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Exploration geophysics calculator programs for use on Hewlett-Packard models 67 and 97 programmable calculators

by

David L. Campbell and Raymond D. Watts

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Use of brand names and model numbers in this report is for the sake of description only, and does not constitute endorsement by the Geological Survey.

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David L. Campbell and Raymond D. Watts

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Abstract

Program listing, instructions, and example problems are given for 12 programs for the interpretation of geophysical data, for use on Hewlett-Packard models 67 and 97 programmable hand-held calculators. These are (1) gravity anomaly over 2D prism with $\leq$ 9 vertices--Talwani method; (2) magnetic anomaly (ΔT, ΔV, or ΔH) over 2D prism with $\leq$ 8 vertices--Talwani method; (3) total-field magnetic anomaly profile over thick sheet/thin dike; (4) single dipping seismic refractor--interpretation and design; (5) $\leq$ 4 dipping seismic refractors--interpretation; (6) $\leq$ 4 dipping seismic refractors--design; (7) vertical electrical sounding over $\leq$ 10 horizontal layers--Schlumberger or Wenner forward calculation; (8) vertical electric sounding: Dar Zarrouk calculations; (9) magnetotelluric planewave apparent conductivity and phase angle over $\leq$ 9 horizontal layers--forward calculation; (10) petrophysics: a.c. electrical parameters; (11) petrophysics: elastic constants; (12) digital convolution with $\leq$ 10-length filter.

Contents

Program Description

Program Title: Gravity: 2-D anomaly

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Program Description, Equations, Variables, etc. A Talwani-type program to calculate gravity anomaly due to a 2-dimensional prism with ≤ 9 vertices.

Eqn: $$\Delta g = 2G\Delta\rho \sum_{i=1}^{n} \frac{b_i}{d_i}\left\{a_i(z)\left[\ln R_{i+1} - \ln R_i\right] + a_i(x)\left[\theta_{i+1} - \theta_i\right]\right\}$$

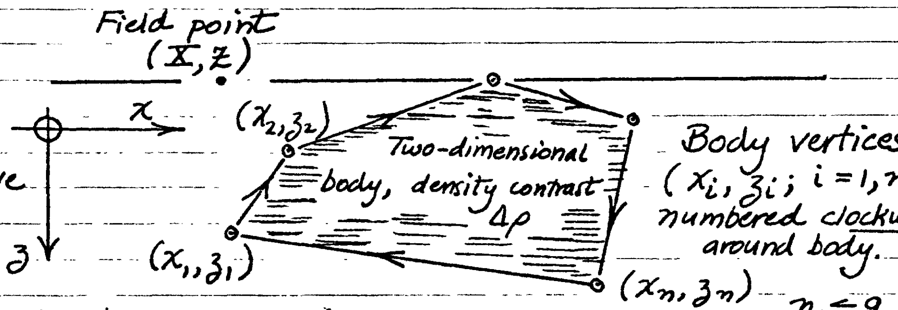
where

$R_i^2 = x_i^2 + z_i^2$ $a_i(x) = x_{i+1} - x_i$ $b_i = x_i z_{i+1} - x_{i+1} z_i$

$\theta_i = \tan^{-1} x_i / z_i$ $a_i(z) = z_{i+1} - z_i$ $d_i = (a_i(x))^2 + (a_i(z))^2$

Geometry:

All coordinates w.r.t. arbitrary origin. (z positive downward.)



Body vertices $(x_i, z_i;\ i = 1, n)$ numbered clockwise around body.

$n \le 9$

Units: Δg in milligals

x, z, X, Z in Km (default) or Kft (flag 0 set).

Δρ in g/cm³.

Reference: Grant, F.S., and West, G.F., 1965, *Interpretation Theory in Applied Geophysics*: New York, McGraw-Hill, p. 289, eqn. 10-7.

Operating Limits and Warnings Total body vertices $n \le 9$. "Error" flashes when $n > 9$. Field point should not coincide with body vertex #1. (Other vertexes o.k.) Program returns 0.00 in this case.

Program assumes I=0 at start of subroutine B (normally the case.) If displayed index is incorrect, reset I to 0, and restart body vertex input.

DO NOT USE THIS SPACE

User Instructions

◀1	Gravity: 2-D anomaly			2▶
Δρ	x↑z	X↑Z →Δg		

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load side 1 and side 2			
2	Set flags, as needed			
	For HP97 print option		SF 0	
	If distances in Kft		SF 1	
	(default – flag 1 cleared – is Km)			
3	Key density difference	Δρ (g/cc)	A	
4	Key body vertices (x_i, z_i; $i=1, n$)	x_i	E↑	
		z_i	B	i
	Repeat step 4 for all body vertices, working successively around body in a clockwise direction. Vertex #1 is not repeated as in some Talwani programs.			
5	Key field points (X, Z)	X	E↑	
		Z	C	Δg (mgal)
	Field points may be anywhere, including inside body, except at vertex #1.			
	Step 5 may be repeated, as desired, to find gravity anomaly due to This body.			
	Steps 2, 3, and 4 may be repeated independently of each other to change body parameters or body geometry.			
6	For a new case, clear registers and go to step 2.			

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	A: Input Δρ
002	SPC	16-11	(Fφ on if Kft.)
003	F1?	16 23 01	
004	GTO0	22 00	
005	4	04	
006	0	00	
007	x	-35	Constant 2GΔρ
008	3	03	for Km input.
009	÷	-24	
010	STOA	35 11	
011	RTN	24	
012	*LBL0	21 00	0:
013	4	04	
014	.	-62	
015	0	00	Constant 2GΔρ
016	3	03	
017	2	02	for Kft input.
018	x	-35	
019	STOA	35 11	
020	RTN	24	
021	*LBLB	21 12	B: Input $\binom{x_i}{z_i}$
022	ISZI	16 26 46	
023	STOi	35 45	z_i
024	R↓	-31	
025	P⇄S	16-51	
026	STOi	35 45	x_i
027	0	00	← These steps clear Old Z
028	STO0	35 00	and old X: in case user
029	P⇄S	16-51	forgot to CL REG at step
030	STO0	35 00	6 of instructions.
031	9	09	
032	RCLI	36 46	
033	X>Y?	16-34	
034	GSBe	23 16 15	← "Error" exit, since
035	STOB	35 12	n — no such address exists.
036	SPC	16-11	
037	RTN	24	
038	*LBLC	21 13	C: Input $\binom{X}{Z}$
039	STOC	35 13	Z
040	R↓	-31	
041	STOD	35 14	X
042	GSBc	23 16 13	Coordinate shift
043	P⇄S	16-51	to put field point
044	RCLD	36 14	at origin.
045	STOC	35 13	
046	GSBc	23 16 13	
047	P⇄S	16-51	
048	R↓	-31	
049	RCL1	36 01	x_1
050	GSBd	23 16 14	z_1 Initialize for
051	RCLB	36 12	n iteration
052	STOI	35 46	Thru set of
053	0	00	body points.
054	STOC	35 13	
055	*LBL1	21 01	1: Iteration entry
056	GSBb	23 16 12	for Σ.

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	GSBd	23 16 14	Get(ΔlnR, Δθ)
058	X=0?	16-43	
059	GTO2	22 02	
060	P⇄S	16-51	
061	GSBa	23 16 11	Δx
062	P⇄S	16-51	
063	x	-35	
064	X⇄Y	-41	
065	GSBa	23 16 11	Δz
066	x	-35	
067	+	-55	Δz·ΔlnR + Δx·Δθ
068	RCLi	36 45	Now get coeff b_i
069	ISZI	16 26 46	If i=n, set
070	RCLB	36 12	i+1=n
071	RCLI	36 46	
072	X>Y?	16-34	
073	GSB6	23 06	
074	STOI	35 46	
075	R↓	-31	These steps avoid having to take
076	R↓	-31	vertex n ≡ vertex 1,
077	RCLi	36 45	as in some Talwani
078	P⇄S	16-51	programs.
079	RCLi	36 45	
080	R↓	-31	
081	X⇄Y	-41	
082	R↑	16-31	
083	x	-35	
084	X⇄Y	-41	
085	DSZI	16 25 46	
086	GTO3	22 03	
087	RCLB	36 12	If i+1=n, set i=n.
088	STOI	35 46	
089	R↓	-31	
090	*LBL3	21 03	3:
091	RCLi	36 45	
092	P⇄S	16-51	
093	x	-35	
094	-	-45	
095	CHS	-22	← b_i now calculated
096	x	-35	
097	GSBa	23 16 11	Now get denom d_i
098	X²	53	
099	P⇄S	16-51	
100	GSBa	23 16 11	
101	P⇄S	16-51	
102	X²	53	
103	+	-55	← d_i now calculated.
104	÷	-24	
105	RCLA	36 11	
106	x	-35	
107	RCLC	36 13	
108	+	-55	
109	STOC	35 13	
110	*LBL2	21 02	2: Entry if Δθ=0.
111	DSZI	16 25 46	
112	GTO1	22 01	

REGISTERS

0	1	2	3	4	5	6	7	8	9
Old Z	z_1	z_2	z_3	. . .					

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
Old X	x_1	x_2	x_3	. . .					

A	B	C	D	E	I
2GΔρ	n	New X, Σ	ln R	θ	Used

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
113	F0?	16 23 00	
114	PRTX	-14	
115	SPC	16-11	
116	RTN	24	
117	*LBLa	21 16 11	a: Get $a_i(x)$
118	ISZI	16 26 46	If $i=n$, set $i+1=1$ (because vertex $n \neq$ vertex 1)
119	RCLB	36 12	
120	RCLI	36 46	
121	X>Y?	16-34	
122	GSB6	23 06	
123	STOI	35 46	
124	R↓	-31	
125	R↓	-31	
126	RCLi	36 45	
127	DSZI	16 25 46	
128	GTO5	22 05	If $i+1=n$, Set $i=n$.
129	RCLB	36 12	
130	STOI	35 46	
131	R↓	-31	
132	*LBL5	21 05	5:
133	RCLi	36 45	
134	-	-45	
135	RTN	24	
136	*LBL6	21 06	6:
137	R↓	-31	
138	1	01	
139	RTN	24	
140	*LBLb	21 16 12	b: Get body vertex i $\binom{x_i}{z_i}$
141	P⇄S	16-51	
142	RCLi	36 45	
143	P⇄S	16-51	
144	RCLi	36 45	
145	RTN	24	
146	*LBLc	21 16 13	c: Coord. Shift
147	RCLB	36 12	
148	STOI	35 46	
149	*LBL4	21 04	4: New x = old x + Old X − new X
150	RCLi	36 45	
151	RCL0	36 00	
152	+	-55	
153	RCLC	36 13	
154	-	-45	
155	STOi	35 45	
156	DSZI	16 25 46	
157	GTO4	22 04	
158	RCLC	36 13	Replace Old X by New X.
159	STO0	35 00	
160	RTN	24	
161	*LBLd	21 16 14	d: Input $\binom{x_i}{z_i}$
162	X=0?	16-43	
163	GTO9	22 09	
164	*LBL8	21 08	8:
165	→P	34	
166	RCLD	36 14	
167	X⇄Y	-41	
168	X≠0?	16-42	
169	LN	32	
170	STOD	35 14	← STO $\ln R_i$ in D
171	-	-45	
172	X⇄Y	-41	
173	RCLE	36 15	
174	X⇄Y	-41	
175	STOE	35 15	← STO θ_i in E
176	-	-45	
177	X<0?	16-45	These marked steps deal with the (unlikely) case when field point is inside the body.
178	SF2	16 21 02	
179	ABS	16 31	
180	Pi	16-24	
181	X>Y?	16-34	
182	GTO7	22 07	
183	2	02	
184	x	-35	
185	-	-45	
186	F2?	16 23 02	
187	CHS	-22	
188	RTN	24	
189	*LBL7	21 07	7:
190	R↓	-31	
191	F2?	16 23 02	
192	CHS	-22	
193	RTN	24	
194	*LBL9	21 09	9:
195	X≠Y?	16-32	
196	GTO8	22 08	
197	RCLD	36 14	
198	0	00	
199	STOD	35 14	
200	RTN	24	Return $\binom{\Delta \ln R}{\Delta\theta}$
210			
220			

LABELS

A Δe	B x_i↑z_i	C X↑Z→Δg	D —	E —
a $a_i(x)$	b body vertex	c Coord. shift	d Δθ, Δ ln R	e Error exit
0 Used in A	1 Used in C	2 Used in C	3 Used in C	4 Used in c
5 Used in a	6 Used in a	7 Used in d	8 Used in d	9 Used in d

FLAGS

0	Print
1	Kft
2	Used in c
3	—

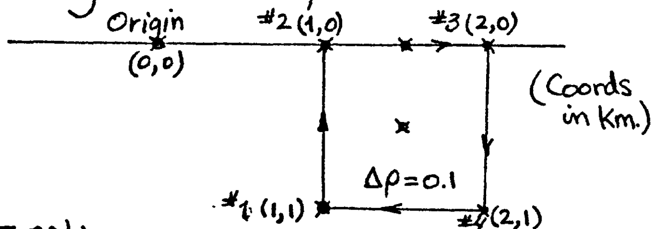
SET STATUS

FLAGS	ON	OFF
0	☐	☒
1	☐	☒
2	☐	☒
3	☐	☐

TRIG	
DEG	☐
GRAD	☐
RAD	☒

DISP	
FIX	☒
SCI	☐
ENG	☐
n	2

EXAMPLE: Investigate gravity anomaly due to the 2-D square, 1 Km on as side, shown here. Suppose density contrast $\Delta\rho = 0.10\,g/cm^3$.



SOLUTION:

Printer output	Comment
SF0	Set flag 0 for printer output.
.10 GSBA	Input Δρ (Step 3).
1.00 ENT↑ 1.00 GSBB 1.00 ENT↑ 0.00 GSBB 2.00 ENT↑ 0.00 GSBB 2.00 ENT↑ 1.00 GSBB	Input body vertices (Step 4).
	Input field points (Step 5).
0.00 ENT↑ 0.00 GSBC 0.26 ***	First field point (0,0) has $\Delta g = 0.26$ mgal.
1.00 ENT↑ 0.00 GSBC 1.51 ***	Second field point (1,0), at body vertex #2, has $\Delta g = 1.51$ mgal.
1.50 ENT↑ 0.00 GSBC 2.31 ***	Third field point, located on center top edge of body, has $\Delta g = 2.31$ mgal.
2.00 ENT↑ 0.00 GSBC 1.51 ***	Forth field point, located symmetrically from second one, has same Δg.
1.00 ENT↑ 1.00 GSBC 0.00 ***	Program gives (wrong) $\Delta g = 0$ if field point is placed at body vertex #1.
1.50 ENT↑ .50 GSBC -1.000000000-09 ***	In very center of body, Δg should equal zero. A very small round-off residual is calculated.
2.00 ENT↑ 1.00 GSBC -1.51 ***	At body's bottom corner, field is negative of that at top corner.

Program Description

Program Title *Two-dimensional magnetic anomaly for body of ≤ 8 vertices.*

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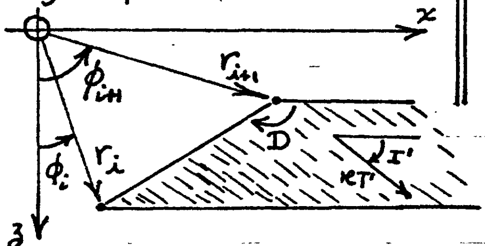
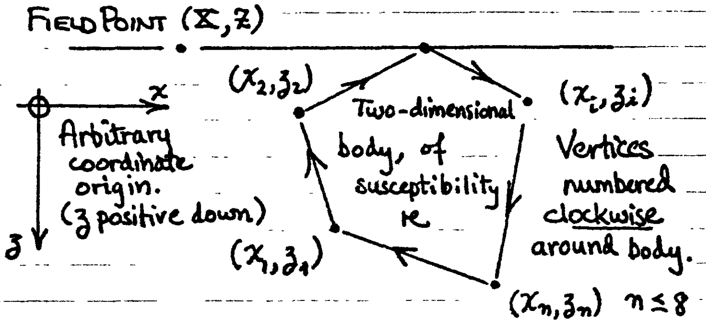
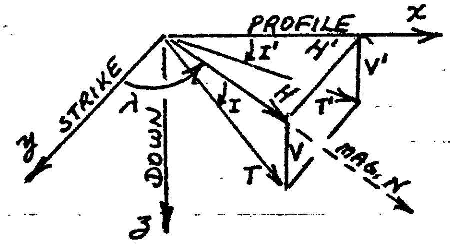
Program Description, Equations, Variables, etc. A Talwani-type program to calculate $\Delta T'$, $\Delta H'$, or $\Delta V'$ magnetic anomaly due to 2-dimensional prism of ≤ 8 vertices.

Equations: Field is superposition of fields due to n angle-edged horizontal plates like the one below:





$$\Delta T' = 2\kappa T h^2 \sin D \left[\sin(2I'-D)\,\Delta\phi + \cos(2I'-D)\,\Delta \ln R\right]$$



$$\Delta H' = 2\kappa T h \sin D \left[\sin(I'-D)\,\Delta\phi + \cos(I'-D)\,\Delta \ln R\right]$$

$\Delta V'$ = same as $\Delta H'$, with $I' \leftarrow I' + \frac{\pi}{2}$

$h^2 = 1 - \cos^2 I \cos^2 \lambda \qquad I' = \tan^{-1}\left(\frac{\tan I}{\sin \lambda}\right)$

$\Delta\phi = \phi_{i+1} - \phi_i \qquad \Delta \ln R = \ln r_{i+1} - \ln r_i$

I = field inclination; λ = angle, strike to mag N.

Unprimed coordinates represent earth's true field;
Primed coordinates are projected into x-z plane.

Reference: Hiertzler, J.R., Peter, G., Talwani, M., and Zurflueh, E.G., 1962, Lamont Geol. Obs. (Columbia Univ.) Tech. Rept. #6, CU-6-62 (Note I've changed some notation in obvious ways.)

Operating Limits and Warnings General: Equations used assume negligible demagnetization effect and that $\Delta T' \ll T$. These conditions are usually met if $\kappa \ll 1$.

This program: "Error" flashes if you try to input more than 8 body vertices. Always repeat Step 3 if flags F0, F1 are re-set to do $\Delta H'$ or $\Delta V'$ calculations. Field point may not occupy body vertex # 1.

DO NOT USE THIS SPACE

User Instructions

Magnetics: 2-D anomaly

1 ◀ ▶ 2

$\lambda \uparrow I \uparrow \kappa T$ $x_i \uparrow z_i$ $X \uparrow Z$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load side 1 and side 2			
2	Set flags, as necessary			

FIELD	FLAG STATUS	
$\Delta F'$	flag 0	flag 1
$\Delta T'$	set	set ← default status
$\Delta H'$	cleared	set
$\Delta V'$	cleared	cleared

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
3	Key field parameters (λ, I, κT)			
	Angle, strike to magnetic north	λ (deg)	ENT↑	
	Inclination of magnetic field	I (deg)	ENT↑	
	Field strength x magnetic susceptibility	κT	A	
4	Key body vertices (x_i, z_i; $i = 1, n$)	x_i	ENT↑	
		z_i	B	i
	Repeat step 4 for all body vertices, working successively around body in a clockwise direction. Vertex #1 is not repeated, as in some Talwani programs.			
5	Key field points (X, Z)	X	ENT↑	
		Z	C	$\Delta F'$
	Field points may be anywhere, including inside body, except at vertex #1.			
	Step 5 may be repeated as desired to find $\Delta F'$ at various field points due to this body.			
	Steps 3 and 4 may be repeated independently of each other to change field geometry or body geometry, respectively. On resetting flags (step 2), Step 3 must be repeated.			
6	For a new case, clear registers and go to step 2.			
	Units: all distances (x_i, z_i, X, Z) must be in same units, e.g., feet. Units of $\Delta F'$ are same as those of κT.			

