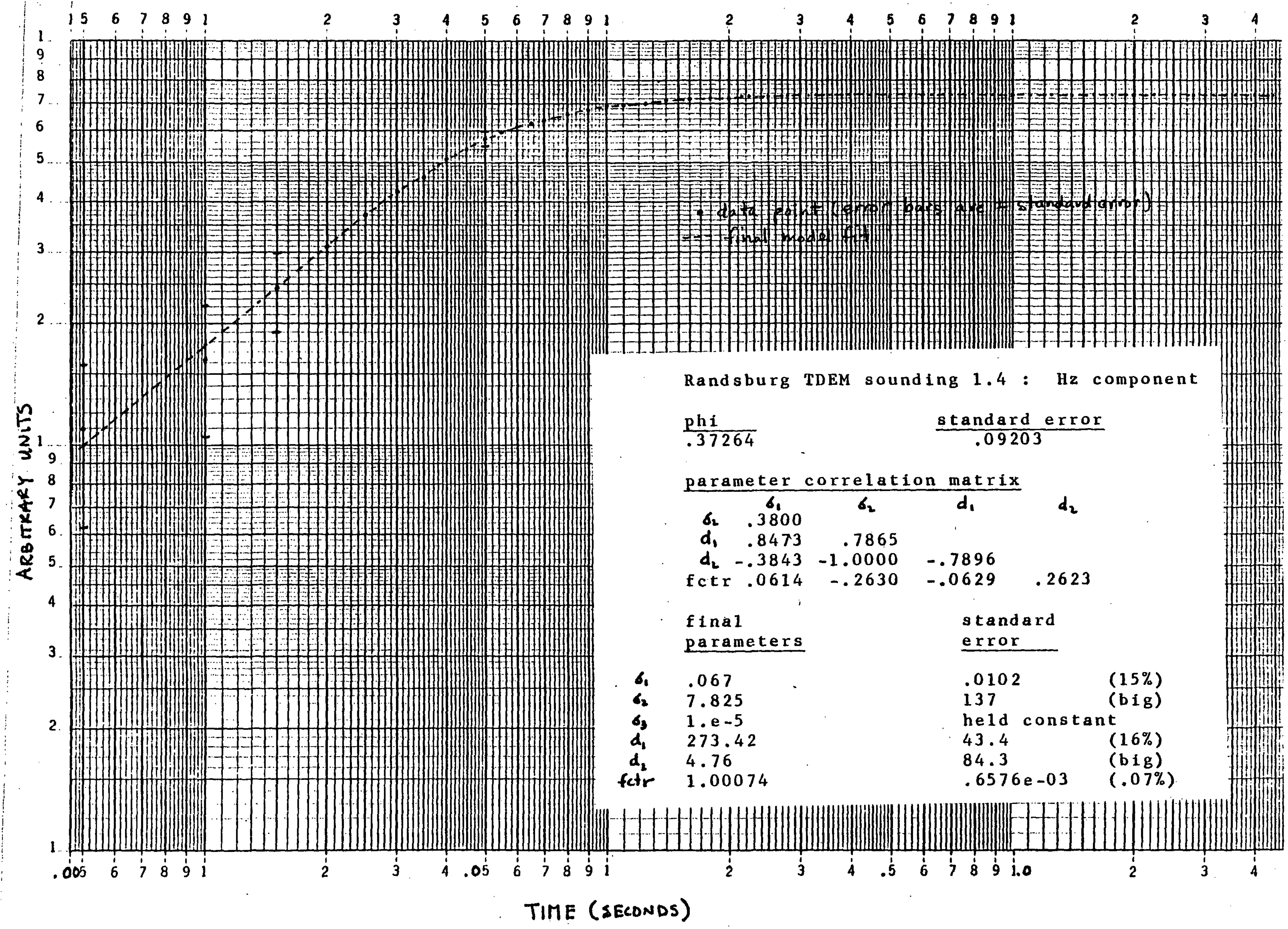


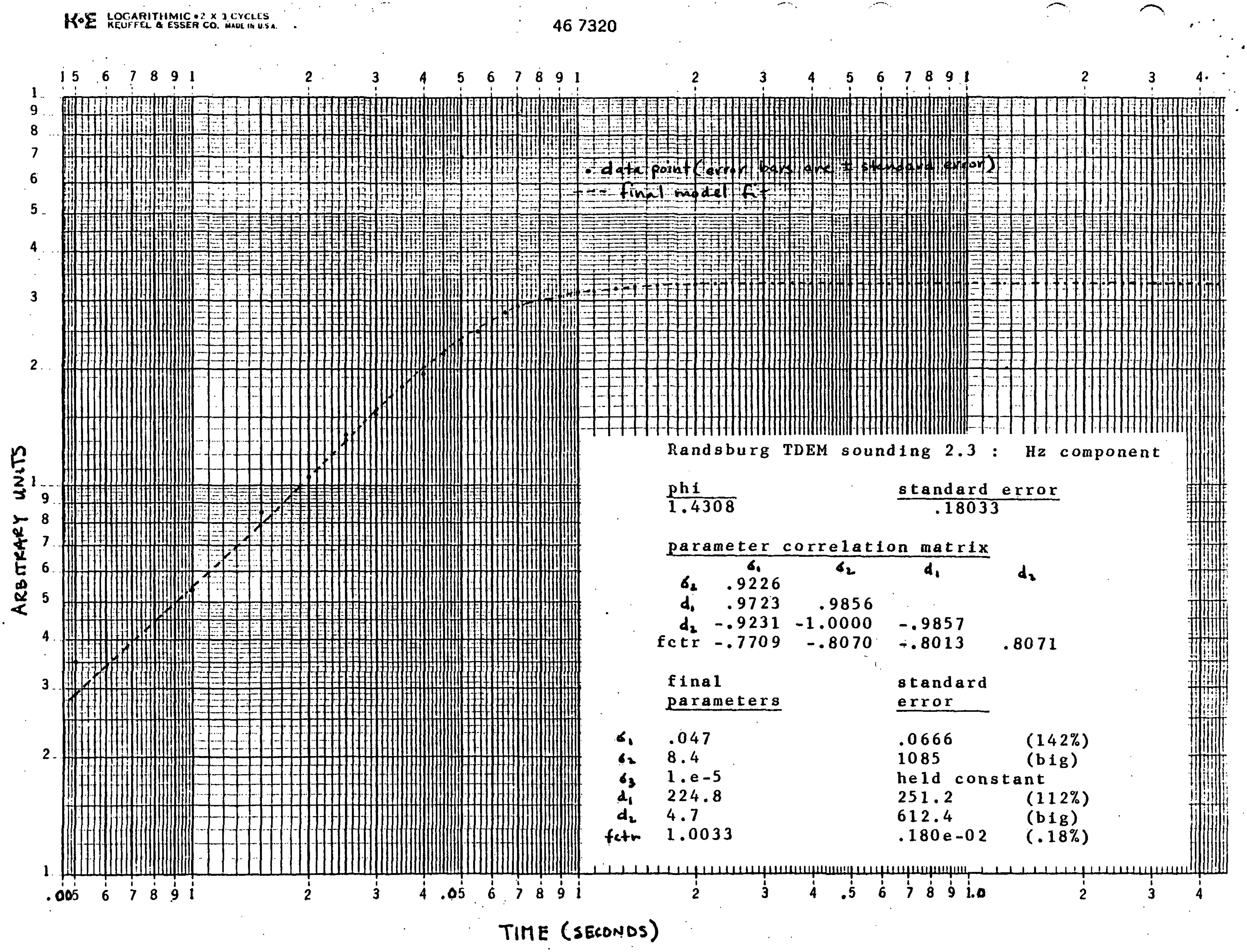
Randsburg TDEM sounding 1.4 : Hz component

phi	standard error
.37264	.09203

parameter correlation matrix

	σ_1	σ_2	d_1	d_2
σ_2	.3800			
d_1	.8473	.7865		
d_2	-.3843	-1.0000	-.7896	
fctr	.0614	-.2630	-.0629	.2623

	final parameters	standard error	
σ_1	.067	.0102	(15%)
σ_2	7.825	137	(big)
σ_3	1.e-5	held constant	
d_1	273.42	43.4	(16%)
d_2	4.76	84.3	(big)
fctr	1.00074	.6576e-03	(.07%)