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	A: $\lambda \uparrow I \uparrow \kappa T$
002	DEG	16-21	
003	STOA	35 11	
004	R↓	-31	
005	STOC	35 13	
006	R↓	-31	
007	STOD	35 14	
008	SIN	41	
009	RCLC	36 13	
010	TAN	43	
011	X⇄Y	-41	
012	X=0?	16-43	$I' = \tan^{-1}\left(\frac{\tan I}{\tan \lambda}\right)$
013	GTO0	22 00	
014	÷	-24	
015	TAN⁻¹	16 43	
016	*LBL2	21 02	2: Entry from 0
017	D→R	16 45	
018	STO9	35 09	
019	1	01	
020	RCLD	36 14	
021	COS	42	
022	RCLC	36 13	
023	COS	42	
024	×	-35	
025	X²	53	
026	-	-45	
027	√X	54	$h = \sqrt{1 - \cos^2\lambda \cos^2 I}$
028	F0?	16 23 00	For ΔT' case, use h^2.
029	X²	53	
030	2	02	
031	×	-35	
032	RCLA	36 11	
033	×	-35	
034	STOA	35 11	
035	SPC	16-11	
036	F1?	16 23 01	For ΔV' case, use $I' + 90°$
037	RTN	24	
038	PI	16-24	
039	2	02	
040	÷	-24	
041	ST+9	35-55 09	
042	RTN	24	
043	*LBL0	21 00	0: fix-up when $\lambda = 0$. Then $I' = 90°$
044	9	09	
045	0	00	
046	GTO2	22 02	
047	*LBLB	21 12	B: $x_i \uparrow z_i$ (Body vertices)
048	ISZI	16 26 46	
049	STOi	35 45	z_i
050	R↓	-31	
051	P⇄S	16-51	
052	STOi	35 45	x_i
053	0	00	
054	STO0	35 00	
055	P⇄S	16-51	
056	STO0	35 00	

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	8	08	If $n > 8$, display "Error." (LBL e is a non-existant address)
058	RCLI	36 46	
059	X>Y?	16-34	
060	GSBe	23 16 15	
061	STOB	35 12	
062	SPC	16-11	
063	RTN	24	
064	*LBLC	21 13	C: Field points $X \uparrow Z$
065	RAD	16-22	
066	STOC	35 13	
067	R↓	-31	
068	STOD	35 14	X
069	GSBc	23 16 13	Coordinate shift to put field point at origin.
070	P⇄S	16-51	
071	RCLD	36 14	
072	STOC	35 13	
073	GSBc	23 16 13	
074	P⇄S	16-51	
075	R↓	-31	x_1
076	RCL1	36 01	z_1
077	GSBd	23 16 14	
078	RCLB	36 12	n Initialize for iteration.
079	STOI	35 46	
080	0	00	
081	STOC	35 13	
082	*LBL1	21 01	1: Iteration entry
083	GSBa	23 16 11	Δz
084	P⇄S	16-51	
085	GSBa	23 16 11	Δx
086	→P	34	
087	R↓	-31	
088	STO9	35 09	D
089	P⇄S	16-51	
090	GSBb	23 16 12	
091	GSBd	23 16 14	← Here have $\begin{pmatrix}\Delta\phi \\ \Delta \ln R\end{pmatrix}$
092	X⇄Y	-41	$2I' - D$ or $I' - D$
093	GSBE	23 15	
094	TAN	43	
095	÷	-24	
096	+	-55	$\Delta\phi + \cot(I' - D) \cdot \Delta \ln R$
097	GSBE	23 15	
098	SIN	41	
099	×	-35	$\sin(I' - D)[\Delta\phi + \cot \cdot \Delta \ln R]$
100	P⇄S	16-51	
101	RCL9	36 09	D
102	P⇄S	16-51	
103	SIN	41	
104	CHS	-22	
105	×	-35	$-\sin D[\sin \cdot \Delta\phi + \cos \cdot \Delta \ln]$
106	RCLA	36 11	
107	×	-35	
108	RCLC	36 13	$\Sigma + h \cdot$ (this n contrib)
109	+	-55	
110	STOC	35 13	
111	DSZI	16 25 46	
112	GTO1	22 01	

REGISTERS

0	1	2	3	4	5	6	7	8	9
Z	z_1	z_2	z_3	…					I'
S0	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
X	x_1	x_2	x_3	…					D

A	B	C	D	E	I
$\kappa T \cdot 2h$ or $\kappa T \cdot 2h^2$	n	Σ	old $\ln R$	old ϕ	Used

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
113	PRTX	-14	
114	SPC	16-11	
115	RTN	24	
116	*LBLa	21 16 11	a: Get Δx
117	ISZI	16 26 46	If $i=n$, set $i+1=1$ (Since vertex $n \neq$ vertex 1 under this program's convention.)
118	RCLB	36 12	
119	RCLI	36 46	
120	X>Y?	16-34	
121	GSB6	23 06	
122	STOI	35 46	
123	R↓	-31	
124	R↓	-31	
125	RCLi	36 45	
126	DSZI	16 25 46	
127	GTO5	22 05	If $i+1=1$, set $i=n$
128	RCLB	36 12	
129	STOI	35 46	
130	R↓	-31	
131	*LBL5	21 05	5:
132	RCLi	36 45	
133	-	-45	
134	RTN	24	
135	*LBL6	21 06	6: Subroutine for index switching.
136	R↓	-31	
137	1	01	
138	RTN	24	
139	*LBLb	21 16 12	b: Get body vertex$\binom{x}{z}$ (This sub a holdover from 2-D gravity program: Could go in sub C.)
140	P⇄S	16-51	
141	RCLi	36 45	
142	P⇄S	16-51	
143	RCLi	36 45	
144	RTN	24	
145	*LBLc	21 16 13	c: Coordinate shift
146	RCLB	36 12	
147	STOI	35 46	
148	*LBL4	21 04	4: new x = old x + old X − new X
149	RCLi	36 45	
150	RCL0	36 00	
151	+	-55	
152	RCLC	36 13	
153	-	-45	
154	STOi	35 45	
155	DSZI	16 25 46	
156	GTO4	22 04	
157	RCLC	36 13	Replace old X by new X
158	STO0	35 00	
159	RTN	24	
160	*LBLd	21 16 14	d: input x z
161	X=0?	16-43	
162	GTO9	22 09	
163	*LBL8	21 08	
164	→P	34	
165	RCLD	36 14	
166	X⇄Y	-41	
167	X≠0?	16-42	
168	LN	32	
169	STOD	35 14	
170	-	-45	
171	X⇄Y	-41	
172	RCLE	36 15	
173	X⇄Y	-41	
174	STOE	35 15	
175	-	-45	
176	X<0?	16-45	
177	SF2	16 21 02	
178	ABS	16 31	
179	Pi	16-24	
180	X>Y?	16-34	
181	GTO7	22 07	
182	2	02	
183	×	-35	
184	-	-45	
185	F2?	16 23 02	
186	CHS	-22	
187	RTN	24	
188	*LBL7	21 07	7:
189	R↓	-31	
190	F2?	16 23 02	
191	CHS	-22	
192	RTN	24	
193	*LBL9	21 09	9:
194	X≠Y?	16-32	
195	GTO8	22 08	
196	RCLD	36 14	Return $\binom{\Delta \ln R}{\Delta \phi}$
197	0	00	
198	STOD	35 14	
199	RTN	24	
200	*LBLE	21 15	E: Get $2I'-D$ if F0 on; $I'-D$ if F0 off.
201	RCL9	36 09	
202	F0?	16 23 00	
203	2	02	
204	F0?	16 23 00	
205	×	-35	
206	P⇄S	16-51	
207	RCL9	36 09	
208	P⇄S	16-51	
209	-	-45	
210	RTN	24	
220			

LABELS

A: $\lambda \uparrow I \uparrow \kappa T$	B: $x_i \uparrow z_i$	C: $X \uparrow Z \to \Delta F'$	D: —	E: —
a: Δx	b: body vertex	c: Coord shift	d: Get $\frac{\Delta \ln R}{\Delta \phi}$	e: error
0: Used in A	1: Iteration in C	2: Entry in A	3: —	4: Entry in c
5: Entry in a	6: Subr in a	7: Used in d	8: Entry in d	9: Subr in d

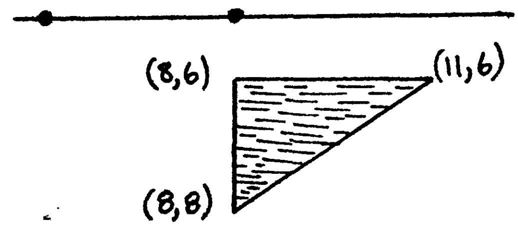
FLAGS

0	Off for $\Delta H'$, $\Delta V'$
1	off for $\Delta V'$
2	used
3	—

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☒
1	☒	☐	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☐			n	2

EXAMPLE: Find $\Delta T'$, $\Delta H'$ and $\Delta V'$ at field points $\binom{X}{Z} = \binom{5}{5}$ and $\binom{8}{5}$ due to 2-D triangular body shown. Take $\lambda = 60°$, $I = 10°$, $T = 50{,}000\,\gamma$, $\kappa = 0.001$ emu (i.e., $\kappa T = 50\,\gamma$).



Solution:

```
60.00 ENT↑
10.00 ENT↑
50.00 GSBA      — Input field parameters (step 3).

8.00 ENT↑
8.00 GSBB

8.00 ENT↑
6.00 GSBB

11.00 ENT↑
6.00 GSBB       — Input body points (step 4).

5.00 ENT↑
5.00 GSBC
10.94  ***      — First field point (step 5): ΔT' = 10.94 γ.

8.00 ENT↑
5.00 GSBC
-12.55  ***     — Second field point: ΔT' = -12.55 γ.

CF0             — Clear flag 0, so as to calculate ΔH'.
60.00 ENT↑
10.00 ENT↑
50.00 GSBA      — Repeat step 3 after changing flag.

5.00 ENT↑
5.00 GSBC
11.14  ***      — First field point: ΔH' = 11.14 γ.

8.00 ENT↑
5.00 GSBC
-25.50  ***     — Second field point: ΔH' = -25.50 γ.

CF1             — Clear flag 1, so as to calculate ΔV'.
60.00 ENT↑
10.00 ENT↑
50.00 GSBA      — Repeat step 3 after changing flag.

5.00 ENT↑
5.00 GSBC
8.25  ***       — First field point: ΔV' = 8.25 γ.

8.00 ENT↑
5.00 GSBC
53.01  ***      — Second field point: ΔV' = 53.01 γ.
```

Program Description

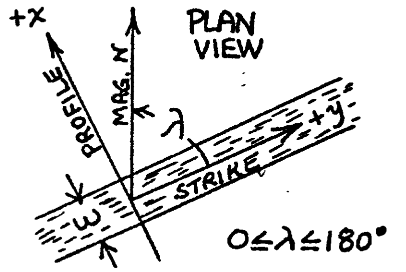
Program Title: Magnetic profiles — thick sheet/thin dike

Name: David L. Campbell — Date: May 1978

Address: U.S. Geological Survey

City: Denver — State: CO — Zip Code: 80225

Program Description, Equations, Variables, etc. This program calculates magnetic anomaly profiles over a two-dimensional dipping thick sheet or thin dike. Sheet or dike is assumed infinitely long along strike (±y direction) and its bottom edge is infinitely deep. Anomalies in total field $\Delta T'$, in horizontal field $\Delta H'$, or in vertical field $\Delta V'$ may be calculated. If thickness w is known, program uses sheet equations; if unknown, program uses dike equations.

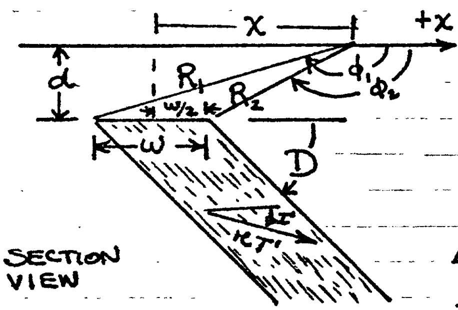


EQUATIONS FOR SHEET:

$$\Delta T' = 2\kappa T h^2 \sin D \left[\sin(2I'-D)\cdot\Delta\phi - \cos(2I'-D)\cdot\Delta \ln R\right]$$

$$\Delta H' = 2\kappa T h \sin D \left[\sin(I'-D)\cdot\Delta\phi - \cos(I'-D)\cdot\Delta \ln R\right]$$

$\Delta V'$ = Same as $\Delta H'$, with $I' \leftarrow I' + \pi/2$.



EQUATIONS FOR DIKE:

$$\frac{\Delta T'}{w} = 2\kappa T h^2 \sin D \left[\sin(2I'-D)\cdot\frac{d}{R^2} - \cos(2I'-D)\cdot\frac{x}{R^2}\right]$$

$$\frac{\Delta H'}{w} = 2\kappa T h \sin D \left[\sin(I'-D)\cdot\frac{d}{R^2} - \cos(I'-D)\cdot\frac{x}{R^2}\right]$$

$\frac{\Delta V'}{w}$ = Same as $\frac{\Delta H'}{w}$, with $I' \leftarrow I' + \frac{\pi}{2}$.

$\Delta\phi = \phi_1 - \phi_2 \quad \Delta \ln R = \ln R_1/R_2 \quad h^2 = 1 - \cos^2\lambda \cos^2 I$

$\tan I' = \tan I / \sin\lambda$: I = true field inclination. κ = susceptibility

Reference: S. Parker Gay, Jr., 1967, Curves for interpretation of magnetic anomalies, in Mining Geophysics, v. II: Society of Exploration Geophysicists, Tulsa, OK, pps. 512–548.

Operating Limits and Warnings GENERAL: Equations used assume negligible demagnetization effect and That $\Delta T' \ll T$. These conditions are usually met if susceptibility $\kappa \ll 1$.

THIS PROGRAM: Whenever step 5 is skipped, so no value of w is input, the program uses the thin dike algorithm. This algorithm gives little error as long as $w < d$. Note in This case output field values are normalized by dike's horizontal Thickness, w.

Output horizontal field $\Delta H'$ is along profile direction x, not ΔH, The component along magnetic north direction. To get ΔH, use $\Delta H = \Delta H' \sin\lambda$.

DO NOT USE THIS SPACE

User Instructions

MAGNETIC PROFILES — thick sheet/thin dike

$\lambda \uparrow I \uparrow \kappa T$	$D \uparrow d$	(w)	x_0	Δx

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load side 1 and side 2			
2	Set flags as necessary			

FIELD ΔF	FLAG STATUS flag 0	flag 1	
$\Delta T'$	set	set	← default status
$\Delta H'$	cleared	set	
$\Delta V'$	cleared	cleared	

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
3	Key field parameters			
	Angle, strike to magnetic north	λ (deg)	ENT↑	
	Inclination of magnetic field	I (deg)	ENT↑	
	FIELD strength x magnetic susceptibility	κT (γ)	A	various
	(To generate type curves, or if κ is unknown, set $\kappa T = 1$.)			
4	Key body parameters			
	Dip of sheet or dike, pos down from +x	D (deg)	ENT↑	
	Depth to top of sheet or dike	d	B	d
5	(Thick sheet only) horizontal width	w	C	$w/2$
6	Key initial x coordinate	x_0	D	$\Delta F'(x_0)$
7	Key increment of x	Δx	E	profile
	Output profile consists of pairs $(x, \Delta F'(x))$ where $x = x_0 + n\Delta x$; $n = 1, \cdots, 15$.			
	Profile may be reviewed by [f P⇄S], [REG].			
	Steps 6 and 7 may be repeated separately to interpolate values, extend the profile, etc.			
8	For a new case, clear registers and go to step 2.			
	Units: If κT in gammas, $\Delta F'$ will be in gammas. All length units (for d, w, x_0, Δx) must be same; e.g., all in feet or all in meters.			

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	A: λ↑I↑κT
002	STO6	35 06	
003	R↓	-31	
004	STOC	35 13	
005	R↓	-31	
006	STOA	35 11	
007	SIN	41	
008	RCLC	36 13	
009	TAN	43	
010	X⇄Y	-41	
011	X=0?	16-43	
012	GTO0	22 00	
013	÷	-24	Get $I' = \tan^{-1}\left(\frac{\tan I}{\sin\lambda}\right)$
014	TAN⁻¹	16 43	
015	*LBL1	21 01	
016	STO0	35 00	$I' \rightarrow R_0$
017	1	01	
018	RCLA	36 11	
019	COS	42	
020	RCLC	36 13	
021	COS	42	
022	×	-35	
023	X²	53	
024	−	-45	
025	√X	54	$h = \sqrt{1-\cos^2\lambda\cos^2 I}$
026	F0?	16 23 00	For ΔT' case, use h^2
027	X²	53	
028	2	02	
029	×	-35	
030	ST×6	35-35 06	$\kappa T \cdot 2h \rightarrow R_6$
031	SPC	16-11	
032	F1?	16 23 01	For ΔV' case, use I'+90°
033	RTN	24	
034	9	09	
035	0	00	
036	ST+0	35-55 00	
037	RTN	24	
038	*LBL0	21 00	0: fix-up in case λ=0.
039	9	09	
040	0	00	
041	GTO1	22 01	
042	*LBLB	21 12	B: D↑d
043	CF2	16 22 02	← (Flag 2 may have been on from previous case.)
044	STO1	35 01	
045	R↓	-31	
046	STO7	35 07	
047	RCL0	36 00	
048	F0?	16 23 00	For ΔT' case, use 2I'.
049	2	02	
050	F0?	16 23 00	
051	×	-35	
052	RCL7	36 07	
053	−	-45	$\theta_F = I' - D$
054	SIN	41	
055	STO8	35 08	$\sin\theta_F \rightarrow R_8$
056	LSTX	16-63	

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	COS	42	
058	STO9	35 09	$\cos\theta_F \rightarrow R_9$
059	RCL7	36 07	
060	SIN	41	
061	ST×6	35-35 06	$2h \cdot \kappa T \cdot \sin D \rightarrow R_6$
062	SPC	16-11	
063	RTN	24	
064	*LBLC	21 13	C: (ω)
065	2	02	
066	÷	-24	
067	STO2	35 02	$\omega/2 \rightarrow R_2$
068	SF2	16 21 02	(Set flag 2 to tell Subr. D to use Thick sheet equation.)
069	SPC	16-11	
070	RTN	24	
071	*LBLD	21 14	D: x
072	F2?	16 23 02	If thick sheet, go to 2
073	GTO2	22 02	
074	STO3	35 03	
075	X²	53	
076	RCL1	36 01	
077	X²	53	
078	+	-55	
079	STO4	35 04	$R^2 \rightarrow R_4$
080	RCL1	36 01	
081	RCL4	36 04	
082	÷	-24	
083	RCL8	36 08	
084	×	-35	← $\frac{d}{R^2}\sin\theta_F$
085	RCL3	36 03	
086	RCL4	36 04	
087	÷	-24	
088	RCL9	36 09	
089	×	-35	← $\frac{x}{R^2}\cos\theta_F$
090	−	-45	
091	RCL6	36 06	
092	×	-35	
093	RTN	24	$2h\kappa T \sin D\left[\frac{d}{R^2}\sin - \frac{x}{R^2}\cos\right]$
094	*LBL2	21 02	2: thick sheet case
095	SF2	16 21 02	← reset flag 2.
096	STO3	35 03	
097	RCL2	36 02	
098	GSB3	23 03	Get $\binom{\phi_1}{R_1}$
099	STO4	35 04	
100	X⇄Y	-41	$R_1 \rightarrow$ Reg 4
101	STO5	35 05	$\phi_1 \rightarrow$ Reg 5
102	RCL2	36 02	
103	CHS	-22	
104	GSB3	23 03	Get $\binom{\phi_2}{R_2}$
105	ST÷4	35-24 04	
106	X⇄Y	-41	$\phi_1 - \phi_2 \rightarrow$ Reg 4; $R_1/R_2 \rightarrow$ Reg 5
107	ST-5	35-45 05	
108	RCL5	36 05	
109	D→R	16 45	
110	RCL8	36 08	$\Delta\phi \cdot \sin\theta_F$
111	×	-35	
112	RCL4	36 04	

REGISTERS

0	1	2	3	4	5	6	7	8	9
I', Δφ	d	ω/2	x	ΔlnR, R²	Δφ	$2h^2\kappa T \sin D$	Δx	$\sin\theta_F$	$\cos\theta_F$

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
$\Delta F'(x_0+\Delta x)$	$\Delta F'(x_0+2\Delta x)$	. . .							

A	B	C	D	E	I
		. . .	$\Delta F'(x_0+14\Delta x)$	$\Delta F'(x_0+15\Delta x)$	used

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
113	LN	32	
114	RCL9	36 09	
115	x	-35	$-\Delta \ln R \cdot \cos\theta_F$
116	-	-45	
117	RCL6	36 06	
118	x	-35	$2\kappa T \cdot h \cdot \sin D\,[\Delta\phi \sin - \Delta \ln \cdot \cos]$
119	RTN	24	
120	*LBL3	21 03	Subr 3: input $\pm \frac{\omega}{2}$
121	RCL3	36 03	$\binom{x+\frac{\omega}{2}}{d} \rightarrow \binom{d}{-x-\frac{\omega}{2}}$
122	+	-55	
123	CHS	-22	
124	RCL1	36 01	$\xrightarrow{\text{Polar}} \binom{\phi}{R}$
125	X⇄Y	-41	
126	→P	34	
127	RTN	24	
128	*LBLE	21 15	E: Profile Iterator
129	STO7	35 07	
130	9	09	
131	STOI	35 46	
132	*LBL4	21 04	4: Entry to repeat procedure.
133	RCL3	36 03	
134	RCL7	36 07	
135	+	-55	old $x+\Delta x \rightarrow$ Reg 3
136	PRTX	-14	
137	GSBD	23 14	Get $\Delta F'$ and print it
138	PRTX	-14	
139	SPC	16-11	
140	ISZI	16 26 46	Store $\Delta F'$ in secondary registers.
141	STOi	35 45	
142	2	02	
143	3	03	Have we used all free registers? If not, do it again.
144	RCLI	36 46	
145	X≤Y?	16-35	
146	GTO4	22 04	
147	RTN	24	
148	R/S	51	

LABELS

A	B	C	D	E
$\lambda \uparrow I \uparrow \kappa T$	$D \uparrow d$	(ω)	x_0	Δx

a	b	c	d	e

0	1	2	3	4
$\sin\lambda = 0$ Case	Entry in A	thick sheet	Get R	Entry in E

5	6	7	8	9

FLAGS

Flag	
0	Used
1	Used
2	Used
3	—

SET STATUS

FLAGS	ON	OFF
0	☒	☐
1	☒	☐
2	☐	☒
3	☐	☐

TRIG	
DEG	☒
GRAD	☐
RAD	☐

DISP	
FIX	☒
SCI	☐
ENG	☐
n	2

Example: thick sheet or thin dike with $\lambda = 30°$, $I = 60°$, and $kT = 50$ gammas. Dip $D = 120°$ (i.e. 60° from $-x$ direction), $d = 1$ unit, and $w = 4$ units for sheet calculation. Find $\Delta T'$ from $x = -7$ to $x = +8$, incrementing by $\Delta x = 1$ unit.

Sdn: Shown for sheet at left, dike at right.

* means value shown in display, not printed.

24.00 means iteration is complete.