Randsburg TDEM sounding 2.3 : Hz component

phi	standard error
1.4308	.18033

parameter correlation matrix

	σ_1	σ_2	d_1	d_2
σ_2	.9226			
d_1	.9723	.9856		
d_2	-.9231	-1.0000	-.9857	
fctr	-.7709	-.8070	-.8013	.8071

	final parameters	standard error	
σ_1	.047	.0666	(142%)
σ_2	8.4	1085	(big)
σ_3	1.e-5	held constant	
d_1	224.8	251.2	(112%)
d_2	4.7	612.4	(big)
fctr	1.0033	.180e-02	(.18%)

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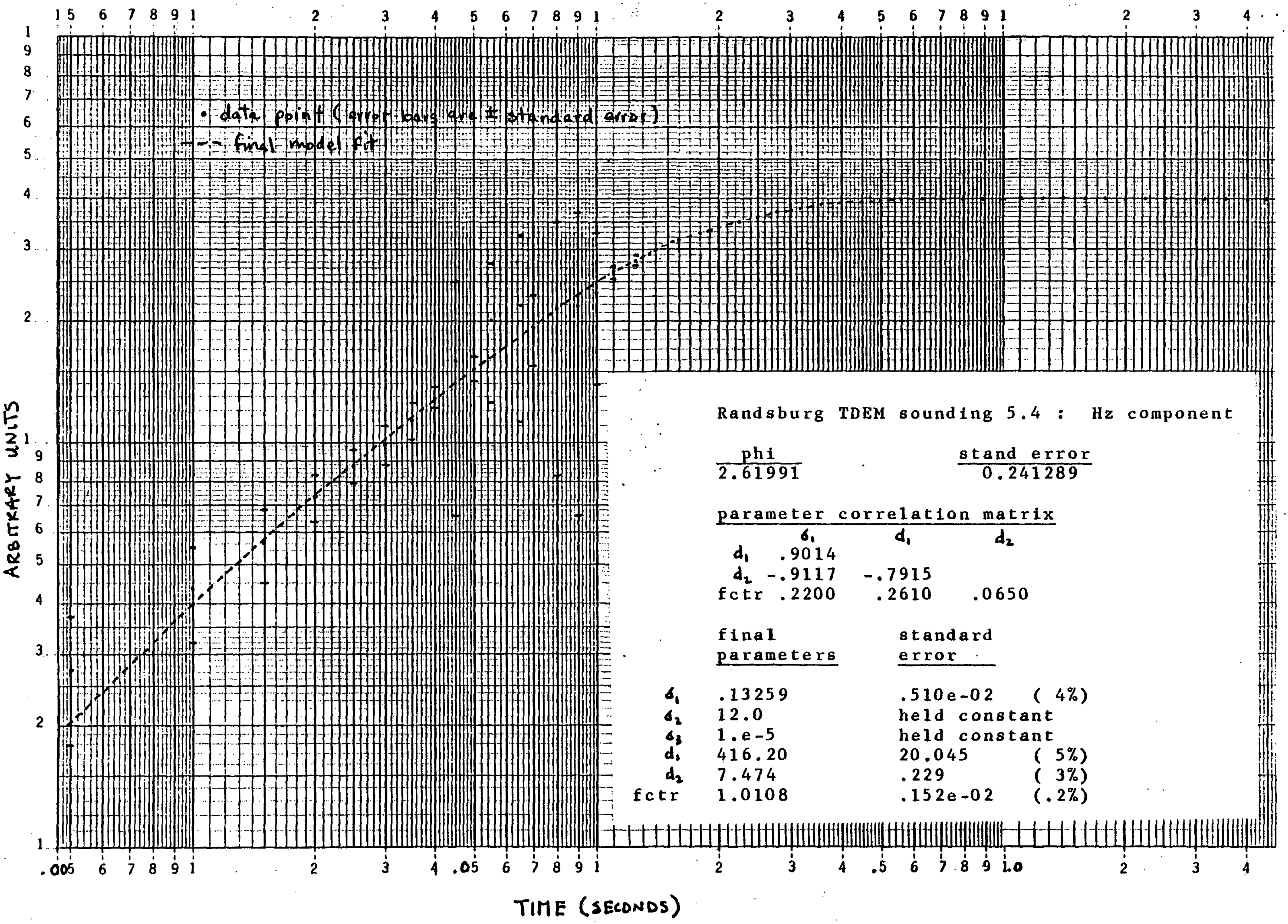