SHEET

	30.00	ENT↑
	60.00	ENT↑
	50.00	GSBA
	120.00	ENT↑
	1.00	GSBE
	4.00	GSBC
	-7.00	GSBD
*	38.59	***
	1.00	GSBE
	-6.00	***
	45.76	***
	-5.00	***
	55.99	***
	-4.00	***
	72.09	***
	-3.00	***
	95.12	***
	-2.00	***
	131.68	***
	-1.00	***
	116.35	***
	0.00	***
	72.56	***
	1.00	***
	16.66	***
	2.00	***
	-44.67	***
	3.00	***
	-60.53	***
	4.00	***
	-52.50	***
	5.00	***
	-44.19	***
	6.00	***
	-37.78	***
	7.00	***
	-32.96	***
	8.00	***
	-29.11	***
*	24.00	***

DIKE

	30.00	ENT↑
	60.00	ENT↑
	50.00	GSBA
	120.00	ENT↑
	1.00	GSBE
	-7.00	GSBD
*	9.37	***
	1.00	GSBE
	-6.00	***
	10.96	***
	-5.00	***
	13.23	***
	-4.00	***
	16.56	***
	-3.00	***
	21.95	***
	-2.00	***
	31.46	***
	-1.00	***
	47.53	***
	0.00	***
	32.61	***
	1.00	***
	-14.72	***
	2.00	***
	-18.34	***
	3.00	***
	-15.39	***
	4.00	***
	-12.72	***
	5.00	***
	-10.71	***
	6.00	***
	-9.21	***
	7.00	***
	-8.06	***
	8.00	***
	-7.16	***
*	24.00	***

Program Description

Program Title DIPPING SEISMIC REFRACTOR

Name David L. Campbell

Address U.S. Geological Survey

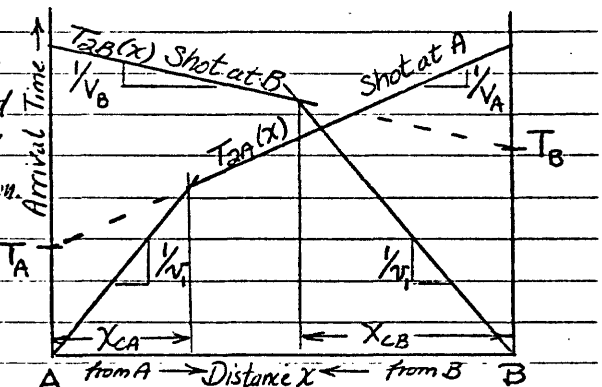
City Denver **State** CO **Zip Code** 80225

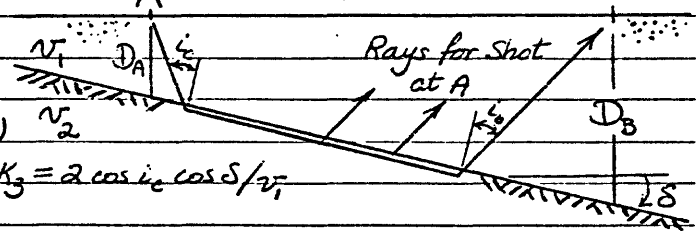
Date

Program Description, Equations, Variables A single seismic refractor of velocity v_2 dips under an overburden of velocity v_1. Shots are fired at both ends, A and B, of an in-line array of geophones, and first arrivals are plotted as shown.

This program does: A. INTERPRETATION — finds v_2, δ, D_A, D_B, given v_1, V_A, V_B, T_A, T_B.

B. DESIGN — finds V_A, V_B, X_c (A or B), $T_2(x)$ (A or B), given v_1, δ, and D (A or B).





Equations: $v_2 > v_1$

$\sin i_c = v_1/v_2$

$v_1 = V_A \sin(i_c+\delta) = V_B \sin(i_c-\delta)$

$T_{2A}(x) = x/V_A + D_A K_3$ $\quad K_3 = 2\cos i_c \cos\delta / v_1$

$T_{2B}(x) = x/V_B + D_B K_3$

$X_{CI} = D_I K_3 / \left(\frac{1}{v_1} - \frac{1}{V_I}\right)$, $I = A$ or B

References: Slotnick, Morris M., 1959, Lessons in Seismic Computing: Society of Exploration Geophysicists, P.O. Box 3098, Tulsa, OK 74135, p. 103–118.

Mooney, Harold M., 1977, Handbook of Engineering Geophysics: Bison Instruments, Inc., 5708 West 38th St., Minneapolis, Minn. 55416; Chapt. 11, 12.

Operating Limits and Warnings GENERAL: Equations assume constant v_1, v_2; clearly an approximation. Practical experience is useful to estimate resulting errors. Dip δ is apparent dip along geophone line, not necessarily true dip. Depth D is in plane of refracted wave.

THIS PROGRAM: Note point A is drawn updip from point B on above diagram, and that dips are positive down from horizontal. Thus negative dips mean $V_A > V_B$, that A is downdip from B. User should check to assure $T_A < T_B$ when $V_A < V_B$.

DO NOT USE THIS SPACE

User Instructions

DIPPING SEISMIC REFRACTOR

1 | V_A | V_B | v_2 | $D \xrightarrow{d} x$ (δ) | $x \xrightarrow{e} T$ ($T \xrightarrow{E} D$) | 2

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
0	Load side 1				
	PROBLEM A: INTERPRETATION				
A1	INPUT				
	true velocity of overburden	v_1	STO	1	
	apparent velocity of refractor–A direction	V_A	STO	A	
	apparent velocity of refractor–B direction	V_B	STO	B	
A2	COMPUTE				
	true velocity of refractor			C	v_2
	dip of refractor			D	δ
A3	INPUT zero-time intercepts; COMPUTE				
	depths to refractor	T_A		E	D_A
		T_B		E	D_B
	PROBLEM B: DESIGN				
B1	INPUT				
	true velocity of overburden	v_1	STO	1	
	true velocity of refractor	v_2	STO	C	
	dip of refractor	δ	STO	D	
B2	COMPUTE apparent velocities of				
	refractor – A and B directions.			A	V_A
				B	V_B
B3	INPUT depth to refractor; COMPUTE x_c	D_A	f	D	x_{cA}
B4	COMPUTE $T_{2A}(x)$	x	f	E	$T_{2A}(x)$
	Repeat step B4 as desired for other x.				
	Note: These results are calculated for A-direction.				
	To do calculation for B-direction, reverse roles				
	of A and B by changing sign of dip in step				
	B1. Then proceed with steps B2, B3, B4 as above.				
	UNITS: Dip δ is in degrees, positive down from				
	horizontal. Other units are compatible;				
	e.g., if velocities are in ft/msec, say, all				
	depths will be in ft, all times in msec.				

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLC	21 13	C: Get v_2
002	GSBD	23 14	
003	COS	42	$v_2 = \frac{2V_A V_B}{V_A + V_B}\cos\delta$
004	RCLA	36 11	
005	RCLB	36 12	
006	x	-35	
007	2	02	
008	x	-35	
009	RCLA	36 11	
010	RCLB	36 12	
011	+	-55	
012	÷	-24	
013	x	-35	
014	STOC	35 13	
015	RTN	24	
016	*LBLD	21 14	D: Get dip δ
017	RCL1	36 01	
018	RCLA	36 11	
019	÷	-24	
020	SIN⁻¹	16 41	$\delta = \left[\sin^{-1}\frac{v_1}{V_A} - \sin^{-1}\frac{v_1}{V_B}\right]/2$
021	RCL1	36 01	
022	RCLB	36 12	
023	÷	-24	
024	SIN⁻¹	16 41	
025	-	-45	
026	2	02	
027	÷	-24	
028	STOD	35 14	
029	RTN	24	
030	*LBLE	21 15	E: Get D_I
031	GSB3	23 03	$D_I = T_I / K_3$
032	÷	-24	
033	STOE	35 15	
034	RTN	24	
035	*LBLB	21 12	B: Get V_B
036	RCL1	36 01	
037	RCLD	36 14	
038	CHS	-22	$V_B = v_1 / \sin(i_c - \delta)$
039	GSB2	23 02	
040	STOB	35 12	
041	RTN	24	
042	*LBLA	21 11	A: Get V_A
043	RCL1	36 01	
044	RCLD	36 14	
045	GSB2	23 02	$V_A = v_1 / \sin(i_c + \delta)$
046	STOA	35 11	
047	RTN	24	
048	*LBLd	21 16 14	d: Get x_{c_I}
049	STOE	35 15	
050	GSB3	23 03	
051	x	-35	$x_{c_I} = \frac{D_I \cdot K_3}{\left(\frac{1}{v_1} - \frac{1}{V_I}\right)}$
052	RCL1	36 01	
053	1/X	52	
054	RCLA	36 11	
055	1/X	52	
056	-	-45	

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	÷	-24	
058	RTN	24	
059	*LBLe	21 16 15	e: Get $T_{2I}(x)$
060	RCLA	36 11	
061	÷	-24	$T_{2I}(x) = \frac{x}{V_2} + D_I K_3$
062	GSB3	23 03	
063	RCLE	36 15	
064	x	-35	
065	+	-55	
066	RTN	24	
067	*LBL3	21 03	Subroutine 3: Get K_3
068	GSB1	23 01	
069	COS	42	
070	RCLD	36 14	
071	COS	42	$K_3 = \frac{2\cos i_c \cos\delta}{v_1}$
072	x	-35	
073	2	02	
074	x	-35	
075	RCL1	36 01	
076	÷	-24	
077	RTN	24	
078	*LBL1	21 01	Subroutine 1:
079	RCL1	36 01	
080	RCLC	36 13	$i_c = \sin^{-1}\frac{v_1}{v_2}$
081	÷	-24	
082	SIN⁻¹	16 41	
083	RTN	24	
084	*LBL2	21 02	Subroutine 2:
085	GSB1	23 01	Get $(y)/\sin(i_c + \alpha)$,
086	+	-55	a quantity used in both
087	SIN	41	Subs A & B.
088	÷	-24	
089	RTN	24	
090			
100			
110			

REGISTERS

0	1	2	3	4	5	6	7	8	9
—	v_1	—	—	—	—	—	—	—	—

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
—	—	—	—	—	—	—	—	—	—

A	B	C	D	E	I
V_A	V_B	v_2	δ	D	—

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
				170			
120				180			
130				190			
140				200			
150				210			
160				220			

LABELS				
A V_A	B V_B	C v_2	D δ	E $T \rightarrow D$
a —	b —	c —	d $D \rightarrow x$	e $x \rightarrow T$
0 —	1 i_c	2 Used	3 K_3	4 —
5 —	6 —	7 —	8 —	9 —

FLAGS
0
1
2
3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☐	DEG	☒	FIX	☒
1	☐	☐	GRAD	☐	SCI	☐
2	☐	☐	RAD	☐	ENG	☐
3	☐	☐			n 3	

EXAMPLES: A. INTERPRETATION

Given $v_1 = 2000$ m/sec, $V_A = 4000$ m/sec, $V_B = 5000$ m/sec, $T_A = 30$ msec ($= 0.030$ sec), $T_B = 45$ msec ($= 0.045$ sec)

Find v_2, δ, D_A, D_B.

```
2000.000 STO1
4000.000 STOA
5000.000 STOB

         GSBC
4437.467  ***

         GSBD
   3.211  ***

    .030 GSBE
  33.660  ***

    .045 GSBE
  50.490  ***
```

<u>SOLUTION</u>: 2000 STO 1, 4000 STO 2, 5000 STO B

C Read $v_2 = 4437.467$ m/sec*

D Read $\delta = 3.211°$

0.030 E Read $D_A = 33.660$ m*

0.045 E Read $D_B = 50.490$ m*

* In practice, the 3 decimals aren't significant. An experienced engineer would round to $D_A = 34$ m, $D_B = 50$ m and further warn his client that an error of perhaps 10% is possible here.

B. DESIGN

Given $v_1 \simeq 5000$ ft/sec, $v_2 \simeq 9000$ ft/sec, dip δ unknown but presumed $\simeq 0$, $D \simeq 100$ ft.

Design a refraction system to find true v_1, v_2, δ, D.

```
5000.000 STO1
9000.000 STOC
   0.000 STOD

         GSBA
9000.000  ***
         GSBB
9000.000  ***

 100.000 GSBd
 374.166  ***

         GSBe
   0.075  ***

   0.000 GSBe
   0.033  ***

 600.000 GSBe
   0.100  ***
```

<u>SOLUTION</u>: 5000 STO 1, 9000 STO C, 0 STO D,

A Read $V_A = 9000$ ft/sec, B Read $V_B = 9000$ ft/sec.

100 f D Read $x_c = 374.166$ ft

f E Read $T_2(x_c) = 0.075$ sec

0 f E Read $T_2(0) = 0.033$ sec

600 f E Read $T_2(600) = 0.100$ sec

Hence several geophones must be placed at > 375 ft from shot points to record $T_2(x)$. Zero-intercept time will be ~ 33 msec, crossover time ~ 75 msec. A geophone at 600 ft will see a first arrival at ~ 100 msec.

Program Description

Program Title ≤ 4 dipping seismic refractors: interpretation
Name David L. Campbell Date 30 Dec 77
Address U.S. Geological Survey
City Denver State CO Zip Code 80225

Program Description, Equations, Variables, etc. A number $N \leq 4$ of seismic refractors of velocities v_i dip with dips δ_i under an overburden of velocity v_1. Shots are fired at both ends, A and B, of an in-line array of geophones, and apparent velocities V_{Ai}, V_{Bi} and zero intercept times T_{Ai} are measured on the resulting travel time graph. Using this data, this program finds true velocities v_i and dips δ_i, and depth D_{Ai} to layer below shot point A, for successive layers i.

Equations and diagrams on next page. If there is only one refractor, it is more convenient to use "dipping seismic refractor" program instead of this one.

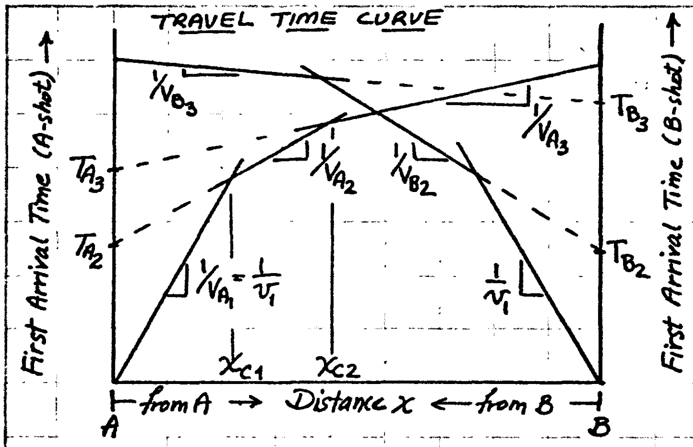
General warning: Equations used assume constant velocities v_i in each layer. Practical experience is useful to estimate errors due to this approximation. Dips δ_i are assumed constant for each layer, and are apparent dips along geophone line, not necessarily true dips. Depth D_{Ai} and thickness h_i are under shot A, and are in plane of the refracted ~~wave~~ ray. All layer velocities increase with depth; i.e. $v_{i+1} > v_i$ for all i.

Reference: Mooney, Harold M., 1977, Handbook of Engineering Geophysics: Bison Instruments, Inc., 5708 West 38th St., Minneapolis, Minn 55416; Chapt. 11, 12.

Operating Limits and Warnings "Error" flashes if attempt is made to input >4 layers. Dips are positive down, viewed from A-side. No checks for compatibility of data or units are made automatically. After an A-side interpretation, user should repeat for B-side to check compatibility of D_A, D_B and δ.

DO NOT USE THIS SPACE

Program Description
(CONTINUATION SHEET)



nomenclature:

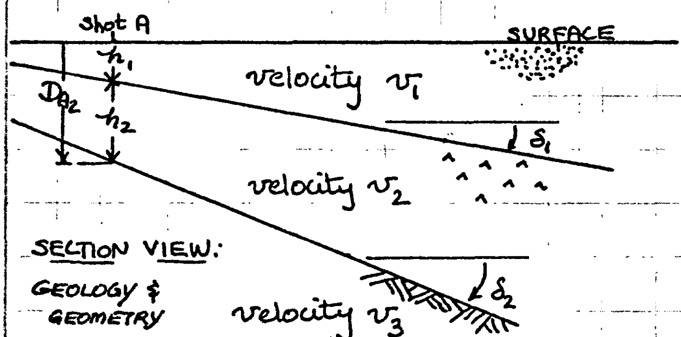
Branch 1 of travel time curve has slope $1/v_1$ and zero intercept, $T_{A1} = 0$.

Branch 2 has slope $1/V_{A2}$ (or $1/V_{B2}$) and zero-intercept T_{A2} (T_{B2}).

Branch 3 has slope $\frac{1}{V_{A3}}$ (or $1/V_{B3}$) and intercept T_{A3} (T_{B3})... and so on.

Crossover distances x_{c1}, x_{c2} are those at which first arrivals begin to occur on a new branch.

- Convention: dips δ are regarded positive down from horizontal.



Snell's law relations:

n^{th} layer: $\sin\alpha_n = \sin\beta_n = \frac{v_n}{v_{n+1}}$

elsewhere: $v_i \sin\beta_{i-1} = v_{i-1} \sin Q_i$

$v_i \sin\alpha_{i-1} = v_{i-1} \sin P_i$

at surface: $V_B = v_1 / \sin\alpha_1$

$V_A = v_1 / \sin\beta_1$

thicknesses: $h_i = S_i (T_{Ai} - \Sigma T)$

where $S_i = v_i / (\cos\alpha_i + \cos\beta_i)$

and $\Sigma T = \sum_{1}^{i-1} h_i / S_i$

Indexes: i = summation index

n = layer index, this calculation.

N = total no. of layers.

angles:

a, b = angles, layer normal to ray

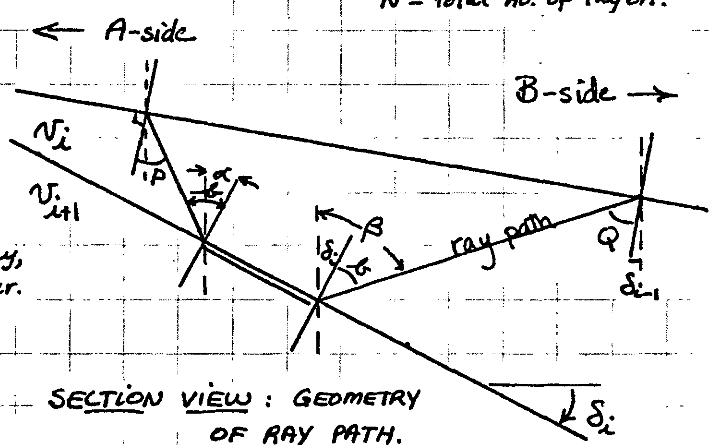
α, β = angles, vertical to ray

P, Q = angles, layer normal to ray, $i-1^{st}$ layer.

geometry:

$\alpha_i = a_i - \delta_i = P_i - \delta_{i-1}$

$\beta_i = b_i + \delta_i = Q_i + \delta_{i-1}$



SECTION VIEW: GEOMETRY OF RAY PATH.

User Instructions

≤ 4 dipping seismic refractors: interpretation

1	A	B	C	D	E	2
	V_A	V_B	v_n	δ_n	n	
			$\rightarrow v_n, \delta_n$	$T_{A_n} \rightarrow D_{A_n}$		

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Load side 1 and side 2 of card				
2	Store v_1 in R_1	v_1	STO	1	
3	Input layer parameters				
	layer index number, $n = 2,3,4$	n	STO	E	
	apparent velocity, A-side	V_{A_n}	STO	A	
	apparent velocity, B-side	V_{B_n}	STO	B	
4	Calculate true velocity, dip			C	v_i
			RCL	D	δ_{i-1}
5	Calculate depths from zero-intercept times	T_{A_n}		D	D_{A_n}
6	Go to step 3 for next layer.				
7	Go to step 2 for next case.				

Notes: (1) Depths and thicknesses are for A-side only. To calculate them for B-side, interchange A and B roles and repeat from step 2.

(2) Units: dip δ is in degrees and is positive down from horizontal (this convention is opposite of that used in the reference.) Other units are compatible; e.g., if $V_{A,B}$ are in ft/msec, say, all distances will be in ft, all times in msec.

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLC	21 13	C: Get v_n, δ_n
002	0	00	
003	P⇄S	16-51	Zero ΣT
004	STO0	35 00	
005	P⇄S	16-51	
006	RCL1	36 01	v_1
007	RCLA	36 11	V_A
008	÷	-24	
009	SIN⁻¹	16 41	
010	STOA	35 11	$\beta_1 \to A$
011	RCL1	36 01	v_1
012	RCLB	36 12	V_B
013	÷	-24	
014	SIN⁻¹	16 41	$\alpha_1 \to B$
015	STOB	35 12	
016	2	02	Check for single
017	RCLE	36 15	layer case.
018	X≤Y?	16-35	
019	GTO3	22 03	
020	5	05	"Error" if >5 layers.
021	X⇄Y	-41	
022	X>Y?	16-34	
023	GSBe	23 16 15	(Secondary regs. up)
024	P⇄S	16-51	
025	RCLB	36 12	α_1
026	RCL1	36 01	δ_1
027	+	-55	
028	STO5	35 05	$a = \alpha_1 + \delta_1$
029	RCLA	36 11	
030	RCL1	36 01	
031	-	-45	
032	STO6	35 06	$b = \beta_1 + \delta_1$
033	1	01	
034	STOI	35 46	
035	GSB6	23 06	Initialize loop.
036	2	02	
037	STOI	35 46	
038	*LBL0	21 00	0: Entry to begin loop.
039	RCL6	36 06	b
040	GSB2	23 02	
041	STO8	35 08	Q
042	RCL5	36 05	a
043	GSB2	23 02	
044	STO7	35 07	P
045	RCLI	36 46	
046	RCLE	36 15	bottom layer?
047	1	01	($n-1 = i$?)
048	-	-45	If so leave loop.
049	X=Y?	16-33	
050	GTO1	22 01	
051	RCL8	36 08	
052	RCLi	36 45	
053	DSZI	16 25 46	
054	RCLi	36 45	
055	ISZI	16 26 46	
056	-	-45	$\Delta S = \delta_i - \delta_{i-1}$
057	-	-45	$b = Q - \Delta S$
058	STO6	35 06	
059	LSTX	16-63	
060	RCL7	36 07	
061	+	-55	$a = P + \Delta S$
062	STO5	35 05	
063	RCLi	36 45	
064	STOD	35 14	
065	GSB5	23 05	
066	GSB6	23 06	
067	ISZI	16 26 46	
068	GTO0	22 00	
069	*LBL1	21 01	1: Exit from loop
070	RCL7	36 07	
071	RCL8	36 08	
072	+	-55	
073	2	02	
074	÷	-24	
075	STO5	35 05	$a = \frac{P+Q}{2}$
076	STO6	35 06	
077	RCL8	36 08	
078	RCL7	36 07	
079	-	-45	
080	2	02	
081	÷	-24	
082	DSZI	16 25 46	
083	RCLi	36 45	δ_i
084	ISZI	16 26 46	
085	+	-55	
086	STOD	35 14	$\delta_n = \delta_i + (\frac{Q-P}{2})$
087	GSB5	23 05	
088	P⇄S	16-51	
089	GSB4	23 04	
090	P⇄S	16-51	
091	RCLD	36 14	δ_n
092	STOi	35 45	
093	RCL5	36 05	a
094	SIN	41	
095	RCLC	36 13	v_i
096	X⇄Y	-41	
097	÷	-24	
098	STOC	35 13	$v_n = v_i / \sin a$
099	ISZI	16 26 46	(Primary regs. up)
100	P⇄S	16-51	
101	STOi	35 45	← Return v_n
102	RTN	24	
103	*LBL3	21 03	3: Calc. for single dipping refractor.
104	0	00	
105	STO0	35 00	
106	1	01	
107	STOI	35 46	
108	GSB4	23 04	
109	RCLA	36 11	α_1
110	RCLB	36 12	β_1
111	-	-45	
112	2	02	

REGISTERS

0 Σh	1 v_1	2 v_2	3 v_3	4 v_4	5 v_5	6 h_1	7 h_2	8 h_3	9 h_4
S0 ΣT	S1 δ_1	S2 δ_2	S3 δ_3	S4 δ_4	S5 a	S6 b	S7 P	S8 Q	S9 $\frac{\cos\alpha+\cos\beta}{v}$

A β_i, V_A	B α_i, V_B	C v_i	D δ_i	E n	I used

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
113	÷	-24	
114	STOD	35 14	$\delta_1 = (\alpha_1 - \beta_1)/2$
115	P⇄S	16-51	
116	STO1	35 01	$\delta_1 \to S_1$
117	P⇄S	16-51	
118	RCLB	36 12	β_1 }
119	RCLA	36 11	α_1 }
120	+	-55	
121	2	02	
122	÷	-24	
123	SIN	41	
124	RCL1	36 01	
125	X⇄Y	-41	
126	÷	-24	
127	STOC	35 13	$v_2 = v_1 / \sin^{-1}\left(\frac{\alpha_1+\beta_1}{2}\right)$
128	STO2	35 02	
129	RTN	24	
130	*LBL4	21 04	4: (Assumes primary regs. up)
131	RCLB	36 12	
132	COS	42	
133	RCLA	36 11	
134	COS	42	
135	+	-55	Get $\frac{\cos\alpha_i + \cos\beta_i}{v_i}$
136	RCLi	36 45	
137	÷	-24	
138	P⇄S	16-51	
139	STO9	35 09	Store in S_9.
140	P⇄S	16-51	
141	RTN	24	
142	*LBL2	21 02	2: Input a or b
143	P⇄S	16-51	
144	SIN	41	
145	RCLi	36 45	Calculate P or Q
146	x	-35	
147	DSZI	16 25 46	
148	RCLi	36 45	$= \sin^{-1}\left(\frac{v_i}{v_{i+1}} \cdot \sin A, B\right)$
149	ISZI	16 26 46	
150	÷	-24	
151	SIN⁻¹	16 41	
152	P⇄S	16-51	
153	RTN	24	
154	*LBL5	21 05	5: Calc. α, β
155	RCL5	36 05	
156	RCLD	36 14	
157	-	-45	
158	STOB	35 12	$\alpha = a - \delta$
159	LSTX	16-63	
160	RCL6	36 06	
161	+	-55	
162	STOA	35 11	$\beta = b + \delta$
163	RTN	24	
164	*LBL6	21 06	6: Get ΣT
165	P⇄S	16-51	
166	GSB4	23 04	and store in S_0.
167	RCLI	36 46	
168	5	05	

STEP	KEY ENTRY	KEY CODE	COMMENTS
169	+	-55	(Conceived as a subr. because design problem -part II- would use this procedure. However, there wasn't storage to put part II on this card, too.)
170	X⇄I	16-41	
171	RCLi	36 45	
172	X⇄Y	-41	
173	X⇄I	16-41	
174	R↓	-31	
175	x	-35	
176	P⇄S	16-51	
177	ST+0	35-55 00	
178	RTN	24	
179	*LBLD	21 14	D: $T_{A_n} \to D_{A_n}$
180	P⇄S	16-51	
181	RCL0	36 00	
182	-	-45	
183	RCL9	36 09	Get $h_n = \frac{T_{A_n} - \Sigma T}{S_9}$
184	÷	-24	
185	P⇄S	16-51	
186	ST+0	35-55 00	$D = \sum^{n-1} h + h_n$
187	RCLE	36 15	
188	4	04	
189	+	-55	
190	X⇄I	16-41	
191	R↓	-31	
192	STOi	35 45	$h_n \to R_{n+5}$
193	RCL0	36 00	
194	RTN	24	

LABELS

A —	B —	C $\to v, \delta$	D $T \to D$	E —
a —	b —	c —	d —	e error msg.
0 entry in C	1 entry in C	2 $\to A, B$	3 $\to v_2, \delta_2$	4 $\frac{\cos\alpha + \cos\beta}{v}$
5 $\to \alpha, \beta$	6 $\to \frac{\Sigma H}{v} \cos$	7 —	8 —	9 —

FLAGS

0	—
1	—
2	—
3	—

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☐	DEG	☒	FIX	☒
1	☐	☐	GRAD	☐	SCI	☐
2	☐	☐	RAD	☐	ENG	☐
3	☐	☐			n	2

Program Description

Program Title ≤4 dipping seismic refractors: design

Name David L. Campbell **Date** 30 Dec 77

Address U.S. Geological Survey

City Denver **State** CO **Zip Code** 80225

Program Description, Equations, Variables, etc. A number $N \leq 4$ of seismic refractors of velocities v_i dip with dips δ_i under an overburden of velocity v_1. Thicknesses of each layer vertically under shotpoint A are h_i. This program calculates apparent velocities V_{Ai}, V_{Bi} and arrival times $T_{Ai}(x)$ of the refracted arrivals on the n'th branch of the resulting travel time graph, due to the n^{th} refracting horizon, and crossover ~~time~~ distance x_{cn} to the intersection of n^{th} and $n-1^{st}$ branches.

For further explanation, equation and diagrams, see "Part I: interpretation". If there is only one refractor, it is more convenient to use "dipping seismic refractor" program instead of this one.

Operating Limits and Warnings In Step 4, values $n=1$ and $n \geq N$ (= total no. input layers) are not allowed. Other warnings as for "Part I: interpretation".

DO NOT USE THIS SPACE

User Instructions

≤ 4 dipping seismic refractors: design

1 | 2

$h \uparrow v \uparrow \delta$ | $n \rightarrow V_A$ | $T_A(x)$ | x_c

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load side 1 and side 2 of card			
2	Clear primary and secondary registers		f CL REG	
			f P⇄S	
			f CL REG	
3	Store known layer parameters			
	a. vertical thickness under A of layer i	h_i	ENT↑	
	b. true velocity of layer i	v_i	ENT↑	
	c. dip of interface at base of layer i	δ_i	A	$i+1$
	Repeat for all layers from shallowest ($i=1$) to deepest ($i \leq 5$). Note input values h_i, δ_i for deepest layer are not used by the program: for this layer, only input v_i must be correct.			
4	Key layer index n; calculate app. veloc.	n	C	V_{An}
	(optional) recall V_B		RCL B	V_{Bn}
5	(optional) Calculate arrival times $T_{A_n}(x)$	x	D	$T_{A_n}(x)$
	Repeat as desired for other x.			
6	(optional) Calculate crossover distance		E	x_{cn}
	Caution: function E calculates crossover distances between last 2 travel-time branches considered. (If this is first pass through the program, between first branch and present branch.)			
7	Go to step 4 for next layer			
	(Because of feature described under step 6, its best to work through layers from shallowest to deepest, not skipping any.)			
8	For a new layered case, go to step 2.			

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	A: data input (h, v, δ)
002	ISZI	16 26 46	
003	P⇄S	16-51	$\delta_i \to S_i$
004	STOi	35 45	
005	P⇄S	16-51	
006	R↓	-31	$v_i \to R_i$
007	STOi	35 45	
008	5	05	
009	RCLI	36 46	N → Reg. E
010	STOE	35 15	
011	+	-55	
012	STOI	35 46	
013	R↓	-31	
014	R↓	-31	
015	STOi	35 45	$h_i \to R_{i+5}$
016	5	05	
017	RCLI	36 46	
018	5	05	
019	-	-45	
020	STOI	35 46	"Error" if >5 layers are tried.
021	X>Y?	16-34	
022	GSBe	23 16 15	
023	1	01	
024	+	-55	Display i+1
025	RTN	24	
026	*LBLC	21 13	C: $n \to V_{An}$
027	STOI	35 46	
028	5	05	"Error" if n>N
029	X≤Y?	16-35	
030	GSBe	23 16 15	
031	RCLA	36 11	
032	STO0	35 00	Initialize, starting with bottom layer.
033	1	01	
034	P⇄S	16-51	
035	GSB9	23 09	
036	STO5	35 05	Starting values A, B
037	STO6	35 06	
038	RCL0	36 00	← Steps for fcn E.
039	STO9	35 09	
040	0	00	Zero ΣT.
041	STO0	35 00	
042	DSZI	16 25 46	
043	RCLi	36 45	
044	STOD	35 14	
045	*LBL7	21 07	7: Entry for loop.
046	RCL5	36 05	
047	RCLD	36 14	(Steps identical to Sub#5 in part I.)
048	-	-45	
049	STOB	35 12	
050	LSTX	16-63	
051	RCL6	36 06	Calculate α, β
052	+	-55	
053	STOA	35 11	
054	P⇄S	16-51	(Steps identical to Sub#4 in part I.)
055	RCLB	36 12	
056	COS	42	
057	RCLA	36 11	Get (cos α + cos β)/v
058	COS	42	
059	+	-55	
060	RCLi	36 45	
061	÷	-24	
062	RCLI	36 46	(Steps identical to sub#6 in part I.)
063	5	05	
064	+	-55	
065	X⇄I	16-41	
066	RCLi	36 45	Get ΣT and store in S_0.
067	X⇄Y	-41	
068	X⇄I	16-41	
069	R↓	-31	
070	x	-35	
071	P⇄S	16-51	
072	ST+0	35-55 00	
073	RCL5	36 05	
074	RCLD	36 14	
075	DSZI	16 25 46	Is this top layer? If not, do steps of sub 8.
076	GTO8	22 08	
077	P⇄S	16-51	
078	RCL1	36 01	
079	RCLB	36 12	
080	SIN	41	
081	÷	-24	
082	STOB	35 12	
083	RCL1	36 01	If so, get V_A, V_B and stop.
084	RCLA	36 11	
085	SIN	41	
086	÷	-24	
087	STOA	35 11	
088	RTN	24	
089	*LBL8	21 08	8:
090	RCLi	36 45	
091	STOD	35 14	
092	ISZI	16 26 46	
093	-	-45	
094	-	-45	Get P, Q and repeat loop
095	STO7	35 07	
096	LSTX	16-63	
097	RCL6	36 06	
098	+	-55	
099	STO8	35 08	
100	SIN	41	
101	GSB9	23 09	
102	STO6	35 06	
103	RCL7	36 07	
104	SIN	41	
105	GSB9	23 09	
106	STO5	35 05	
107	DSZI	16 25 46	
108	GTO7	22 07	
109	*LBL9	21 09	9: for input x,
110	P⇄S	16-51	
111	RCLi	36 45	
112	DSZI	16 25 46	

REGISTERS

0	1	2	3	4	5	6	7	8	9
Old V_A	v_1	v_2	v_3	v_4	v_5	h_1	h_2	h_3	h_4

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
ΣT	δ_1	δ_2	δ_3	δ_4	a	b	P	Q	Old ΣT

A	B	C	D	E	I
α, V_{AN}	β, V_{Bn}	v_n	δ_n	$N = n_{max}$	used

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
113	RCL i	36 45	find $\sin^{-1}\left(x \cdot \frac{v_{i-1}}{v_i}\right)$
114	ISZI	16 26 46	
115	X⇄Y	-41	
116	÷	-24	
117	x	-35	
118	SIN⁻¹	16 41	
119	P⇄S	16-51	
120	RTN	24	
121	*LBLD	21 14	D: $T_{A_n}(x) = \frac{x}{V_A} + \Sigma T$
122	RCLA	36 11	
123	÷	-24	
124	P⇄S	16-51	
125	RCL0	36 00	
126	P⇄S	16-51	
127	+	-55	
128	RTN	24	
129	*LBLE	21 15	E: crossover dist $x_c = \frac{(\Sigma_1^n T - \Sigma T_{old})}{\left(\frac{1}{V_{old}} - \frac{1}{V_A}\right)}$ where ΣT_{old} was from step 039 and V_{old} from 032. $V_{old} = v_1$ if zero.
130	RCL0	36 00	
131	X=0?	16-43	
132	RCL1	36 01	
133	1/X	52	
134	RCLA	36 11	
135	1/X	52	
136	-	-45	
137	P⇄S	16-51	
138	RCL0	36 00	
139	RCL9	36 09	
140	P⇄S	16-51	
141	-	-45	
142	X⇄Y	-41	
143	÷	-24	
144	RTN	24	

LABELS

A	B	C	D	E
h↑v↑δ	–	$n \rightarrow V_{A_n}$	$T_{A_n}(x)$	x_{c_n}
a	b	c	d	e error msg
0	1	2	3	4
5	6	7 Used	8 Used	9 Used

FLAGS: 0, 1, 2, 3

SET STATUS

FLAGS (ON / OFF)	TRIG	DISP
0 ☐ ☐	DEG ☐	FIX ☐
1 ☐ ☐	GRAD ☐	SCI ☐
2 ☐ ☐	RAD ☐	ENG ☐
3 ☐ ☐		n ____

EXAMPLE 1: Interpretation —

Suppose $v_1 = 1200$ m/sec;

$V_{A2} = 2700$ m/sec; $V_{B2} = 3300$ m/sec; $T_{A2} = 0.056$ sec;

$V_{A3} = 7400$ m/sec; $V_{B3} = 9400$ m/sec; $T_{A3} = 0.208$ sec;

```
1200.00 ST01

   2.00 STOE
2700.00 STOA
3300.00 STOB
        GSBC
2967.10  ***
        RCLD
   2.53  ***

   .056 GSBD
  36.77  ***

   3.00 STOE
7400.00 STOA
9400.00 STOB
        GSBC
8262.27  ***
        RCLD
  -1.49  ***

   .208 GSBE
 271.10  ***
```

Store v_1 in R_1 (Step 2).

Input layer parameters for layer 2 (Step 3).

Calculate $v_2 = 2967.10$ m/sec; $\delta_1 = 2.53°$. (Step 4)

Calculate depth to interface #1 = 36.77 m. (Step 5)

Input layer parameters for layer 3 (Step 3).

Calculate $v_3 = 8262.27$ m/sec; $\delta_2 = -1.49°$ (Step 4).

Calculate depth to interface #2 = 271.10 m (Step 5).

Example 2: Design — Given tabled values:

n	h_n (m)	v_n (m/sec)	δ_n (deg)
1	36.77	1200	2.53
2	234.33	2967	-1.47
3	—	8262	—

```
              CLRG
              P⇄S
              CLRG

  36.770 ENT↑
1200.000 ENT↑
   2.530 GSBA

 234.330 ENT↑
2967.000 ENT↑
  -1.476 GSBA

8262.000 ENT↑
         ENT↑
         ENT↑
         GSBA

   2.000 GSBC
2700.114  ***
         RCLB
3299.570  ***
   0.000 GSBD
   0.055  ***
         GSBE
 120.940  ***

   3.000 GSBC
7394.895  ***
         RCLB
9407.123  ***
   0.000 GSBD
   0.206  ***
         GSBE
 646.488  ***
```

Step 2.

Store layer parameters (Step 3).
Note values h_n, δ_n for layer $n=3$ are not used, so any convenient value (here, v_3) is entered in their place.

Calculate $V_{A2} = 2700.114$ m/sec; $V_{B2} = 3299.57$ m/sec; $T_{A2} = 0.056$ sec; $x_{c1} = 120.940$ m.
(Steps 4, 5, 6 for layer 2).

Calculate $V_{A3} = 7394.895$ m/sec; $V_{B3} = 9407.123$ m/sec; $T_{A3} = 0.208$ sec; $x_{c2} = 646.488$ m.
(Steps 4, 5, 6 for layer 3).

Program Description

Program Title VERTICAL ELECTRIC SOUNDINGS: Schlumberger or Wenner

Name David L. Campbell Date

Address U.S. Geological Survey

City Denver State CO Zip Code 80225

Program Description, Equations, Variables, etc. Given an input resistivity structure of ≤ 10 horizontal "layers" (≤ 9 true layers plus underlying half-space), program on Card 1 calculates a numerical kernal function $B(x)$. This function may in turn be input to Card 2 (for Schlumberger arrays), or Card 3 (for Wenner arrays), to calculate the theoretical vertical electric sounding ("VES") which would be seen over the layered structure. Output consists of pairs $[AB/2, \rho_a(AB/2)]$, where $AB/2$ = array spacing, and $\rho_a(AB/2)$ = apparent resistivity at that spacing, sampled at 3 points per log cycle.

REFERENCES:

Zohdy, Adel A.R., and Bisdorf, R., 1974, A computer program for the automatic interpretation of Schlumberger sounding curves over horizontally stratified media: National Technical Information Service document NTIS PB-232703/AS, Springfield, VA 22161.

Ghosh, D.P., 1971, Inverse filter coefficients for the computation of apparent resistivity standard curves for a horizontally stratified earth: Geophys. Prosp. [Netherlands], v. XIX, no. 4, p. 769-775.

Operating Limits and Warnings The Ghosh filter has been found to have too few coefficients to adequately track a rapidly falling curve. Thus curves produced by this program may be somewhat in error in cases where a very good conductor underlies a relatively resistant layer.

"Error" flashes if attempt is made to enter more than 10 layers. See "Comments" for several other warnings!

DO NOT USE THIS SPACE

User Instructions

VERTICAL ELECTRIC SOUNDINGS —

1 2

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Load side 1 of card 1				
2	Set flags as necessary (see comment 1)				
3	Input layer resistivities, thicknesses				
	a. Resistivity of layer i	ρ_i (ohm-m)		ENT↑	
	b. Thickness of layer i	h_i (m)		A	i
	Repeat step 3 for all layers from shallowest				
	(i=0) to deepest (i ≤ 9). Program takes final				
	input layer to be infinite half-space, no matter				
	what h value you key.				
4	Key XMIN (see comment 3)	XMIN		C	XMIN
5	Calculate B(x).	x		E	x, B(x)
	Program cycles indefinitely. Record [x, B(x)]				
	pairs through range of interest. To stop	PRESS		R/S	
6	Load sides 1 and 2 of card 2 (Schlumberger)				
	or Card 3 (Wenner).				
7	Prime program (comment 4)			A	
8	For HP97 printed output (comment 5)		SF	∅	
9	Key XMIN	XMIN		ENT↑	
10	Key B(XMIN)	B(XMIN)		B	next-x
11	(optional) to enter data without convolving,				
	Key	B(this-x)		D	next-x
12	to convolve	B(this-x)		C	AB/2, $\rho_a(\frac{AB}{2})$
	Record [AB/2, ρ_a (AB/2)] pairs.				
	If flag ∅ set, next-x also appears in				
	display. Otherwise, to display next-x	PRESS		R/S	next-x.
	Repeat step 12 as desired.				
13	Error recovery — if an erroneous B-value				
	is entered in step 11 or 12, allow the				
	procedure to complete. Then	PRESS		E	(old) next-x.