Randsburg TDEM sounding 5.4 : Hz component

phi	stand error
2.61991	0.241289

parameter correlation matrix

$$\begin{array}{lccc} & \sigma_1 & d_1 & d_2 \\ d_1 & .9014 & & \\ d_2 & -.9117 & -.7915 & \\ \text{fctr} & .2200 & .2610 & .0650 \end{array}$$

	final parameters	standard error	
σ_1	.13259	.510e-02	(4%)
σ_2	12.0	held constant	
σ_3	1.e-5	held constant	
d_1	416.20	20.045	(5%)
d_2	7.474	.229	(3%)
fctr	1.0108	.152e-02	(.2%)

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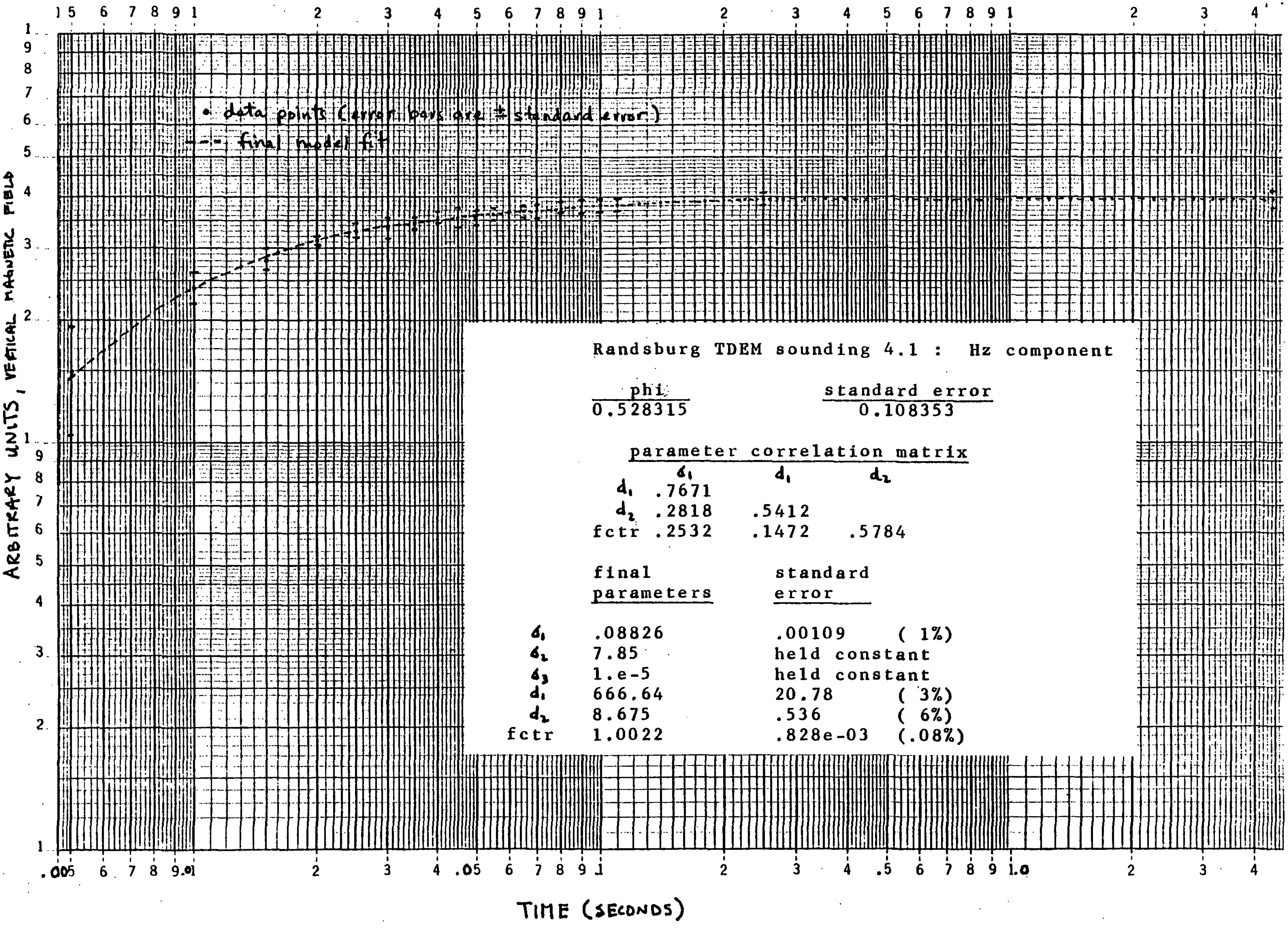