VES Card 1 program listing —

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	A: Store $\left(\frac{\rho}{h}\right)$ pairs.
002	P⇄S	16-51	$h_i \rightarrow S_i$
003	STOi	35 45	
004	P⇄S	16-51	
005	R↓	-31	$\rho_i \rightarrow R_i$
006	STOi	35 45	
007	1	01	
008	0	00	
009	RCLI	36 46	"Error" if $n \geq 10$.
010	X>Y?	16-34	
011	GSBe	23 16 15	$n \rightarrow$ E-register
012	STOE	35 15	
013	ISZI	16 26 46	
014	RTN	24	
015	*LBLC	21 13	C: XMIN
016	STOC	35 13	xmin → C-register
017	3	03	
018	1/X	52	
019	10ˣ	16 33	
020	STOD	35 14	$\Delta x \rightarrow$ D-register
021	RCLC	36 13	
022	RTN	24	
023	*LBLE	21 15	E: Get B(x)
024	PRTX	-14	
025	STOC	35 13	Initialize loop:
026	1	01	
027	STOB	35 12	B = 1
028	RCLE	36 15	
029	STOI	35 46	i=n
030	*LBL2	21 02	2:
031	RCLB	36 12	
032	RCLi	36 45	
033	x	-35	$P = \rho_n \times B$
034	ENT↑	-21	
035	DSZI	16 25 46	
036	*LBL1	21 01	← a "NO OP" to avoid the I=0 switch.
037	RCLi	36 45	
038	-	-45	
039	X⇄Y	-41	
040	LSTX	16-63	
041	+	-55	
042	÷	-24	
043	CHS	-22	
044	P⇄S	16-51	$K = \dfrac{\rho_{n-1} - P}{\rho_{n-1} + P}$
045	RCLi	36 45	
046	P⇄S	16-51	
047	RCLC	36 13	
048	1/X	52	
049	x	-35	
050	2	02	
051	CHS	-22	
052	x	-35	
053	GSBa	23 16 11	← Accomodate Wenner, Sch.
054	eˣ	33	
055	x	-35	↖ $\exp(-2hx)$
056	ENT↑	-21	↖ $Q = K \cdot \exp$

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	ENT↑	-21	
058	1	01	
059	-	-45	
060	CHS	-22	
061	X⇄Y	-41	
062	1	01	
063	+	-55	$(1-Q)/(1+Q)$
064	÷	-24	
065	STOB	35 12	
066	RCLI	36 46	Test for end of loop.
067	X≠0?	16-42	
068	GTO2	22 02	
069	RCLB	36 12	Normalize by ρ_0
070	RCL0	36 00	
071	x	-35	Display B(x)
072	PRTX	-14	
073	SPC	16-11	
074	RCLC	36 13	
075	RCLD	36 14	Get next-x
076	x	-35	
077	GTOE	22 15	
078	*LBLa	21 16 11	a: flag test
079	F0?	16 23 00	
080	GTO3	22 03	
081	F1?	16 23 01	
082	GTO4	22 04	
083	RTN	24	
084	*LBL3	21 03	
085	1	01	Ghosh's factor for Schlumberger = 1.05
086	.	-62	
087	0	00	
088	5	05	
089	÷	-24	
090	RTN	24	
091	*LBL4	21 04	Ghosh's factor for Wenner = 1.36.
092	2	02	Resulting curve has ρ_a vs. $a = \frac{AB}{3}$.
093	.	-62	To translate to $\frac{AB}{2}$ curve,
094	7	07	multiply by $2/3$.
095	2	02	
096	ENT↑	-21	
097	3	03	
098	÷	-24	
099	÷	-24	
100	RTN	24	
110			

REGISTERS

0	1	2	3	4	5	6	7	8	9
ρ_0	ρ_1	ρ_2	etc.	———					→
S0	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
h_0	h_1	h_2	etc.	———					→

A	B	C	D	E	I
—	Σ	XMIN	Δx	n = # layers	used

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS

LABELS					FLAGS
A ℓ↑h	B —	C xMIN	D —	E B(x)	0 Used
a flag test	b	c	d	e "error"	1 Used
0	1 NO OP	2 Entry in E	3 Used in a	4 Used in a	2 —
5	6	7	8	9	3 —

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☐	FIX	☒
1	☒	☐	GRAD	☐	SCI	☐
2	☐	☐	RAD	☐	ENG	☐
3	☐	☐			n 4	

COMMENTS (Card 1)

1. Subroutine "a" shifts true kernal function somewhat to the left to make convolved values (Cards 2 or 3) come out right. This is done using flags, as shown in table. On loading Card 1, flags ϕ and 1 are set, so to make Schlumberger the default calculation. If Wenner results are desired, CF ϕ at Step 2 of the instructions.

	Flag ϕ	Flag 1
Schlumberger	set	(set)
Wenner	cleared	set
no shift	cleared	cleared

NOTE: Both programs calculate VES in which apparent resistivity ρ_a is plotted versus center-to-end electrode spacing AB/2. Sometimes, though, Wenner VES are plotted versus AB/3. To produce such a plot, the shift factor at label 4 must be changed to 1.36, rather than 2/3 x 1.36, which is its present value.

A tip: When making your own program card from the listing on page 35, be sure to set flags ϕ and 1 before recording the card. If you happen to forget, you may lose a lot of time trying to track down a very subtle error!

2. Program assumes bottom layer, layer n, is infinitely thick. Hence no value h_n need be entered.

Programmer's point: To accomodate possible 10-layer structures, registers Rϕ, Sϕ are used for first-layer parameters; R1, S1 for second layer; and so on. Somewhat cumbersome coding at steps 40, 71, and 72 results.

3. Subroutine E in program listed on page 35 is an infinite loop, starting with an arbitrary value of x called XMIN, and calculating values (x, B(x)) at the rate of three evenly-spaced x's per log cycle.

Question: How do I choose XMIN? Answer: Usually XMIN = 10^k, where k = positive or negative integer. Also choose XMIN<<h_o, the first layer thickness. (For example, if h_o = 2, take XMIN = 0.1). Exception: To get VES calculated at closer AB/2 spacings than the 3 points/cycle the program usually affords, a subsequent run is made to interpolate between earlier x-values. On such runs, choose XMIN = $(10^{1/6})^k$. (See example and Comments 8,9).

Question: When do I stop the loop? Answer: Stop the loop (by pressing R/S) when x is 100 times (3 points beyond) the highest AB/2 value of interest. For Wenner, only 1 point beyond is sufficient. (Illustrated in example.)

Programmer's point: Infinite-loop program at left is for HP97 printed output. HP67 users may prefer to delete steps 27 and 75, and replace step 76 with R/S, step 80 with RTN. Then pairs (x, B(x)) may be copied down at the user's own pace by alternately pressing [R/S] and [E].

4. A tip: Users who may need the related program "VES: Dar Zarrouk functions" can save card space by storing it on side 2 of card 1.

CARD 2 – SCHLUMBERGER (This program goes on side 2–card 2)

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	A: Prime P↔S
002	P⇄S	16-51	
003	RTN	24	
004	*LBLB	21 12	B: XMIN ↑ B(xmin)
005	STOD	35 14	Initialize
006	R↓	-31	
007	STOA	35 11	
008	9	09	
009	STOI	35 46	
010	RCLD	36 14	
011	*LBL7	21 07	B(xMIN) → all primary regs.
012	STO*i*	35 45	
013	DSZI	16 25 46	
014	GTO7	22 07	
015	3	03	Calculate Δx and store in C.
016	1/X	52	
017	10ˣ	16 33	
018	STOC	35 13	
019	*LBL8	21 08	8: Increment-x Subroutine
020	RCLA	36 11	
021	RCLC	36 13	
022	x	-35	
023	STOA	35 11	
024	RTN	24	
025	*LBLD	21 14	D: Data input Initialize
026	STOB	35 12	
027	0	00	
028	STOI	35 46	
029	RCL0	36 00	
030	STOE	35 15	
031	*LBL1	21 01	1: loop $B_i \rightarrow Reg_{i-1}$
032	ISZI	16 26 46	
033	RCL*i*	36 45	
034	DSZI	16 25 46	
035	ENT↑	-21	
036	STO*i*	35 45	Save B_0 in Reg E for possible error recovery.
037	ISZI	16 26 46	
038	9	09	
039	RCLI	36 46	
040	X=Y?	16-33	
041	GTO2	22 02	
042	GTO1	22 01	
043	*LBL2	21 02	2: end loop. New B → Reg 9.
044	RCLB	36 12	
045	STO9	35 09	
046	GSB8	23 08	
047	RTN	24	
048	*LBLC	21 13	C: Convolve Initialize
049	GSBD	23 14	
050	9	09	
051	STOI	35 46	
052	0	00	
053	*LBL3	21 03	3: convolution process.
054	RCL*i*	36 45	
055	P⇄S	16-51	
056	RCL*i*	36 45	

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	P⇄S	16-51	(Ghosh coeffs are stored in flipped order for direct product.)
058	x	-35	
059	+	-55	
060	DSZI	16 25 46	
061	GTO3	22 03	
062	STOD	35 14	
063	RCLA	36 11	
064	1	01	
065	0	00	
066	RCLC	36 13	
067	x	-35	
068	÷	-24	
069	F0?	16 23 00	
070	GTO4	22 04	
071	PSE	16 51	← Display AB/2
072	RCLD	36 14	
073	R/S	51	← Display ρ_a
074	RCLA	36 11	
075	RTN	24	Get next-x.
076	*LBLE	21 15	E: Error recovery
077	9	09	
078	STOI	35 46	
079	*LBL5	21 05	5: loop $B_{i-1} \rightarrow Reg_i$
080	DSZI	16 25 46	
081	*LBL9	21 09	
082	RCL*i*	36 45	
083	ISZI	16 26 46	
084	STO*i*	35 45	
085	DSZI	16 25 46	
086	*LBL9	21 09	
087	1	01	
088	RCLI	36 46	
089	X=Y?	16-33	
090	GTO6	22 06	
091	GTO5	22 05	
092	*LBL6	21 06	6: end loop. Restore old value of next-x.
093	RCLE	36 15	
094	STO0	35 00	
095	RCLA	36 11	
096	RCLC	36 13	
097	÷	-24	
098	STOA	35 11	
099	RTN	24	
100	*LBL4	21 04	4: Printout subroutine for HP97's.
101	PRTX	-14	
102	RCLD	36 14	
103	PRTX	-14	
104	SPC	16-11	
105	RCLA	36 11	
106	RTN	24	
107	R/S	51	
110			

REGISTERS

0	1	2	3	4	5	6	7	8	9
B_0	B_1	B_2	. . .	KERNAL	VALUES		. . .	B_8	B_9

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
D_0	D_1	D_2	. . .	GHOSH	COEFFICIENTS		. . .	D_8	D_9

A	B	C	D	E	I
next-x	used	Δx	used	last B_0	used

CARD 3 - WENNER **Program Listing** (This program goes on Side 2 of Card 3.)

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	
002	P⇄S	16-51	
003	RTN	24	
004	*LBLB	21 12	
005	STOD	35 14	
006	R↓	-31	
007	STOA	35 11	
008	9	09	
009	STOI	35 46	
010	RCLD	36 14	
011	*LBL7	21 07	
012	STOi	35 45	
013	DSZI	16 25 46	
014	GTO7	22 07	
015	3	03	
016	1/X	52	
017	10^x	16 33	
018	STOC	35 13	
019	*LBL8	21 08	
020	RCLA	36 11	
021	RCLC	36 13	
022	×	-35	
023	STOA	35 11	
024	RTN	24	
025	*LBLD	21 14	
026	STOB	35 12	
027	0	00	
028	STOI	35 46	
029	RCL0	36 00	
030	STOE	35 15	
031	*LBL1	21 01	
032	ISZI	16 26 46	
033	RCLi	36 45	
034	DSZI	16 25 46	
035	ENT↑	-21	
036	STOi	35 45	
037	ISZI	16 26 46	
038	9	09	
039	RCLI	36 46	
040	X=Y?	16-33	
041	GTO2	22 02	
042	GTO1	22 01	
043	*LBL2	21 02	
044	RCLB	36 12	
045	STO9	35 09	
046	GSB8	23 08	
047	RTN	24	
048	*LBLC	21 13	
049	GSBD	23 14	
050	9	09	
051	STOI	35 46	
052	0	00	
053	*LBL3	21 03	
054	RCLi	36 45	
055	P⇄S	16-51	
056	RCLi	36 45	
057	P⇄S	16-51	
058	×	-35	
059	+	-55	
060	DSZI	16 25 46	
061	GTO3	22 03	
062	RCLi	36 45	These steps (only) differ from Card 2 program because Wenner convolution lags only 1/3 of a log cycle, not 1 log cycle, as for Schlumberger. (steps 062–075)
063	P⇄S	16-51	
064	RCLi	36 45	
065	P⇄S	16-51	
066	×	-35	
067	+	-55	
068	STOD	35 14	
069	RCLA	36 11	
070	RCLC	36 13	
071	LOG	16 32	
072	2	02	
073	×	-35	
074	10^x	16 33	
075	÷	-24	
076	F0?	16 23 00	
077	GTO4	22 04	
078	PSE	16 51	
079	RCLD	36 14	
080	R/S	51	
081	RCLA	36 11	
082	RTN	24	
083	*LBLE	21 15	
084	9	09	
085	STOI	35 46	
086	*LBL5	21 05	
087	DSZI	16 25 46	
088	*LBL9	21 09	← (LBL9 is a false step to avoid the DSZI switch.)
089	RCLi	36 45	
090	ISZI	16 26 46	
091	STOi	35 45	
092	DSZI	16 25 46	
093	*LBL9	21 09	←
094	1	01	
095	RCLI	36 46	
096	X=Y?	16-33	
097	GTO6	22 06	
098	GTO5	22 05	
099	*LBL6	21 06	
100	RCLE	36 15	
101	STO0	35 00	
102	RCLA	36 11	
103	RCLC	36 13	
104	÷	-24	
105	STOA	35 11	
106	RTN	24	
107	*LBL4	21 04	
108	PRTX	-14	
109	RCLD	36 14	
110	PRTX	-14	
111	SPC	16-11	
112	RCLA	36 11	
113	R/S	51	← Implied R/S in 2nd half of prog. storage serves as a return.

LABELS					FLAGS	SET STATUS
A PRIME	B BEGIN	C CONVLV	D DATA	E ERROR	0 Printout	FLAGS: ON / OFF — 0 OFF ☒; 1 ☐ ☐; 2 ☐ ☐; 3 ☐ ☐
a	b	c	d	e —	1 —	TRIG: DEG ☐ GRAD ☐ RAD ☐
0	1 loop entry	2 Used in D	3 Used in C.	4 HP97 print	2 —	DISP: FIX ☒ SCI ☐ ENG ☐ n 2
5 Used in E	6 Used in E	7 Used in B	8 Subr.	9 —	3 —	

Data Card Contents

DATA CARD 1		DATA CARD 2		DATA CARD 3	
Register Contents	Reg. #	Register Contents	Reg. #	Register Contents	Reg. #
		0.0000	0	−0.0067	0
		0.0148	1	0.0179	1
		−0.0814	2	−0.0253	2
		0.4018	3	0.0416	3
		−1.5716	4	−0.0935	4
		1.9720	5	0.3473	5
		0.1854	6	−1.3341	6
		0.1064	7	1.5662	7
		−0.0499	8	0.4582	8
		0.0225	9	0.0284	9
		This data stored on Side 1 of Card 2 (Schlumberger).		This data stored on Side 1 of Card 3 (Wenner).	

COMMENTS (continued--Cards 2 and 3)

5. A user who calculates only Schlumberger VES doesn't need Card 3, while one who calculates only Wenner VES doesn't need Card 2. Both are included here for completeness. Cards 2 and 3 are identical except for a few steps (marked on the program listing), and the different data sets stored on side 1.

6. To prepare program card, with Ghosh data on side 1 and program on side 2, do this:

a. Key program into memory from program listing
b. Put values shown on "data card listing" (page 41) in primary storage registers
c. Switch to W/PRGM mode and feed in side 2 of card
d. Switch to RUN mode, press [Σ+] key, press [f] [W/DATA], and feed in side 1 of card. Display now shows "CRD".
e. Clear prompt word by pressing CLX. Card is now ready to use

NOTE: The card so produced is a hybrid, with the program on Side 2, and data on side 1. When side 1 is read in, "CRD" appears in display to prompt user to read in side 2 as well. But, if side 2 is inadvertently read in first, the prompt word does not appear as would happen for a true program card.

7. Ghosh coefficients (constants) are originally read as data off the card into primary registers. "Prime" step (keying A) just performs P⇄S, so as to transfer them to secondary storage. Warning: Subroutine A and/or [P⇄S] should be performed an odd number of times (preferably only once), so as to keep Ghosh coefficients in secondary storage. Whenever answers look funny, the first thing to check is if Ghosh coefficients are in secondary storage, where they belong.

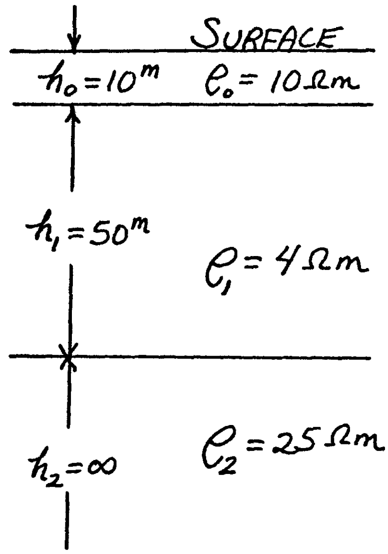
8. "Begin" step (key B) loads current B value into all primary registers. That's why XMIN should be chosen <<h_o (= first-layer thickness), to get accurate ρ_a curves for small AB/2 values.

9. Values B(x) must be entered in order of increasing x-values, with x's chosen evenly spaced at 3 x's per log cycle. Typical x's are therefore $10^{0/3} = 1.00$, $10^{1/3} = 2.15$, $10^{2/3} = 4.64$, etc. To get more detailed VES, a separate run is made with interpolated values of x, e.g., $10^{1/6} = 1.46$, $10^{3/6} = 3.16$, $10^{5/6} = 6.81$, etc. (The program on Card 1 produces such evenly-spaced B(x) automatically.)

10. During convolution, the Ghosh coefficients (constants) are in secondary storage and kernal values B(x) are in primary storage, with last entered in R9. When a new B(x) is entered, previous values cascade down through primary registers, i.e., new B goes in R9, previous R9 goes to R8, previous R8 to R7, etc. Previous R0 is saved in register E, and can be restored to R0 in a reverse-cascade if an error is found to have been made. (Subroutine E)

11. When flag ϕ is set, some procedures are invoked which print pairs (AB/2, ρ_a(AB/2)), separated by spaces. Next-x is displayed, but not printed, if flag ϕ is set. This option would normally be used with HP97 calculators. With HP67's, on the other hand, flag ϕ should remain cleared; then AB/2 will be displayed momentarily, followed by ρ_a(AB/2). Next-x may be found by pressing [R/S], an optional, convenience feature.

12. Adel Zohdy (written communication, 1978) has written an HP67/97 program for Schlumberger VES which is similar to this one. It accomodates 6 layers and is very convenient in that (a) the kernal function B(x) does not need to be copied and re-input; and (b) ρ_a(AB/2) is calculated directly for any starting value of AB/2. Because it calculates function B(x) separately for each AB/2, however, Zohdy's program is slower than the present one at calculating an entire VES curve.



<u>EXAMPLE</u>: Calculate VES curves for this structure.

<u>SOLUTION</u>: Suppose we want 6 points per log cycle for AB/2 values from 1 meter to 1000 meters. Since program calculates 3 points/log cycle, we will make 2 passes — the first to give values at $x = 10^{0/6} = 1.00$, $10^{2/6} = 2.15$, $10^{4/6} = 4.64$, etc.; the second to give values at $x = 10^{1/6} = 1.47$, $10^{3/6} = 3.16$, $10^{5/6} = 6.82$, etc.

Start by calculating $B(x)$, the kernal function. Schlumberger tapes will be at left; Wenner tapes at right.

<u>Schlumberger</u>		<u>Wenner</u>
CLRG	Start: Read side 1 of Card 1.	CF0
10.0000 ENT↑ 10.0000 GSBA	Clear flag 0 for wenner →	10.0000 ENT↑ 10.0000 GSBA
4.0000 ENT↑ 50.0000 GSBA 25.0000 ENT↑ 1.+50 GSBA	← Input resistivity structure (step 3) → (1.+50 is a large number representing ∞)	4.0000 ENT↑ 50.0000 GSBA 25.0000 ENT↑ 1.+50 GSBA
1.0000 GSBC	← Input XMIN (Step 4) → (Use XMIN = $10^{0/6}$ = 1 << h_0)	1.0000 GSBC
GSBE 1.0000 *** 10.0000 ***	← Calculate Kernal fcn (Steps) →	GSBE 1.0000 *** 10.0000 ***
2.1544 *** 5.9988 ***		2.1544 *** 5.3997 ***
4.6416 *** 3.8555 ***		4.6416 *** 5.2260 ***

Kernal fcn $B(x)$ calculation.

First number of each pair is x.
Second number is $B(x)$.

Here is max. value of $\frac{AB}{2}$

Wenner ends one point beyond max $\frac{AB}{2}$.

Schlumberger ends three points beyond max $AB/2$.

```
   10.0000  ***
    8.8037  ***

   21.5443  ***
    7.8345  ***

   46.4159  ***
    6.2368  ***

  100.0000  ***
    7.5426  ***

  215.4435  ***
   10.8796  ***

  464.1589  ***
   15.2240  ***

 1000.0000  ***
   19.1571  ***

 2154.4347  ***
   21.8745  ***

 4641.5888  ***
   23.4355  ***

10000.0000  ***
   24.2494  ***
```

```
   10.0000  ***
    9.0984  ***

   21.5443  ***
    7.7510  ***

   46.4159  ***
    6.2438  ***

  100.0000  ***
    7.1138  ***

  215.4435  ***
   10.1211  ***

  464.1589  ***
   14.3643  ***

 1000.0000  ***
   18.4884  ***

 2154.4347  ***
   21.4545  ***
```

First pass done. Begin second pass.

(New xMIN is $10^{\frac{1}{6}} = 1.4678$)
(Step 4.)

Calculate interpolated Kernal function $B'(x')$.

First number of each pair is x'.
Second number is B'.

```
    6.0000  1/X
            10^X
    1.4678  ***
            GSBC

            GSBE
    1.4678  ***
   10.0000  ***

    3.1623  ***
    9.9793  ***

    6.8129  ***
    9.4893  ***

   14.6780  ***
    7.9079  ***

   31.6228  ***
    6.4139  ***

   68.1292  ***
    6.6055  ***
```

```
    6.0000  1/X
            10^X
    1.4678  ***
            GSBC

            GSBE
    1.4678  ***
   10.0000  ***

    3.1623  ***
    9.9920  ***

    6.8129  ***
    9.6691  ***

   14.6780  ***
    8.2601  ***

   31.6228  ***
    6.6077  ***

   68.1292  ***
    6.3967  ***
```

```
 146.7799  ***
   9.8019  ***

 316.2278  ***
  13.8173  ***

 681.2921  ***
  17.3159  ***

1467.7993  ***
  20.6751  ***

3162.2777  ***
  22.7777  ***

6812.9207  ***
  23.9142  ***
```

```
 146.7799  ***
   9.7875  ***

 316.2278  ***
  12.1609  ***

 681.2921  ***
  16.5395  ***

1467.7993  ***
  20.1363  ***
```

Ready to convolve.
Read Card 2 (Schlumberger) or Card 3 (Wenner).

Prime (Step 7)

Set flag 0 for HP97 output (Step 8).

Key xMIN (Step 9), and B(xMIN) (Step 10).

For Schlumberger, can enter 2 data points without convolving. (Convolved output would have been for AB/2 values < 1, possibly of no interest to us here.)

Begin convolution, entering B(x) values found above.

```
         GSBA
         SF0
 1.00 ENT↑
10.00 GSBE

  2.15  ***
9.9988 GSBD

  4.64  ***
9.8595 GSBD

 10.00  ***
8.9007 GSBC
  1.00  ***
  9.96  ***

 21.54  ***
7.0345 GSBC
  2.15  ***
  9.98  ***

 46.42  ***
6.2360 GSBC
  4.64  ***
  9.91  ***

100.00  ***
7.5426 GSBC
 10.00  ***
  9.32  ***
```

```
         GSBA
         SF0
 1.00 ENT↑
10.00 GSBE

  2.15  ***
9.9997 GSBC
  1.00  ***
 10.00  ***

  4.64  ***
9.9263 GSBC
  2.15  ***
 10.00  ***

 10.00  ***
9.0984 GSBC
  4.64  ***
  9.94  ***

 21.54  ***
7.3512 GSBC
 10.00  ***
  9.40  ***

 46.42  ***
6.2430 GSBC
 21.54  ***
  7.37  ***

100.00  ***
7.1186 GSBC
 46.42  ***
  5.23  ***
```

```
  215.44  ***
 10.8796 GSBC
   21.54  ***
    7.05  ***

  464.16  ***
 15.2246 GSBC
   46.42  ***
    5.99  ***

 1000.00  ***
 19.1571 GSBC
  100.00  ***
    6.35  ***

 2154.43  ***
 21.8746 GSBC
  215.44  ***
   10.50  ***

 4641.59  ***
 23.4395 GSBC
  464.16  ***
   15.96  ***

10000.00  ***
 24.2494 GSBC
 1000.00  ***
   20.91  ***
```

For each group:
1st number is x (normally displayed but not printed – I've added extra print statements to this example.)
2nd number is input value $B(x)$, found using Card 1.
3rd number is $AB/2$.
4th number is $\rho_a(AB/2)$.

```
  215.44  ***
 10.1211 GSBC
  100.00  ***
    6.02  ***

  464.16  ***
 14.3043 GSBC
  215.44  ***
    9.84  ***

 1000.00  ***
 18.4984 GSBC
  464.16  ***
   15.13  ***

 2154.43  ***
 21.4545 GSBC
 1000.00  ***
   20.18  ***
```

```
    5.00  1/X
          10^X
    1.47  ***
   10.00 GSBB

    3.16  ***
  9.5792 GSBD

    6.81  ***
  9.4899 GSBD

   14.68  ***
  7.9879 GSBC
    1.47  ***
    9.98  ***

   31.62  ***
  6.4139 GSBC
    3.16  ***
    9.97  ***
```

First pass done. Get interpolated values now.

Input new xMIN and B′(new xMIN)

Again, for Schlumberger, can enter 2 data points without convolving if $\rho_a(AB/2)$ values for $AB/2 < 1$ aren't of interest.

Convolve as before, using B′(x′) values found using Card 1.

```
    6.00  1/X
          10^X
          ENT↑
    1.47  ***
   10.00 GSBB

    3.16  ***
  9.9520 GSBC
    1.47  ***
   10.00  ***

    6.81  ***
  9.6691 GSBC
    3.16  ***
    9.99  ***

   14.68  ***
  8.2601 GSBC
    6.81  ***
    9.79  ***

   31.62  ***
  6.5077 GSBC
   14.68  ***
    8.68  ***
```

```
  68.13  ***
6.6055 GSBC
  6.81   ***
  3.74   ***

 146.78  ***
6.6055 GSBC
 14.68   ***
  8.35   ***

        GSBE

 146.78  ***
9.0015 GSBC
 14.68   ***
  8.40   ***

 316.23  ***
13.0173 GSBC
 31.62   ***
  5.76   ***

 681.29  ***
17.3155 GSBC
 68.13   ***
  5.29   ***

1467.80  ***
20.6791 GSBC
 146.78  ***
  9.15   ***

3162.28  ***
22.7777 GSBC
 316.23  ***
 13.19   ***

6812.92  ***
23.5142 GSBC
 681.29  ***
 16.56   ***
```

Oops! Made an error here!

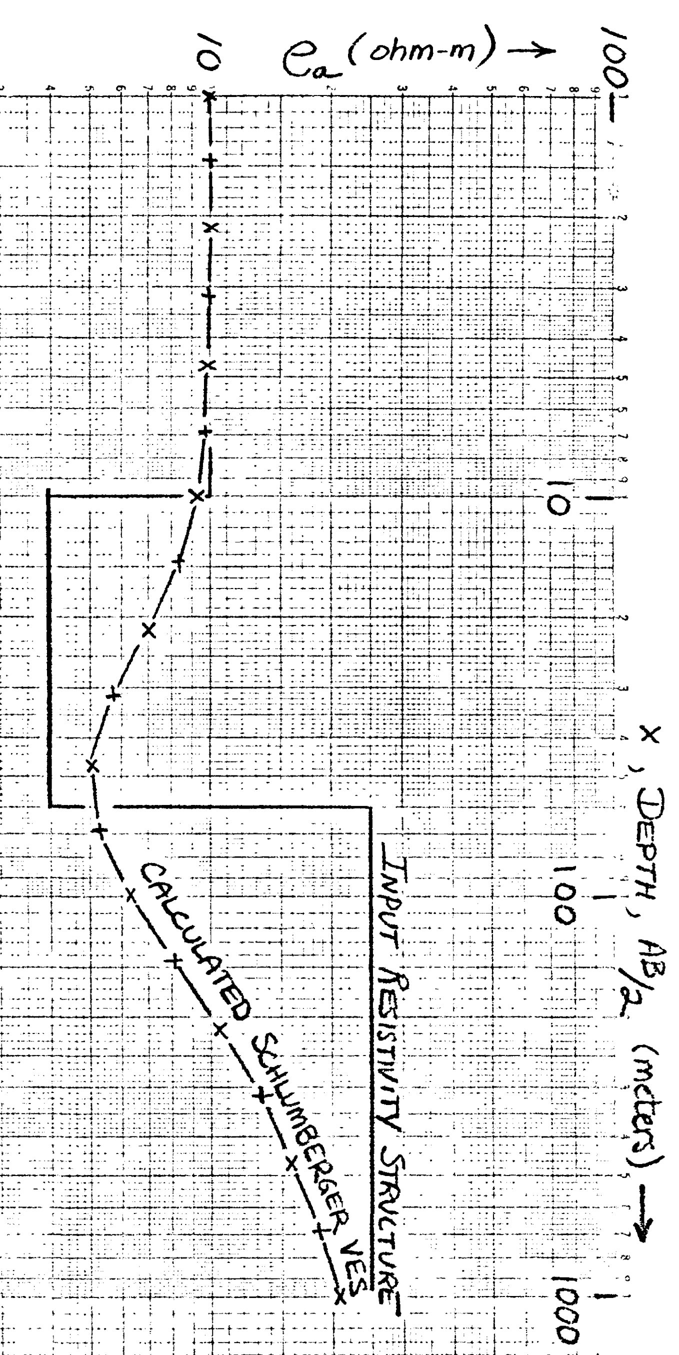
Error recovery.

Continue as before...

```
  68.13  ***
6.3967 GSBC
 31.62   ***
  6.06   ***

 146.78  ***
8.3875 GSBD

        GSBE

 146.78  ***
8.3875 GSBC
 68.13   ***
  5.20   ***

 316.23  ***
12.1809 GSBC
 146.78  ***
  7.63   ***

 681.29  ***
16.5395 GSBC
 316.23  ***
 12.44   ***

1467.80  ***
20.1363 GSBC
 681.29  ***
 17.85   ***
```

Results found here are plotted on Data sheet S (for Schlumberger) and Data sheet W (for Wenner).

x	x'	B(x)	B(x')	ρ_a	ρ_a'
1.00		10.000		9.98	
	1.46		10.0000		9.98
2.15		9.9988		9.98	
	3.16		9.9793		9.97
4.64		9.8595		9.91	
	6.81		9.4899		9.74
10.00		8.8007		9.32	
	14.68		7.9079		8.40
21.54		7.0345		7.05	
	31.62		6.4139		5.76
46.42		6.2360		5.09	
	68.13		6.6055		5.29
100.00		7.5426		6.35	
	146.78		9.0019		8.15
215.44		10.8796		10.50	
	316.23		13.0173		13.18
464.16		15.2240		15.95	
	681.29		17.3159		18.58
1000.00		19.1571		20.81	
	1467.80		20.6791		
2154.43		21.8748			
	3162.28		22.7777		
4641.59		23.4395			
	6812.92		23.9142		
10,000.00		24.2491			



x = Initial (Unprimed) Series

+ = Interpolated (primed) Series

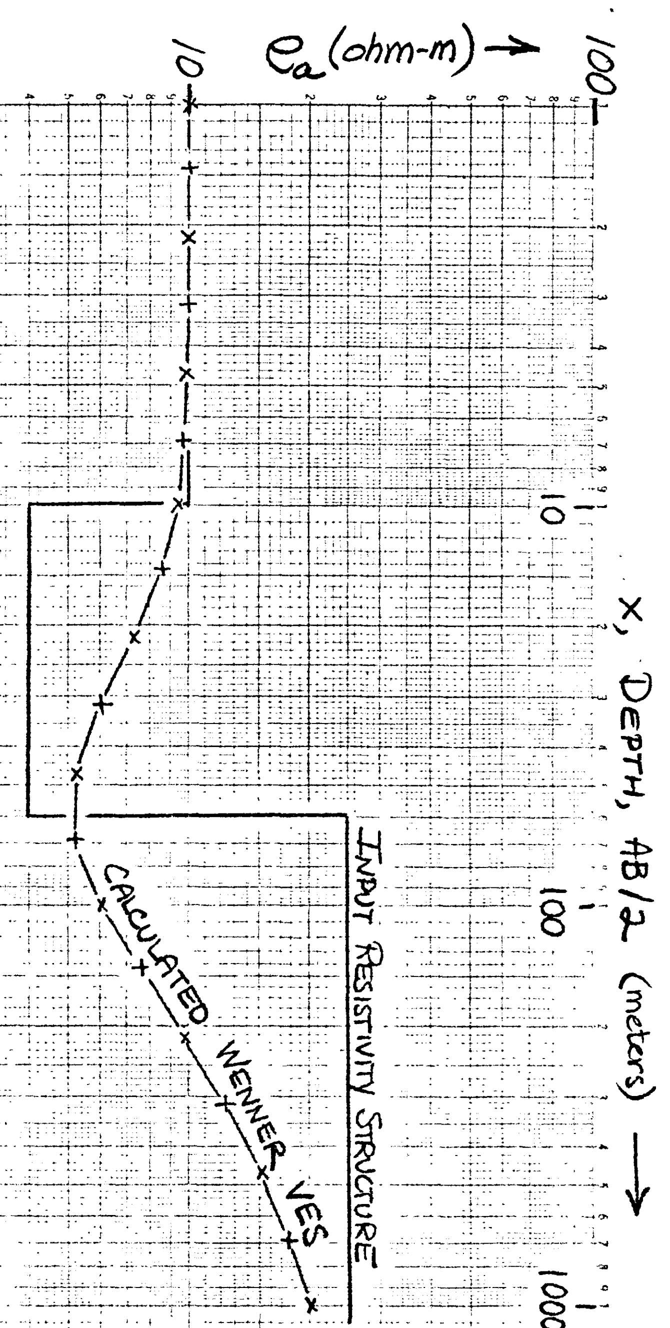
DATA SHEET S

Dave Campbell
USGS-Oct77

Example p. 67

GPO 835-846

X	B(X)	ρ_a	X'	B(X')	ρ'_a
1.00	10.0000	10.00			
			1.46	10.0000	10.00
2.15	9.9997	10.00			
			3.16	9.9920	9.99
4.64	9.9263	9.94			
			6.81	9.6691	9.79
10.00	9.0984	9.40			
			14.68	8.2601	8.60
21.54	7.3510	7.37			
			31.62	6.6077	6.06
46.42	6.2430	5.23			
			68.13	6.3987	5.20
100.00	7.1188	6.03			
			146.78	8.3875	7.63
215.44	10.1211	9.84			
			316.23	12.1809	12.44
464.16	14.3843	15.19			
			681.29	16.5395	17.85
1000.0	18.4884	20.18			
			1467.80	20.1363	
2154.43	21.4545				



+ = Interpolated (Primed) Series
x = Initial (Unprimed) Series

DATA SHEET W

Dave Campbell
USGS Oct 77

Example p. 7 of 7

GPO 835-946

Program Description

Program Title VES: Dar Zarrouk functions
Name David L. Campbell **Date** 22 Dec 77
Address U.S. Geological Survey
City Denver **State** CO **Zip Code** 80225

Program Description, Equations, Variables, etc. "Dar Zarrouk curves are used to define the limits of equivalence for multilayer sections, to improve the fit between theoretical and observed VES curves, and to incorporate geological and geophysical constraints in interpreted geoelectric models." —Adel A.R. Zohdy, ref. below

This program calculates Dar Zarrouk resistivity R_j and depth L_j from a given horizontal layering structure (ρ_j, h_j), where ρ_j = resistivity and h_j = thickness of j^{th} layer, and vice-versa.

Equations: function A

$$R_j = \sqrt{T_j/S_j} \qquad L_j = R_j S_j \qquad \text{where} \begin{cases} T_j = \sum_{i=1}^{j} \rho_i h_i \\ S_j = \sum_{i=1}^{j} h_i/\rho_i \end{cases}$$

function C

$$R(L) = \frac{-h_j(\rho_{j+1}^2 - \rho_j^2) + \sqrt{[h_j(\rho_{j+1}^2 - \rho_j^2)]^2 + (2L\rho_j\rho_{j+1})^2}}{2L\rho_j}$$

function E

$$\rho_j = \sqrt{\frac{\Delta_j LR}{\Delta_j L/R}} \qquad h_j = \rho_j \cdot \Delta_j \frac{L}{R} \qquad \text{where} \begin{cases} \rho_1 = R_1, \; h_1 = L_1 \\ \Delta_j LR = L_j R_j - L_{j-1} R_{j-1} \\ \Delta_j \frac{L}{R} = \frac{L_j}{R_j} - \frac{L_{j-1}}{R_{j-1}} \end{cases}$$

Units are compatible, i.e. for distances h, L in ft, ρ, R will be in ohm-ft.

Reference: Zohdy, Adel A.R., 1974, Use of Dar Zarrouk curves in the interpretation of vertical electrical sounding data: U.S. Geological Survey Bulletin 1313-D, 41 p.

Operating Limits and Warnings No points (L_j, R_j) on real DZ curves may lie above or below a 45° cone (on log-log plot) with vertex at (L_{j-1}, R_{j-1}). "Error" flashes if such points are input.

DO NOT USE THIS SPACE

User Instructions

1	VES: Dar Zarrouk functions				2
$\rho, h \to R, L$		R(L)		$R, L \to \rho, h$	

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
0	Load Side 1 of card.				
0'	Set flags as needed *				
	for HP97 printed output		SF	ϕ	
	if h_j = depth to bottom of layer j		SF	1	
	PROBLEM A: Calculate DZ points (R,L) —				
A1	Clear registers		f	CL REG	
A2	Input layering: ($\rho_i, h_i; i=1,j$)				
	resistivity	ρ_i (ohm-m)		ENT↑	
	Thickness (depth if flag 1 set)	h_i (m)		A	R_i, L_i
	Repeat step A2 for layers i, working from				(R_i in ohm-m,
	shallowest to deepest. Note index i is in				L_i in m)
	I-register; R_i in C-register; L_i in D-register.				
	(To change an erroneous entry, repeat step A2				
	with negative h_i and DSZI twice.)				
	PROBLEM C: Calculate DZ function	R(L) —			
C1	Input 2 resistivities and 1 thickness				
	(not depth).	ρ_i (ohm-m)	STO	A	
		h_i (m)	STO	B	
		ρ_{i+1} (ohm-m)	STO	E	
C2	Key DZ depth	L (m)		C	R(L) (ohm-m)
	Repeat step C2 as desired.				
	PROBLEM E: Calculate layering from a given				
	series of DZ points —				
E1	Clear registers		f	CL REG	
E2	Key DZ resistivity	R_j (ohm-m)		ENT↑	
	DZ depth	L_j (m)		E	ρ_j, h_j
	Repeat step E2 for all layers j, from				
	shallowest to deepest. Note index j is in				(ρ in ohm-m,
	I-register; ρ in A-register; h_j in B-register.				h_j in m)
	(h_j represents depth if flag 1 is set.)				
	(To change an erroneous entry, repeat step E2				
	for j-1, ignoring output. Step E2 for j will				
	then give correct results. Reset I by 2 DSZI's.)				
*	Default case has no printed output (flag ϕ cleared)				
	and has h_j representing thickness of layer j				

(flag 1 cleared.).

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	A: $\binom{\rho}{h} \to \binom{R}{L}$
002	ISZI	16 26 46	
003	F1?	16 23 01	
004	GSB1	23 01	
005	STOB	35 12	
006	R↓	-31	
007	STOA	35 11	
008	R↑	16-31	
009	×	-35	
010	ST+3	35-55 03	
011	RCLB	36 12	
012	RCLA	36 11	
013	÷	-24	
014	ST+4	35-55 04	
015	RCL3	36 03	
016	RCL4	36 04	
017	÷	-24	
018	√X	54	
019	STOC	35 13	
020	GSB0	23 00	
021	RCL4	36 04	
022	×	-35	
023	STOD	35 14	
024	GSB0	23 00	
025	SPC	16-11	
026	RTN	24	
027	*LBLE	21 15	E: $\binom{R}{L} \to \binom{\rho}{h}$
028	ISZI	16 26 46	
029	STOD	35 14	
030	R↓	-31	
031	STOC	35 13	
032	R↑	16-31	
033	×	-35	
034	STO5	35 05	
035	RCL1	36 01	
036	-	-45	
037	RCLD	36 14	
038	RCLC	36 13	
039	÷	-24	
040	STO6	35 06	
041	RCL2	36 02	
042	-	-45	
043	STO2	35 02	
044	÷	-24	
045	√X	54	
046	STOA	35 11	
047	GSB0	23 00	
048	RCL2	36 02	
049	×	-35	
050	F1?	16 23 01	
051	GSB2	23 02	
052	STOB	35 12	
053	RCL5	36 05	
054	STO1	35 01	
055	RCL6	36 06	
056	STO2	35 02	

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	RCLB	36 12	
058	GSB0	23 00	
059	SPC	16-11	
060	RTN	24	
061	*LBLC	21 13	C: Get R(L)
062	STOD	35 14	
063	RCLA	36 11	
064	×	-35	
065	2	02	
066	×	-35	
067	STO7	35 07	$2L\rho_j$
068	RCLE	36 15	
069	X²	53	
070	RCLA	36 11	
071	X²	53	
072	-	-45	
073	RCLB	36 12	
074	×	-35	
075	STO8	35 08	$h_j(\rho_{j+1}^2 - \rho_j^2)$
076	X²	53	
077	RCL7	36 07	
078	RCLE	36 15	
079	×	-35	
080	X²	53	
081	+	-55	
082	√X	54	
083	RCL8	36 08	
084	-	-45	
085	RCL7	36 07	
086	÷	-24	
087	STOC	35 13	
088	RTN	24	
089	*LBL1	21 01	1: Change depth to thickness.
090	RCL0	36 00	
091	X>Y?	16-34	
092	GSBe	23 16 15	
093	R↓	-31	
094	STO0	35 00	
095	R↑	16-31	
096	-	-45	
097	RTN	24	
098	*LBL0	21 00	0: Print output subroutine for HP97's.
099	F0?	16 23 00	
100	PRTX	-14	
101	F0?	16 23 00	
102	RTN	24	
103	PSE	16 51	
104	RTN	24	
105	*LBL2	21 02	2: Change thickness to depth.
106	ST+0	35-55 00	
107	RCL0	36 00	
108	RTN	24	
110			

REGISTERS

0	1	2	3	4	5	6	7	8	9
d_{j-1}	$L_{j-1}R_{j-1}$	L_{j-1}/R_{j-1}	$T=\Sigma h\rho$	$S=\Sigma h/\rho$	L_jR_j	L_j/R_j	$2L\rho_j$	$h_j(\rho_{j+1}^2-\rho_j^2)$	—
S0 —	S1 —	S2 —	S3 —	S4 —	S5 —	S6 —	S7 —	S8 —	S9 —

A	B	C	D	E	I
ρ_j	h_j	R_j	L_j	ρ_{j+1}	j

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
120				170			
130				180			
140				190			
150				200			
160				210			
				220			

LABELS

A $\frac{\rho}{h} \to \frac{R}{L}$	B —	C R(L)	D —	E $\frac{R}{L} \to \frac{\rho}{h}$
a —	b —	c —	d —	e error
0 print	1 $d_i \to h_i$	2 $h_i \to d_i$	3 —	4 —
5 —	6 —	7 —	8 —	9 —

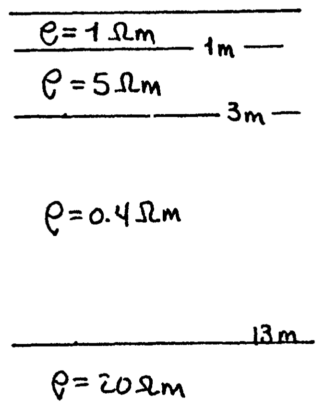
FLAGS

0	print
1	depth
2	—
3	—

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☐	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☐	RAD	☐	ENG	☐
3	☐	☐			n	2

EXAMPLE: Calculate DZ points for structure at right. (a problem of type A.)




```
        SF0
        SF1
       CLRG
1.00   ENT↑
1.00   GSBA
1.00   ***
1.00   ***

5.00   ENT↑
3.00   GSBA
2.80   ***
3.92   ***

.40    ENT↑
13.00  GSBA
0.75   ***
19.90  ***

20.00  ENT↑
1.+50  GSBA
20.00  ***
1.00000000+50  ***
```

- SF0: flag to print output.
- SF1: flag to show h_i represents depth, not thickness.
- CLRG: Step A1.
- Step A2 for 1st layer. ($R_1 = 1.00$ Ωm, $L_1 = 1.00$ m)
- Step A2 for 2nd layer. ($R_2 = 2.80$ Ωm, $L_2 = 3.92$ m)
- Step A2 for 3rd layer ($R_3 = 0.75$ Ωm, $L_3 = 19.90$ m)
- Step A2 for 4th layer. (1.+50 represents ∞; any large number would do here.)