Randsburg TDEM sounding 4.1 : Hz component

phi	standard error
0.528315	0.108353

parameter correlation matrix

	σ_1	d_1	d_2
d_1	.7671		
d_2	.2818	.5412	
fctr	.2532	.1472	.5784

	final parameters	standard error	
σ_1	.08826	.00109	(1%)
σ_2	7.85	held constant	
σ_3	1.e-5	held constant	
d_1	666.64	20.78	(3%)
d_2	8.675	.536	(6%)
fctr	1.0022	.828e-03	(.08%)

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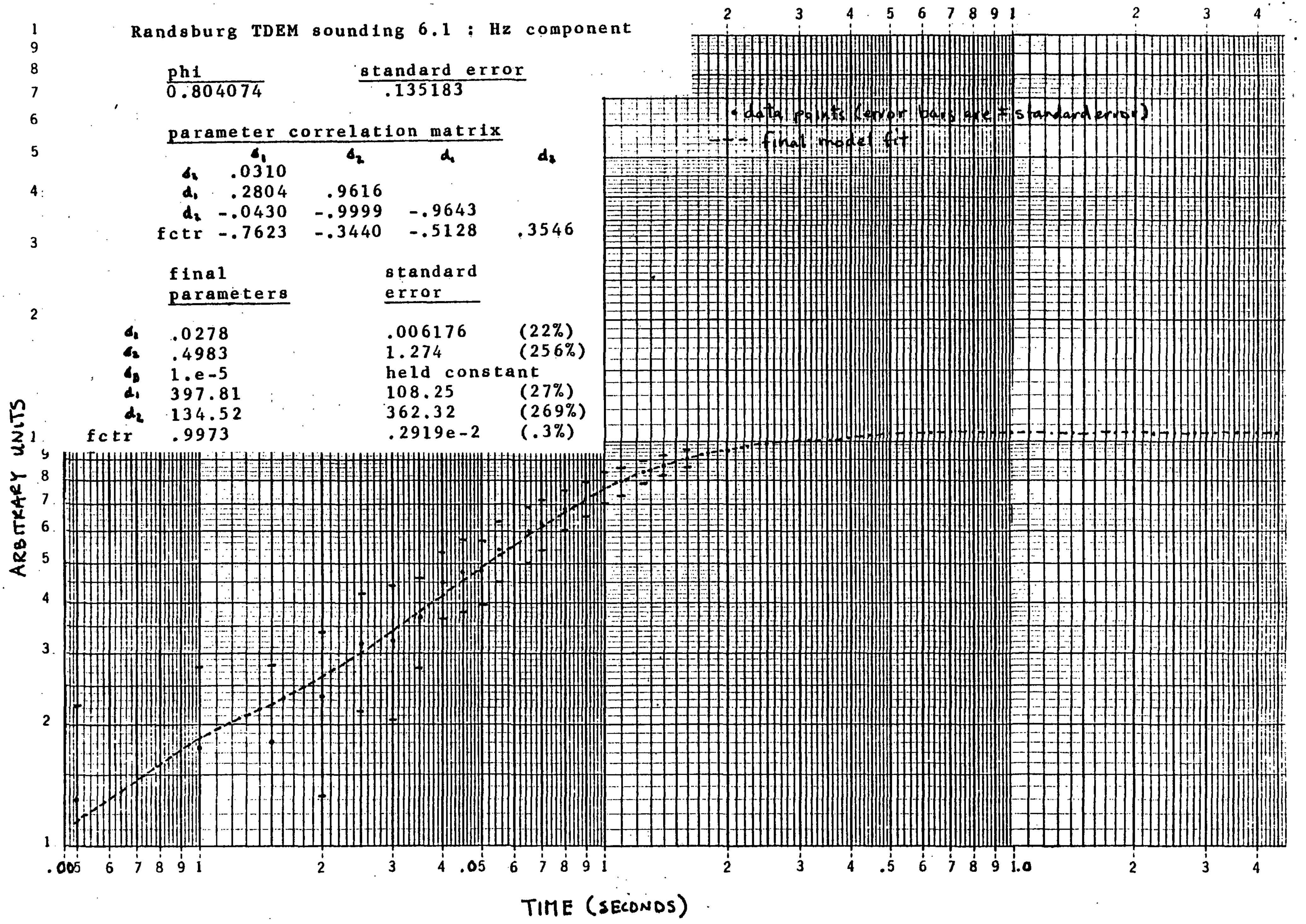
Randsburg TDEM sounding 6.1 : Hz component

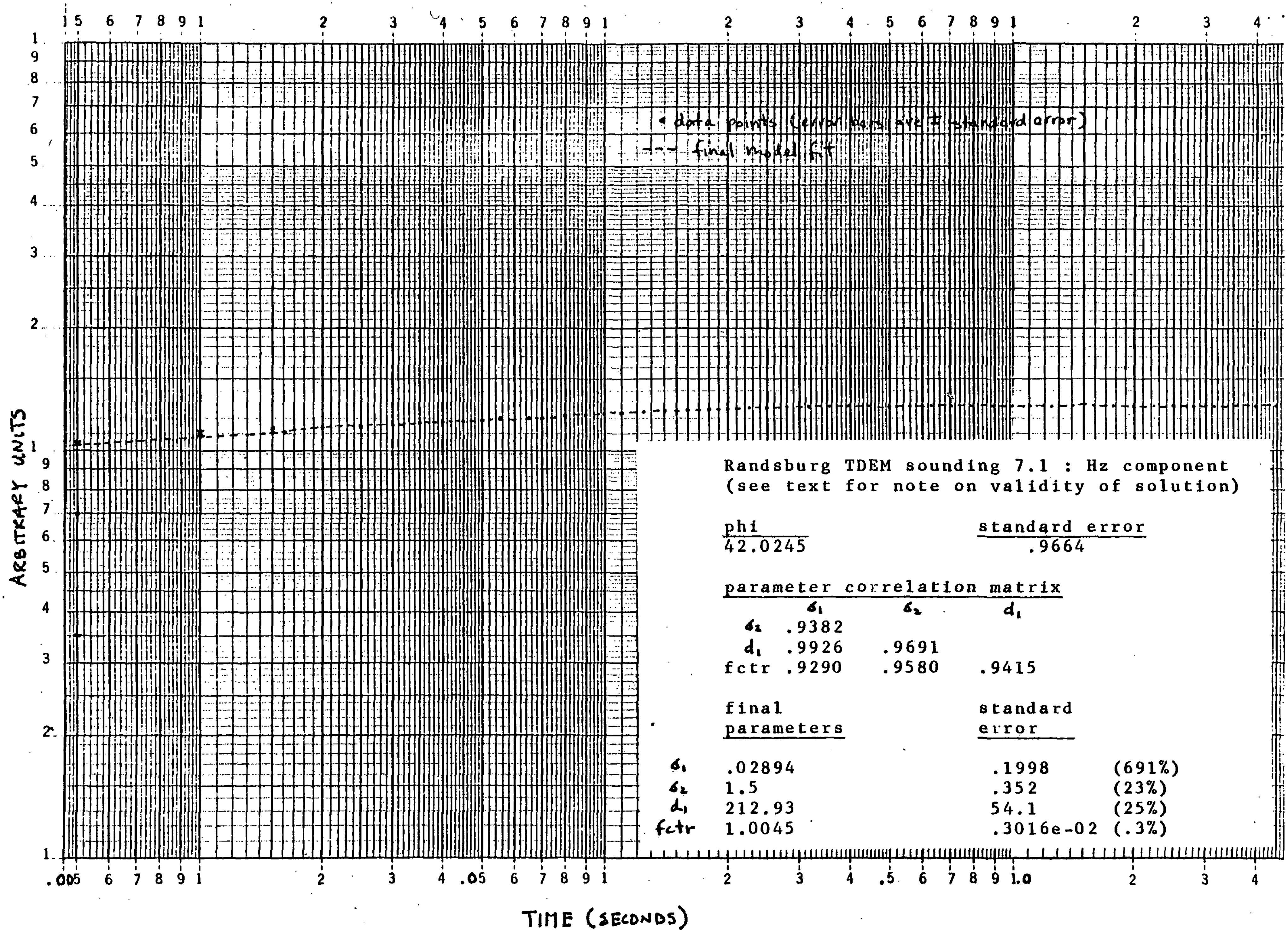
phi	standard error
0.804074	.135183

parameter correlation matrix

	σ_1	σ_2	d_1	d_2
σ_2	.0310			
d_1	.2804	.9616		
d_2	-.0430	-.9999	-.9643	
fctr	-.7623	-.3440	-.5128	.3546

	final parameters	standard error	
σ_1	.0278	.006176	(22%)
σ_2	.4983	1.274	(256%)
σ_3	1.e-5	held constant	
d_1	397.81	108.25	(27%)
d_2	134.52	362.32	(269%)
fctr	.9973	.2919e-2	(.3%)





Randsburg TDEM sounding 7.1 : Hz component
(see text for note on validity of solution)

phi	standard error
42.0245	.9664

parameter correlation matrix

	σ_1	σ_2	d_1
σ_2	.9382		
d_1	.9926	.9691	
fctr	.9290	.9580	.9415

	final parameters	standard error	
σ_1	.02894	.1998	(691%)
σ_2	1.5	.352	(23%)
d_1	212.93	54.1	(25%)
fctr	1.0045	.3016e-02	(.3%)