EXAMPLE: Invert the above DZ series. (a problem of type E)

```
        CLRG
1.00   ENT↑
1.00   GSBE
1.00   ***
1.00   ***

2.80   ENT↑
3.92   GSBE
4.99   ***
3.00   ***

.75    ENT↑
19.90  GSBE
0.40   ***
12.96  ***

20.00  ENT↑
1.+50  GSBE
20.00  ***
1.00000000+50  ***
```

- Flags are still set from above. Step E1.
- Step E2 for 1st layer. ($\rho_1 = 1.00$ Ωm, $h_1 = d_1 = 1.00$ m)
- Step E2 for 2nd layer. ($\rho_2 = 4.99$ Ωm, $d_2 = 3.00$ m)
- Step E2 for 3rd layer ($\rho_3 = 0.40$ Ωm, $d_3 = 12.96$ m)
- Step E2 for 4th layer ($\rho_4 = 20.00$ Ωm, $d_4 = \infty$)

Note some round-off error has occurred in calculating ρ_2, d_3.

EXAMPLE: Calculate R(L) when $\rho_1 = 1 = h_1$, $\rho_2 = 10$. (a problem of type C: resulting curve can be plotted to give a useful template for general DZ curve-fitting.)

```
        CLRG
1.00   STOA
       STOB
10.00  STOE
1.00   GSBC
1.00   ***
2.00   GSBC
1.94   ***
4.00   GSBC
3.54   ***
```

- CLRG step not strictly necessary here: doesn't hurt.
- Data input: step C1.
- R(1.00) = 1.00 Ωm
- R(2.00) = 1.94 Ωm
- R(4.00) = 3.54 Ωm

etc.

Program Description

Program Title MAGNETOTELLURIC PLANE-WAVE APPARENT CONDUCTIVITY

Name Raymond D. Watts Date Oct. 77

Address U.S. Geological Survey

City Denver State CO Zip Code 80225

Program Description, Equations, Variables, etc. Given an input conductivity structure of ≤10 horizontal "layers" (≤9 true layers plus underlying half-space), this program calculates magnetotelluric plane-wave apparent conductivity σ_{app} and phase angle $\angle^{H}_{E}$ at arbitrary frequencies input by user. Alternately, an MT sounding with 10 points per log cycle may be calculated.

Equations: $\sigma_{app} = \omega\mu_0 \left|\frac{H_x}{E_y}\right|^2$ $\angle^{H_x}_{E_y} = \tan^{-1}\frac{H_x}{E_y}$

Reference: Ward, Stanley H., 1967, Electromagnetic Theory for geophysical application: in Society of Exploration Geophysicists: Mining Geophysics, vol. 2 (SEG: Tulsa, OK) p. 107-124.

Operating Limits and Warnings If flag 1 is set, all symbols "σ" in steps 4+5 will be taken to be resistivities $\rho = 1/\sigma$, not conductivities σ.
"Error" flashes for number of layers $n < 2$, or if more than 10 layers are input.

DO NOT USE THIS SPACE

User Instructions

MT plane-wave apparent conductivity

1 ◀ ▶ 2

$\sigma \uparrow h$ | $f \rightarrow \sigma_a, \phi$ | MT Sounding

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load side 1 and side 2			
2	Set flag 0 for HP97 printed output (optional)		SF 0	
3	Set flag 1 for input and output resistivities, rather than conductivities. (optional) —See "warnings"—		SF 1	
4	INPUT conductivity structure			
	(a) conductivity of layer i	σ_i (mho/m)	ENT↑	
	(b) thickness of layer i	h_i (m)	A	i
	Repeat step 4 for all layers from shallowest ($i=1$) to deepest ($i \leq 10$). Final "layer" is regarded as infinite half-space, no matter what h you enter.			
5	Calculate $\sigma_{app}(f)$	f (Hz)	C	$\sigma_{app}(f)$
6	Calculate phase angle $\angle \frac{H}{E}$ (optional) If flag 0 is set, step 6 is performed automatically.		R/S	$\angle \frac{H}{E}$ (deg)
7	Repeat, as desired, starting at step 5 for other frequency f.			
8	To calculate a detailed MT sounding having 10 points / log cycle. (Function E iterates f and repeats steps 5 and 6 indefinitely. To stop, push R/S or any other key.)	f_{start}	E	f σ_{app} $\angle \frac{H}{E}$
9	For a new case, clear both primary and secondary registers, and go to step 2.			

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	A: $\sigma_i \uparrow h_i$
002	ISZI	16 26 46	
003	P⇄S	16-51	
004	STOi	35 45	h_i
005	P⇄S	16-51	
006	R↓	-31	
007	F1?	16 23 01	If F1 set, use
008	1/X	52	
009	STOi	35 45	$\sigma_i = 1/\varrho_i$
010	1	01	
011	0	00	
012	RCLI	36 46	
013	X>Y?	16-34	"Error" if $i > 10$.
014	GSBe	23 16 15	
015	STO0	35 00	Set n.
016	RTN	24	
017	*LBLC	21 13	C: $f \rightarrow \sigma_{app}, \angle^H_E$
018	RAD	16-22	
019	Pi	16-24	
020	X²	53	
021	x	-35	
022	8	08	
023	EEX	-23	
024	CHS	-22	
025	7	07	
026	x	-35	
027	STOA	35 11	$\omega\mu_0 = 8\pi^2 \times 10^{-7} \cdot f$
028	*LBL0	21 00	0: Entry for E
029	SCI	-12	
030	DSP2	-63 02	
031	CLX	-51	$E\uparrow = 0$
032	STOB	35 12	
033	STOC	35 13	
034	STOE	35 15	
035	1	01	$E\downarrow = 1$
036	STOD	35 14	
037	RCL0	36 00	$n \rightarrow x$
038	1	01	
039	-	-45	$n-1 \rightarrow x$
040	X<0?	16-45	Error trap for
041	CLX	-51	$n < 2$.
042	X=0?	16-43	
043	1/X	52	
044	STOI	35 46	$n-1 \rightarrow I$
045	*LBLb	21 16 12	b: loop
046	GSB1	23 01	← layer iterator,
047	DSZI	16 25 46	next layer.
048	GTOb	22 16 12	
049	GSB2	23 02	← $E\uparrow + E\downarrow \rightarrow B$; $E\uparrow - E\downarrow \rightarrow D$
050	RCLC	36 13	$E\uparrow + E\downarrow \rightarrow x, y$
051	RCLB	36 12	
052	→P	34	POLAR
053	X⇄Y	-41	$\angle \rightarrow x$ $\quad \lVert \rightarrow y$
054	RCLE	36 15	$E\uparrow - E\downarrow \rightarrow x, y$
055	RCLD	36 14	
056	→P	34	POLAR

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	R↑	16-31	$\left\lvert \frac{E\uparrow - E\downarrow}{E\uparrow + E\downarrow} \right\rvert$
058	÷	-24	
059	R↓	-31	
060	-	-45	
061	CHS	-22	
062	R↑	16-31	
063	X²	53	$\lVert^2, \angle$
064	RCL1	36 01	
065	x	-35	σ_1 / σ_{app}
066	F1?	16 23 01	If F1 set, output
067	1/X	52	$\varrho_{app} = 1/\sigma_{app}$.
068	F0?	16 23 00	
069	GTO9	22 09	Print if F0 set.
070	R/S	51	– wait –
071	*LBLc	21 16 13	c: Get $\angle^H_E$ degrees
072	X⇄Y	-41	
073	R→D	16 46	
074	1	01	
075	3	03	adjust for normal
076	5	05	mag lag.
077	-	-45	
078	FIX	-11	
079	DSP1	-63 01	
080	X>0?	16-44	RTN if $\angle$ positive
081	RTN	24	
082	3	03	adjust if
083	6	06	$\angle$ negative
084	0	00	
085	+	-55	
086	RTN	24	
087	*LBL1	21 01	1: layer iterator
088	GSB2	23 02	$E\uparrow + E\downarrow \rightarrow B$; $E\uparrow - E\downarrow \rightarrow D$
089	RCLD	36 14	Re D
090	ISZI	16 26 46	$i+1 \rightarrow I$
091	RCLi	36 45	$\sigma_{i+1} \rightarrow x$
092	DSZI	16 25 46	$i \rightarrow I$
093	RCLi	36 45	$\sigma_i \rightarrow x$
094	÷	-24	$\sigma_{i+1}/\sigma_i \rightarrow x$
095	√X	54	
096	x	-35	
097	STOD	35 14	New Re D → D
098	RCLE	36 15	
099	LSTX	16-63	
100	x	-35	
101	STOE	35 15	New Im D → E
102	GSB2	23 02	B+D → B; B−D → D
103	P⇄S	16-51	
104	RCLi	36 45	$h_i \rightarrow x$
105	P⇄S	16-51	
106	2	02	
107	RCLA	36 11	← stack $\begin{pmatrix} h_i \\ 2 \\ \omega\mu_0 \\ \sigma_i \end{pmatrix}$
108	RCLi	36 45	
109	x	-35	
110	x	-35	
111	√X	54	$2/S_i$, D_i
112	x	-35	$2D_i/S_i \rightarrow x$

REGISTERS

0	1	2	3	4	5	6	7	8	9
n	σ_1	σ_2	σ_3	etc.	. . .				

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
σ_{10}	h_1	h_2	h_3	etc.	. . .				

A	B	C	D	E	I
$\omega\mu_0$	Re E↑, Re B	Im E↑, Im B	Re E↓, Re D	Im E↓, Im D	i = layer #

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
113	e^x	33	amp factor
114	LSTX	16-63	Phase factor
115	RCLC	36 13	} E↑
116	RCLB	36 12	
117	→P	34	POLAR
118	R↑	16-31	Apply amp & phase
119	÷	-24	factors for layer
120	R↓	-31	
121	+	-55	
122	R↑	16-31	
123	→R	44	RECTANGULAR
124	STOB	35 12	} E↑ $e^{(1+i)\frac{2D}{S}}$ → B
125	X⇄Y	-41	
126	STOC	35 13	
127	RTN	24	End layer Iteration
128	*LBL2	21 02	2: B+D→B; B−D→D
129	RCLB	36 12	
130	RCLD	36 14	
131	+	-55	
132	STOB	35 12	Real part: sum→B
133	LSTX	16-63	
134	−	-45	
135	LSTX	16-63	
136	−	-45	
137	STOD	35 14	Diff→D
138	RCLC	36 13	Imag. part:
139	RCLE	36 15	
140	+	-55	
141	STOC	35 13	Sum→C
142	LSTX	16-63	
143	−	-45	
144	LSTX	16-63	
145	−	-45	
146	STOE	35 15	Diff→E
147	RTN	24	
148	*LBL9	21 09	9: Print-out subroutine
149	PRTX	-14	
150	GSBc	23 16 13	
151	PRTX	-14	
152	SPC	16-11	
153	RTN	24	
154	*LBLE	21 15	E: MT Sounding
155	GSBC	23 13	
156	*LBL4	21 04	
157	.	-62	
158	1	01	
159	10^x	16 33	new f = old f × $10^{0.1}$
160	RCLA	36 11	
161	×	-35	
162	STOA	35 11	
163	Pi	16-24	
164	X^2	53	
165	÷	-24	
166	8	08	
167	EEX	-23	
168	7	07	

STEP	KEY ENTRY	KEY CODE	COMMENTS
169	CHS	-22	$f = \omega\mu_0 / 8\pi^2 \times 10^{-7}$
170	÷	-24	
171	SCI	-12	
172	DSP2	-63 02	Print f
173	PRTX	-14	
174	RCLA	36 11	
175	GSB0	23 00	Get σ_{app}, ∠.
176	GTO4	22 04	

LABELS

A σ↑h	B —	C f→σ,∠	D —	E MT Sounding
a —	b loop	c Get ∠ H/E	d —	e Error
0 Used in C	1 layer iterat.	2 B+D→B B−D→D	3 —	4 Used in E
5 —	6 —	7 —	8 —	9 Print subr.

FLAGS

0	Print
1	Resistivity
2	—
3	—

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☐	FIX	☐
1	☐	☒	GRAD	☐	SCI	☒
2	☐	☐	RAD	☒	ENG	☐
3	☐	☐			n	2

EXAMPLE: Calculate MT Curves for this structure, using $f = 1; 3; 10; 30; \cdots; 3000; 10{,}000$ Hz.

Layer thickness	Conductivity
$h_1 = 10^m$	$\sigma_1 = 0.1$ mho/m
$h_2 = 50^m$	$\sigma_2 = 0.25$ mho/m
$h_3 = \infty$	$\sigma_3 = 0.04$ mho/m

SOLUTION:

```
         SF0
```
— Set flag 0 to print output (Step 2).

```
         .1 ENT↑
        10. GSBA
        .25 ENT↑
        50. GSBA
        .04 ENT↑
     1.+50 GSBA
```
— Input conductivity structure (Step 4).
(thickness $h_3 = 1.E50$ is arbitrary — program assumes last entered layer is infinitely thick, and doesn't actually use this input value.)

```
         1. GSBC *
   4.98-02  ***
      39.6  ***
```
— For frequency $f = 1$ Hz, find $\sigma_{app} = 0.0498$ mho/m and $\angle^{H}_{E} = 39.6°$ (Steps 5, 6)

```
       3.0 GSBC
   5.80-02  ***
      36.8  ***

      10.0 GSBC
   7.63-02  ***
      33.1  ***

      30.0 GSBC
   1.10-01  ***
      30.8  ***

     100.0 GSBC
   1.76-01  ***
      33.5  ***

     300.0 GSBC
   2.24-01  ***
      43.2  ***

    1000.0 GSBC
   1.83-01  ***
      52.4  ***

    3000.0 GSBC
   1.41-01  ***
      53.3  ***

   10000.0 GSBC
   1.08-01  ***
      52.0  ***
```
— Similarly for other frequencies.

* Note: To get MT sounding sampled at 10 points per log cycle, replace starred step by "GSBE." Remaining output is then automatic.

Program Description

Program Title PETROPHYSICS : a.c. electrical parameters

Name DAVID L. Campbell Date 12Jan78

Address U.S. Geological Survey

City Denver State COLO Zip Code 80225

Program Description, Equations, Variables, etc. The 7 a.c. electrical parameters (frequency, d.c. conductivity, loss tangent, real and imaginary resistivity, and real and imaginary dielectric constant) are algebraicly inter-related. This program comprises a series of short subroutines to calculate an unknown parameter from several known ones.

EQUATIONS :

Complex dielectric constant $k' - j k'' = \varepsilon/\varepsilon_0 = \dfrac{\text{permittivity of rock}}{8.85 \times 10^{-12} \text{ farad/m}}$

Complex resistivity $\rho' - j\rho'' = \dfrac{1}{\omega \varepsilon_0 k'}\left(\dfrac{D - j}{1 + D^2}\right)$

Loss tangent $D = \tan\delta = \dfrac{k''}{k'} + \dfrac{\sigma}{\omega \varepsilon_0 k'}, = \rho'/\rho''$

(δ = phase shift between E and H vectors of EM wave.)

($f = 2\pi\omega$ = frequency in Hz.)

(σ = d.c. conductivity, mho/m.)

REFERENCE: Olhoeft, G.R., 1976, Electrical properties of rocks, in R.G.J. Strens, ed., Physics and Chemistry of Rocks: New York, J. Wiley Co., p. 261-278.

Operating Limits and Warnings The above equations are derived by regarding conductivity σ as fixed and lumping all effects into an equivalent (complex) dielectric constant. This frequently results in high "dielectric constant" values. Note that some authorities take the opposite tack, lumping effects into a complex conductivity. To avoid confusion, the viewpoint being used should be stated whenever calculated values are presented.

DO NOT USE THIS SPACE

User Instructions

PETROPHYSICS: a.c. electrical parameters

1						2
	D	ρ'	ρ''	k'	k''	

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
0	READ IN SIDE 1 + SIDE 2			
1	STORE ALL KNOWN PARAMETERS			
	a. loss tangent	D	STO A	
	b. complex resistivity, real part	ρ'	STO B	
	c. complex resistivity, imag part	ρ''	STO C	
	d. Complex dielectric const, real part	k'	STO D	
	e. complex dielectric const, imag part	k''	STO E	
	f. d.c. conductivity	σ	STO 0	
2	Key frequency, if checked below	f		
3	Find unknown parameter(s), using function Key(s) as shown:			

TO FIND	KNOWING CHECKED VALUES: D	ρ'	ρ''	k'	k''	σ	ENTER f	AND KEY
D	x	✓	✓					A
	x	✓		✓			✓	a
	x			✓	✓	✓	✓	GSB 1
ρ'	✓	x		✓			✓	B
	✓	x	✓					b
ρ''	✓	✓	x					C
	✓		x	✓			✓	c
k'	✓	✓		x			✓	D
	✓			x	✓	✓	✓	d
k''	✓			✓	x	✓	✓	E
σ	✓			✓	✓	x	✓	GSB 0
f	✓	✓		✓			x	GSB 9

Units: All MKS
f in Hz
ρ', ρ'' in ohm-m
D, k', k'' dimensionless

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBL A		A: $D = \rho'/\rho''$
	RCL B		
	RCL C		
	÷		
	STO A		
	RTN		
	*LBL a		a: D = Binomial soln of $D^2 - C_8 D + D = 0$; $C_8 = 1/\epsilon_0\omega \cdot k' \cdot \rho'$ (use $-\sqrt{\ }$, too.)
	GSB 6		
	RCL B		
010	÷		
	RCL D		
	÷		
	STO 8		
	x^2		
	4		
	−		
	√		
	CHS		
	RCL 8		
020	+		
	2		
	÷		
	STO A		
	RTN		
	*LBL 1		1: $D = C_2/k'$
	GSB 7		
	RCL D		
	÷		
	STO A		
030	RTN		
	*LBL B		B: $\rho' = C_1/k'$
	GSB 8		
	RCL D		
	÷		
	STO B		
	RTN		
	*LBL b		b: $\rho' = D\rho''$
	RCL A		
	RCL C		
040	×		
	STO B		
	RTN		
	*LBL C		C: $\rho'' = \rho'/D$
	RCL B		
	RCL A		
	÷		
	STO C		
	RTN		
	*LBL c		c: $\rho'' = \frac{1}{\omega\epsilon_0} \cdot \frac{1}{1+D^2} \cdot \frac{1}{k'}$
050	GSB 6		
	RCL A		
	x^2		
	1		
	+		
	÷		
	RCL D		

STEP	KEY ENTRY	KEY CODE	COMMENTS
	÷		
	STO C		
	RTN		
060	*LBL D		D: $k' = C_1/\rho'$
	GSB 8		
	RCL B		
	÷		
	STO D		
	RTN		
	*LBL d		d: $k' = C_2/D$
	GSB 7		
	RCL A		
	÷		
070	STO D		
	RTN		
	*LBL E		E: $k'' = Dk' - \sigma \cdot \frac{1}{\omega\epsilon_0}$
	GSB 6		
	RCL 0		
	×		
	RCL A		
	RCL D		
	×		
	x⇄y		
080	−		
	STO E		
	RTN		
	*LBL 0		0: $\sigma = \frac{Dk' - \text{[illegible]}''}{1/\epsilon_0\omega}$
	GSB 6		
	RCL A		
	RCL D		
	×		
	RCL E		
	−		
090	x⇄y		
	÷		
	STO 0		
	RTN		
	*LBL 9		9: $f = \frac{1}{C_1(1)} \cdot \frac{1}{\rho' k'}$
	1		
	GSB 8		
	RCL B		
	÷		
	RCL D		
100	÷		
	RTN		
	*LBL 8		8: $C_1 = \frac{1}{\epsilon_0\omega}\left(\frac{D}{1+D^2}\right)$
	GSB 6		
	RCL A		
	ENT		
	x^2		
	1		
	+		
	÷		
110	×		
	RTN		
	*LBL 7		

REGISTERS

0	1	2	3	4	5	6	7	8	9
σ	—	—	—	—	—	—	—	used	—

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
—	—	—	—	—	—	—	—	—	—

A	B	C	D	E	I
D	ρ′	ρ″	k′	k″	—

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
	GSB 6		7: $C_2 = \frac{\sigma}{\omega\epsilon_0} + k''$
	RCL 0		
	×		
	RCL E		
	+		
	RTN		
	*LBL 6		6: $1/\omega\epsilon_0 = [f \cdot 2\pi \cdot 8.85\times10^{-12}]^{-1}$
120	5		
	•		
	5		
	6		
	3		
	EEX		
	1		
	1		
	CHS		
	×		
130	1/x		
	RTN		
140			
150			
160			
170			
180			

EXAMPLES: An oil shale sample has $k' = 12.899$, $D = 0.2630$ at $f = 1000$ Hz.

A. Find ρ'.
Soln 12.899, STO D, 0.2630, STO A, EEX 3 (=f), B, Read $\rho' = 3.423\times10^{5}$ ohm-m.

B. Find phase lag between ρ' and ρ'' and compare with that between E and H.
Soln D, k', ρ', f are all known from Part A.
First find ρ'': C, Read $\rho'' = 1.303\times10^{6}$ ohm-m.
Get phase: CHS (Because $\rho = \rho' - j\rho''$)
RCL B, → P, R↓, Read $\phi_\rho = -1.314$ rn.
Get ϕ_{EH}: RCL A, $\tan^{-1}$, Read $\phi_{EH} = 2.572\times10^{-1}$ rn.
(Note $\phi_\rho + \phi_{EH} = -\pi/2$)

C. Find k''.
Soln No soln possible, since σ not known. (Values of σ can be inferred knowing response of material at several frequencies, however.)