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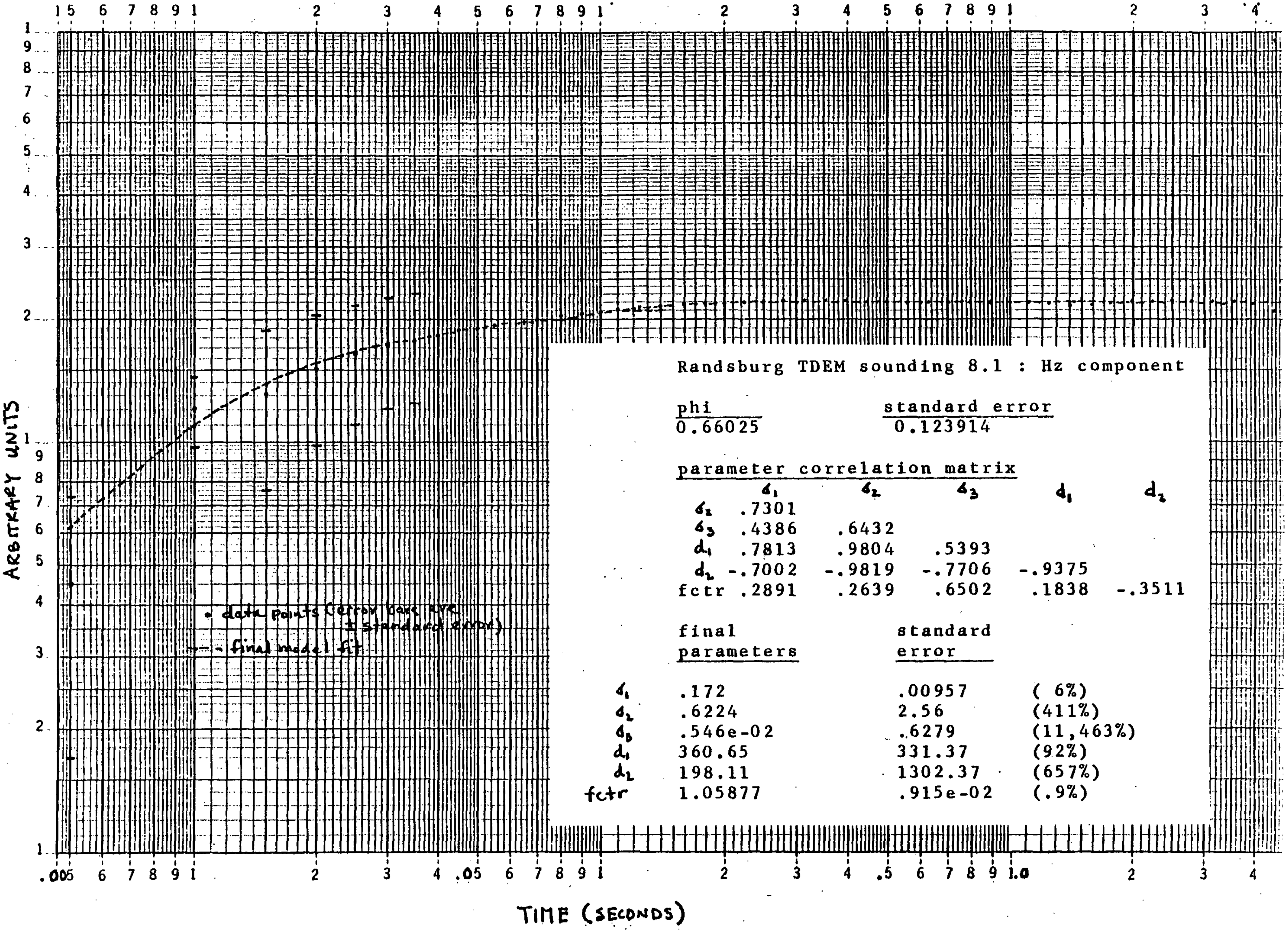


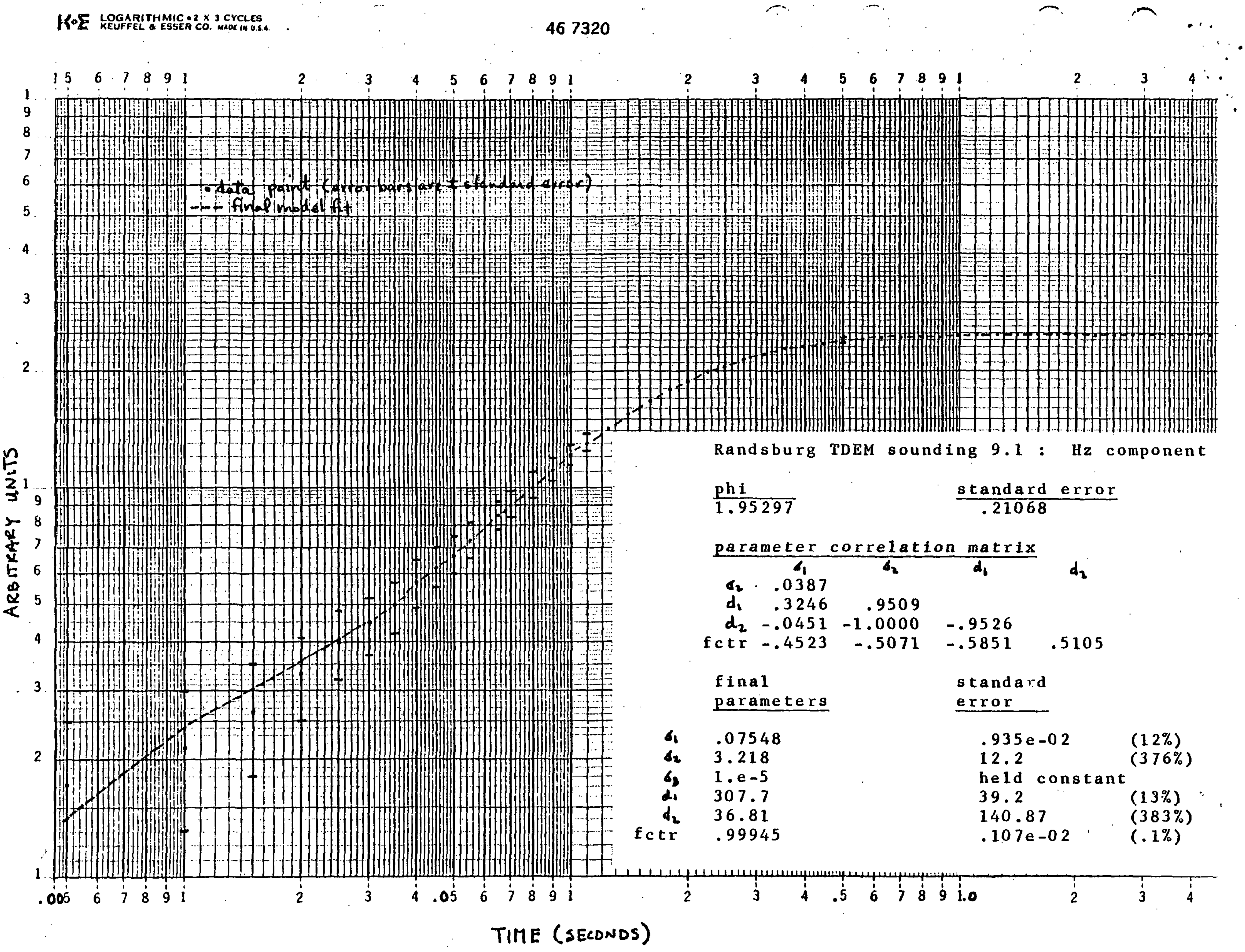
Randsburg TDEM sounding 8.1 : Hz component