D. Suppose $\sigma = 1.69\times10^{-7}$. Find k''.
Soln 1.69, EEX, 7, CHS, STO 0, EEX 3 (=f), E, Read $k'' = 3.545\times10^{-1}$

LABELS

A $\rho', \rho'' \to D$	B $D, k'(f) \to \rho'$	C $D, \rho' \to \rho''$	D $D, \rho'(f) \to k'$	E $D, k', \sigma(f) \to k''$
a $\rho', k'(f) \to D$	b $D, \rho'' \to \rho'$	c $D, k'(f) \to \rho''$	d $D, k'', \sigma(f) \to k$	e —
0 $D, k', k''(f) \to \sigma$	1 $k', k'', \sigma(f) \to D$	2 —	3 —	4 —
5 —	6 $1/\epsilon_0\omega$	7 $\sigma/\epsilon_0\omega + k''$	8 $\frac{1}{\epsilon_0\omega}\left(\frac{D}{1+D^2}\right)$	9 $D, \rho', k' \to f$

FLAGS

0	
1	
2	
3	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☐	DEG	☐	FIX	☐
1	☐	☐	GRAD	☐	SCI	☒
2	☐	☐	RAD	☒	ENG	☐
3	☐	☐			n	3

Program Description

Program Title PETROPHYSICS: Elastic constants

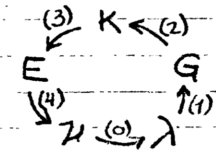
Name David L. Campbell Date 13Jan78
Address U.S. Geological Survey
City Denver State Colo Zip Code 80225

Program Description, Equations, Variables, etc. Given any two of the elastic constants (incompressibility modulus, rigidity modulus, Lamé constant, Poisson's ratio, Young's modulus) this program calculates the other three.

Equations:

		(Number indicates label of subroutine in program.)
0. $\lambda = E\nu/(1+\nu)(1-2\nu)$	5. $E = 3K(1-2\nu)$	
1. $G = \lambda(1-2\nu)/2\nu$	6. $\nu = \lambda/(3K-\lambda)$	
2. $K = \lambda + {}^2/_3 G$	7. $\lambda = 3G\nu/(1-2\nu)$	
3. $E = 9KG/(3K+G)$	8. $G = {}^3/_2(K-\lambda)$	
4. $\nu = (3K-E)/6K$	9. $K = GE/3(3G-E)$	

Reference: Fung, Y.C., 1965, Foundations of Solid Mechanics: Prentice-Hall, Inc., New York. p. 129-130.



Technique: The 5 constants are calculated by working around this circle, calculating each unknown from the 2 previous elements. The user must note which 2 elements are known initially and key the appropriate function to get the progression started in the right place. If the initial two knowns are separated, he keys in an appropriate lower-case function: this fills in the intermediate unknown and then proceeds to work left around the circle as before.

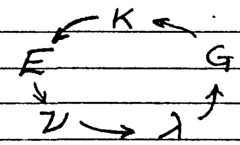
Operating Limits and Warnings: Use only physically realistic values of Poisson's ratio ($0 < \nu < 0.5$). Error exit will occur for $\nu = 0.5$ (equations 0, 5, 7 above) and for $\nu = -1$ (equation 0 above). When $\nu = 0$, a round-off error results in a residual small value being stored in Register D.

DO NOT USE THIS SPACE

User Instructions

PETROPHYSICS : Elastic constants

1 | K | G | λ | ν | E | 2

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
0	Read in Side 1 and Side 2.			
1.	Clear registers		f CL REG	
2	Store any 2 of the following knowns:			
	a. Incompressibility modulus	K	STO A	
	b. Rigidity modulus	G	STO B	
	c. Lamé constant	λ	STO C	
	d. Poisson's ratio	ν	STO D	
	e. Young's modulus	E	STO E	
3	Key associated function, as follows:			
	a. Consider the constants in c/cw cyclic order. 			
	There are 2 possibilities:			
	I. The 2 knowns are adjacent, e.g. K & E.			
	II. The 2 knowns are separated; e.g. K + ν.			
	b. In Case I, key the upper-case function next in cyclic order ("left-shift"); e.g. K, E known, then key the button under ν →		D	0.00
	c. In Case II, key the lower-case function between the two knowns; e.g., K, ν known, key f + button under E →		f e	0.00
4	Recall any unknown of interest			
	a. Incompressibility modulus		RCL A	K
	b. Rigidity modulus		RCL B	G
	c. Lamé constant		RCL C	λ
	d. Poisson's ratio		RCL D	ν
	e. Young's modulus		RCL E	E
5.	Return to Step 1, as desired.			

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBL a		a: E, G		GSB(i)		
	GSB 9		Known		0		
	4				RTN		
	ST I			060	*LBL 0		0:
	GTO C				RCL E		$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)}$
	*LBL b		b: K, λ		RCL D		
	GSB 8		known		×		
	3				RCL D		
	ST I				1		
010	GTO C				+		
	*LBL c		c: G, ν		÷		
	GSB 7		known		1		
	2				RCL D		
	ST I			070	2		
	GTO C				×		
	*LBL d		d: λ, E		−		
	GSB 6		known		÷		
	1				STO C		
	ST I				RTN		
020	GTO C				*LBL 1		1:
	*LBL e		e: ν, K		1		$G = \frac{\lambda(1-2\nu)}{2\nu}$
	GSB 5		known		RCL D		
	0				2		
	ST I			080	×		
	GTO C				STO B		
	*LBL A		A: G, λ		−		
	2		known		RCL C		
	ST I				×		
	GTO C				RCL B		
030	*LBL B		B: λ, ν		÷		
	1		known		STO B		
	ST I				RTN		
	GTO C				*LBL 2		2:
	*LBL D		D: E, K	090	RCL B		$K = \lambda + \frac{2}{3}G$
	4		known		2		
	ST I				×		
	GTO C				3		
	*LBL E		E: K, G		÷		
	3		known		RCL C		
040	ST I				+		
	GTO C				STO A		
	*LBL C		C: Work around the ring, 3 fcns to the left.		RTN		
	GSB(i)				*LBL 3		3:
	ISZ			100	RCL A		$E = \frac{9KG}{3K+G}$
	RCL I				RCL B		
	5				×		
	−				9		
	X=0?				×		
	X⇄I				RCL A		
050	GSB(i)		Check to see if I=5. If so, Reset I=0.		3		
	ISZ				×		
	RC I				RCL B		
	5				+		
	−			110	÷		
	X=0?				STO E		
	X⇄I				RTN		

REGISTERS

0	1	2	3	4	5	6	7	8	9
—	—	—	—	—	—	—	—	—	—
S0	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
—	—	—	—	—	—	—	—	—	—

A	B	C	D	E	I
K	G	λ	ν	E	used

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
	*LBL 4		4:
	RCL A		$\nu = \frac{(3K-E)}{6K}$
	3		
	x		
	STO D		
	RCL E		
	−		
120	RCL D		
	2		
	x		
	÷		
	STO D		
	RTN		
	*LBL 5		5:
	RCL A		$E = 3K(1-2\nu)$
	3		
	x		
130	1		
	RCL D		
	2		
	x		
	−		
	x		
	STO E		
	RTN		
	*LBL 6		6:
	RCL C		$\nu = \lambda/(3K-\lambda)$
140	RCL A		
	3		
	x		
	RCL C		
	−		
	÷		
	STO D		
	RTN		
	*LBL 7		7:
	RCL D		$\lambda = \frac{2G\nu}{1-2\nu}$
150	2		
	x		
	STO C		
	RCL B		
	x		
	1		
	RCL C		
	−		
	÷		
	STO C		
160	RTN		
	*LBL 8		8:
	RCL A		$G = \frac{3}{2}(K-\lambda)$
	RCL C		
	−		
	3		
	x		
	2		
	÷		

STEP	KEY ENTRY	KEY CODE	COMMENTS
	STO B		
170	RTN		
	*LBL 9		9:
	RCL B		$K = GE/3(3G-E)$
	RCL E		
	x		
	RCL B		
	3		
	x		
	RCL E		
	−		
180	3		
	x		
	÷		
	STO A		
	RTN		
190			

EXAMPLE: Given $\nu = 0.25$, $G = 0.5 \times 10^{11}$ dyn/cm^2; find E, K, λ.

Soln: f, CL REG,
0.25, STO D,
0.5, EEX, 11, STO B
f, C (Read 0.00, indicating program ran to completion.)
RCL E (Read $E = 1.25 \times 10^{11}$ dyn/cm^2)
RCL A (Read $K = 8.\bar{3} \times 10^{10}$ dyn/cm^2)
RCL C (Read $\lambda = 5.\bar{0} \times 10^{10}$ dyn/cm^2.)

LABELS					FLAGS
A G, λ	B λ, ν	C ν, E	D E, K	E K, G	0 —
a E, G	b K, λ	c G, ν	d λ, E	e ν, K	1 —
0 $\lambda(E,\nu)$	1 $G(\nu,\lambda)$	2 $K(\lambda,G)$	3 $E(G,K)$	4 $\nu(K,E)$	2 —
5 $E(\nu,K)$	6 $\nu(\lambda,E)$	7 $\lambda(G,\nu)$	8 $G(K,\lambda)$	9 $K(E,G)$	3 —

SET STATUS

FLAGS ON OFF	TRIG	DISP
0 ☐ ☐	DEG ☐	FIX ☒
1 ☐ ☐	GRAD ☐	SCI ☐
2 ☐ ☐	RAD ☐	ENG ☐
3 ☐ ☐		n 2

Program Description

Program Title DIGITAL CONVOLUTION WITH ≤ 10-length filter.

Name David L. Campbell **Date** 14 July 75

Address U.S. Geological Survey

City Denver **State** Colorado **Zip Code** 80225

Program Description, Equations, Variables, etc. Program performs digital convolution of an input data series with a filter of maximum length 10. After initialization, keying each subsequent element of the data series produces one corresponding element of the convolution series. Subroutines are included to initialize subscripts, to store the filter in secondary storage, to store data elements in primary storage, and to recover after inputting an erroneous data element.

Equation:

$$c_m = \sum_{j=i-9}^{i} b_{m-j} \, d_j$$

(c_m = Convolution Element; b_{m-j} = filter element; d_j = data element)

i = current index of data element

m = " " " convolution "

l = lag index, $i - m$

Operating Limits and Warnings Data points must be equally spaced.

DO NOT USE THIS SPACE

User Instructions

Digital Convolution

BEGIN | FILTER | CONVLV | DATA | ERROR

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load side 1 of card			
2	Input filter			
	a. starting index	i (= $-\ell$)	A	i
	b. filter element	b_i	B	next i
	c. repeat step 2b for all filter elements.			
	("Error" flashes if you attempt to enter a filter of greater than 10-length.)			
3	(optional) to enter data without convolving			
	a. starting index	i	A	i
	b. data element	d_i	D	next i
	c. repeat step 3b as desired.			
4	to convolve			
	a. starting index (if needed)	i	A	i
	b. data element	d_i	C	c_m
	c. repeat step 4b as desired.			
5	to recover an error caused by keying the wrong d_i —			
	a. wait for process to complete			
	b. Key E		E	old i
	c. proceed with step 3b or 4b using correct data.			
	Note: If you lose your place while convolving a long data string, you can find it again by			
	a. RCL A to get index i			
	or b. RCL 9 to get last-entered d_i			

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	A: Start
002	CLRG	16-53	Clear regs &
003	STOA	35 11	set I for filter
004	5	05	input.
005	STOI	35 46	
006	RCLA	36 11	
007	RTN	24	
008	*LBLB	21 12	B: Input filter,
009	P⇄S	16-51	store in second-
010	RCLI	36 46	ary regs in
011	X<0?	16-45	reversed order.
012	GSBe	23 16 15	(e is a dummy
013	9	09	address to cause
014	X=Y?	16-33	"Error" message.)
015	GSB7	23 07	
016	R↓	-31	
017	STOI	35 46	
018	R↓	-31	
019	STOi	35 45	
020	P⇄S	16-51	
021	GSB8	23 08	
022	DSZI	16 25 46	
023	RTN	24	
024	RTN	24	
025	*LBL7	21 07	7: When 1st filter
026	R↓	-31	element is entered,
027	RCLA	36 11	clear sec. regs.
028	CLRG	16-53	
029	STOA	35 11	
030	RTN	24	
031	*LBLD	21 14	D: Enter data.
032	STOD	35 14	
033	0	00	
034	STOI	35 46	
035	RCL0	36 00	
036	STOE	35 15	
037	*LBL1	21 01	1: loop entry
038	ISZI	16 26 46	
039	RCLi	36 45	
040	DSZI	16 25 46	
041	*LBL9	21 09	* Cascade values
042	STOi	35 45	down thru primary
043	ISZI	16 26 46	regs — $R_{i+1} \rightarrow R_i$.
044	9	09	
045	RCLI	36 46	
046	X=Y?	16-33	
047	GTO2	22 02	
048	GTO1	22 01	
049	*LBL2	21 02	2: loop exit
050	RCLD	36 14	
051	STO9	35 09	
052	GSB8	23 08	
053	RTN	24	
054	*LBL8	21 08	8: Subroutine
055	RCLA	36 11	to increment
056	1	01	

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	+	-55	contents of
058	STOA	35 11	A reg.
059	RTN	24	
060	*LBLC	21 13	C: Conv'
061	GSBD	23 14	
062	0	00	
063	STOI	35 46	
064	*LBL3	21 03	3: loop entry
065	RCLi	36 45	
066	P⇄S	16-51	
067	RCLi	36 45	
068	P⇄S	16-51	
069	×	-35	
070	+	-55	
071	ISZI	16 26 46	
072	9	09	
073	RCLI	36 46	
074	X>Y?	16-34	
075	GTO4	22 04	
076	R↓	-31	
077	R↓	-31	
078	GTO3	22 03	
079	*LBL4	21 04	4: loop exit
080	R↓	-31	
081	R↓	-31	
082	STOC	35 13	
083	RTN	24	
084	*LBLE	21 15	E: Error
085	9	09	recovery.
086	STOI	35 46	
087	*LBL5	21 05	5: loop entry.
088	DSZI	16 25 46	
089	*LBL9	21 09	* Cascade values
090	RCLi	36 45	up thru primary
091	ISZI	16 26 46	regs — $R_i \rightarrow R_{i+1}$.
092	STOi	35 45	
093	DSZI	16 25 46	
094	*LBL9	21 09	*
095	1	01	
096	RCLI	36 46	
097	X=Y?	16-33	
098	GTO6	22 06	
099	GTO5	22 05	
100	*LBL6	21 06	6: loop exit.
101	RCLE	36 15	
102	STO0	35 00	
103	RCLA	36 11	Decrement A.
104	1	01	
105	-	-45	
106	STOA	35 11	
107	RTN	24	
110			

REGISTERS

0	1	2	3	4	5	6	7	8	9
d_{i-9}	d_{i-8}	d_{i-7}			...			d_{i-1}	d_i

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
$b_{\ell+9}$	$b_{\ell+8}$	$b_{\ell+7}$			...			$b_{\ell+1}$	b_ℓ

A	B	C	D	E	I
Current i	—	C_m	d_i	d_{i-10}	USED

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS
120			
130			
140			
150			
160			

STEP	KEY ENTRY	KEY CODE	COMMENTS
170			
180			
190			
200			
210			
220			

LABELS					FLAGS
A BEGIN	B FILTER	C CONVOLV	D DATA	E ERROR	0
a —	b —	c —	d —	e (Error)	1
0 —	1 Used	2 Used	3 Used	4 Used	2
5 Used in E	6 Used in E	7 Used in B	8 Increment A	9 * NO OP	3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☐	DEG	☐	FIX	☒
1	☐	☐	GRAD	☐	SCI	☐
2	☐	☐	RAD	☐	ENG	☐
3	☐	☐			n	2

EXAMPLE: Smooth the 26-length data string shown in Fig. 1 $d_i = \{2.0, 2.8, 2.0, 2.8, 2.4, \dots\}$, using the 5-length filter $b_i = \{0.05, 0.25, 0.40, 0.25, 0.05\}$.

SOLUTION: Filter indexing starts at $i=-2$ to remind us that filtered output lags input string by 2 points. Since filter length = 5, begin convolution with 5th data point.

1a. 2, CHS, A (Read -2.00)
1b. 0.05, B (Read -1.00),
1c. 0.25, B (0.00), 0.40, B (1.00), 0.25, B (2.00), 0.05, B (3.00)
2a. 0, A (0.00)
2b. 2.0, D (1.00)
2c. 2.8, D (2.00), 2.0, D (3.00), 2.8, D (4.00)
3. 2.4, C (Read $c_{4-2} = c_2 = 2.42$)
4.2, C ($c_3 = 2.57$)
5.4, C ($c_4 = 3.08$)
1.1, C (Oops! That was an error! Display now shows 3.83.)
4. E (Read $i = 7.00$)
3. 11.0, C (Read $c_5 = 4.32$)
etc. as shown on figure...

```
-2.00 GSBA
  .05 GSBB
  .25 GSBB
  .40 GSBB
  .25 GSBB
  .05 GSBB
 0.00 GSBA
 2.00 GSBD
 2.80 GSBD
 2.00 GSBD
 2.80 GSBD
 2.40 GSBD
 2.42  ***

 4.20 GSBC
 2.57  ***

 5.40 GSBC
 3.06  ***

 1.10 GSBC
 3.83  ***

      GSBE
11.00 GSBC
 4.32  ***

 3.60 GSBC
 6.26  ***

 1.60 GSBC
 6.54  ***

  .60 GSBC
 4.89  ***

 2.60 GSBC
 2.37  ***

 2.60 GSBC
 1.10  ***

 4.40 GSBC
 2.14  ***

 5.00 GSBC
 3.07  ***

 3.60 GSBC
 3.97  ***

 4.00 GSBC
 4.33  ***

 3.60 GSBC
 4.05  ***

 4.40 GSBC
 3.87  ***

 6.20 GSBC
 4.03  ***
```

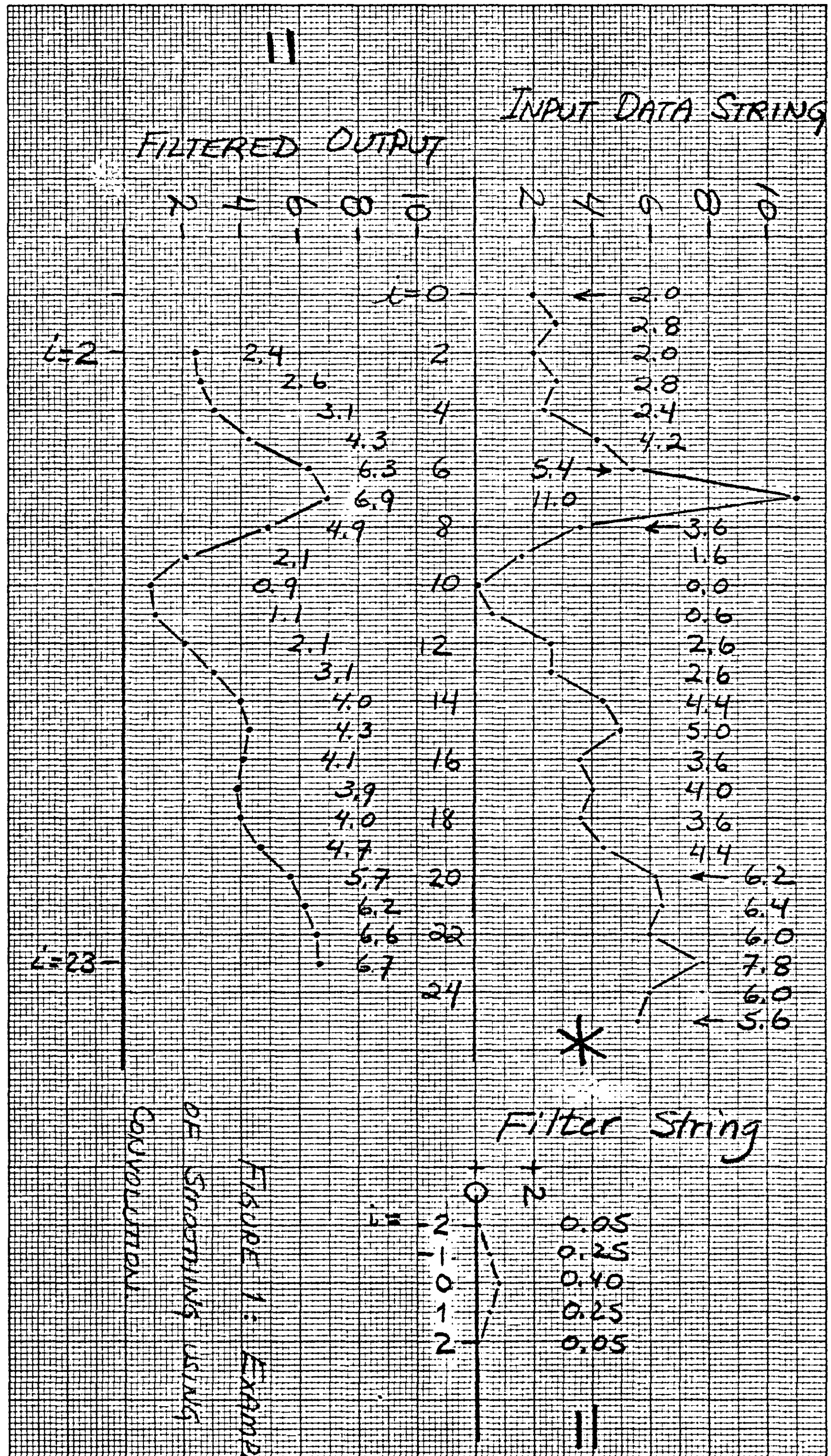


FIGURE 1: EXAMPLE OF SMOOTHING USING CONVOLUTION