phi	standard error
0.66025	0.123914

parameter correlation matrix

	σ_1	σ_2	σ_3	d_1	d_2
σ_2	.7301				
σ_3	.4386	.6432			
d_1	.7813	.9804	.5393		
d_2	-.7002	-.9819	-.7706	-.9375	
fctr	.2891	.2639	.6502	.1838	-.3511

	final parameters	standard error	
σ_1	.172	.00957	(6%)
σ_2	.6224	2.56	(411%)
σ_3	.546e-02	.6279	(11,463%)
d_1	360.65	331.37	(92%)
d_2	198.11	1302.37	(657%)
fctr	1.05877	.915e-02	(.9%)



Randsburg TDEM sounding 9.1 : Hz component

phi	standard error
1.95297	.21068

parameter correlation matrix

	σ_1	σ_2	d_1	d_2
σ_2	.0387			
d_1	.3246	.9509		
d_2	-.0451	-1.0000	-.9526	
fctr	-.4523	-.5071	-.5851	.5105

	final parameters	standard error	
σ_1	.07548	.935e-02	(12%)
σ_2	3.218	12.2	(376%)
σ_3	1.e-5	held constant	
d_1	307.7	39.2	(13%)
d_2	36.81	140.87	(383%)
fctr	.99945	.107e-02	(.1%)

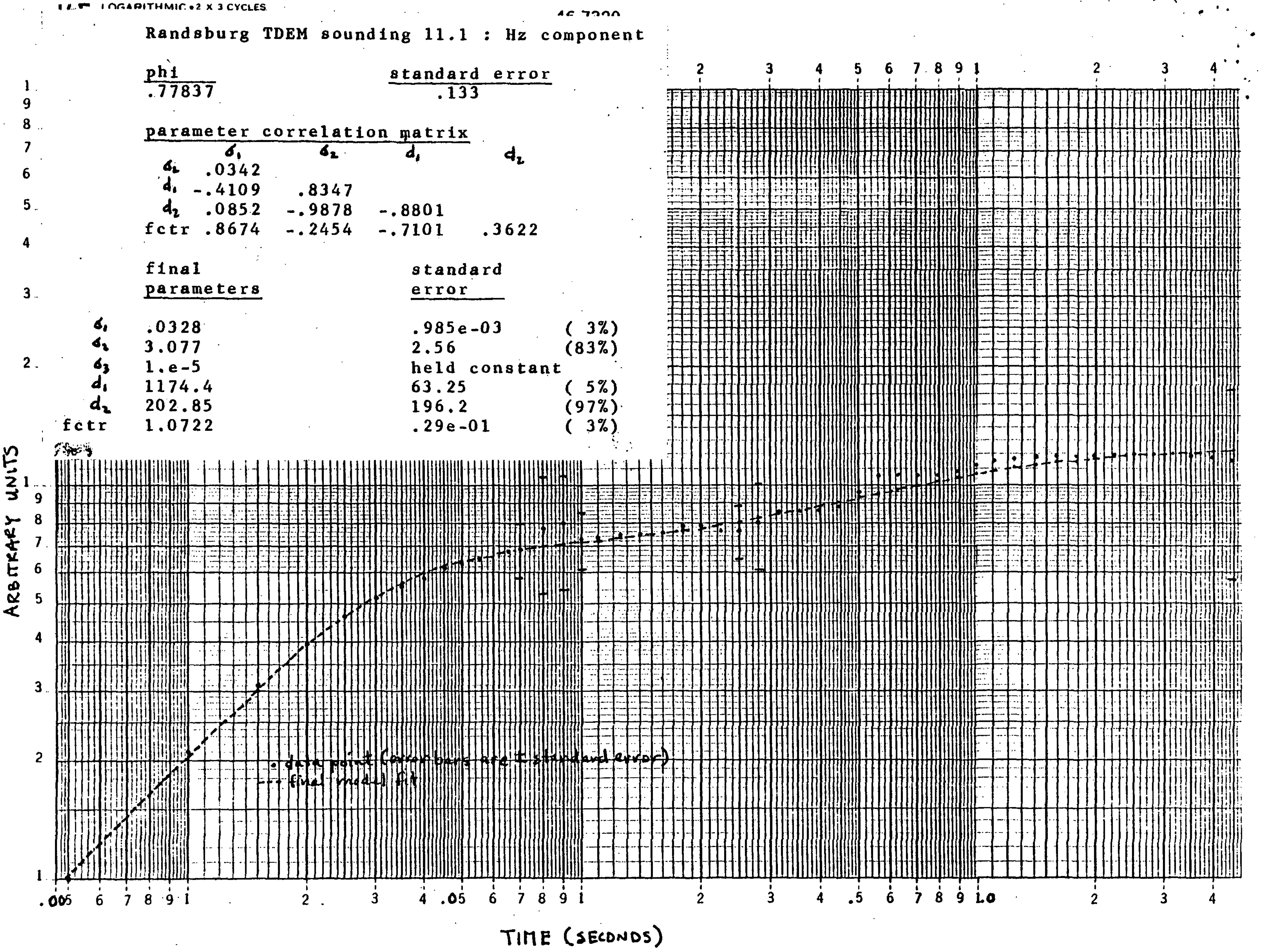
Randsburg TDEM sounding 11.1 : Hz component

phi	standard error
.77837	.133

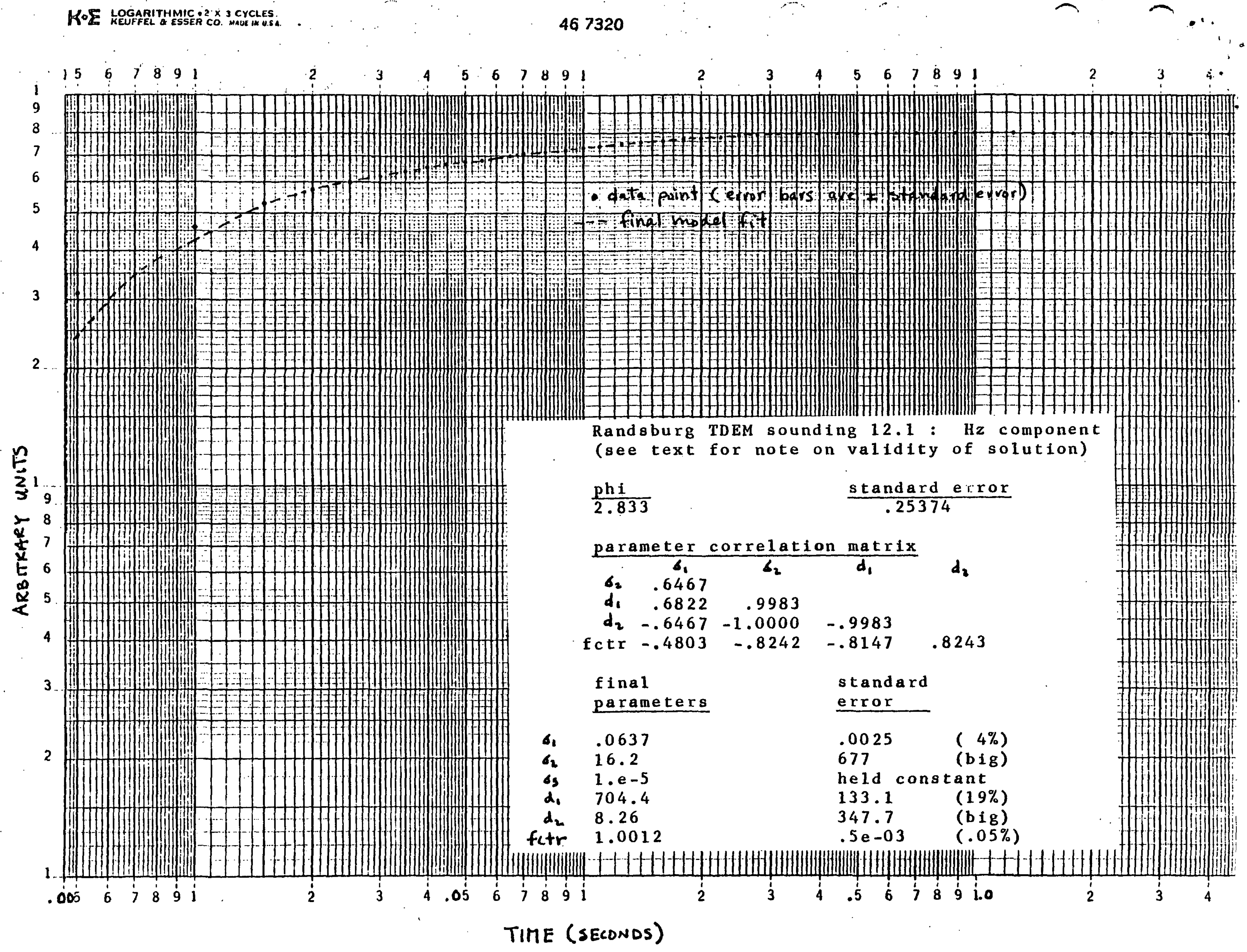
parameter correlation matrix

	σ_1	σ_2	d_1	d_2
σ_2	.0342			
d_1	-.4109	.8347		
d_2	.0852	-.9878	-.8801	
fctr	.8674	-.2454	-.7101	.3622

	final parameters	standard error	
σ_1	.0328	.985e-03	(3%)
σ_2	3.077	2.56	(83%)
σ_3	1.e-5	held constant	
d_1	1174.4	63.25	(5%)
d_2	202.85	196.2	(97%)
fctr	1.0722	.29e-01	(3%)



• data point (error bars are ± standard error)
- - - final model fit



Randsburg TDEM sounding 12.1 : Hz component
(see text for note on validity of solution)

phi	standard error
2.833	.25374

parameter correlation matrix

	σ_1	σ_2	d_1	d_2
σ_2	.6467			
d_1	.6822	.9983		
d_2	-.6467	-1.0000	-.9983	
fctr	-.4803	-.8242	-.8147	.8243

	final parameters	standard error	
σ_1	.0637	.0025	(4%)
σ_2	16.2	677	(big)
σ_3	1.e-5	held constant	
d_1	704.4	133.1	(19%)
d_2	8.26	347.7	(big)
fctr	1.0012	.5e-03	(.05%)