UNITED STATES DEPARTMENT OF INTERIOR

GEOLOGICAL SURVEY

Texas Instruments Model 59 Hand-Calculator Program to Calculate Theoretical MT Planewave Soundings over a Structure of up to 10 Horizontal Layers

By

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Citation of particular manufacturers and model numbers does not constitute endorsement by the U.S. Geological Survey.

Although this program has been extensively tested, the U.S. Geological Survey cannot guarantee that it will give correct results in any or all particular applications.

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PROGRAMMER Dave Campbell DATE

TI Programmable Program Record

Partitioning (Op 17) 479.59 Library Module ML Printer Optional Cards 1

(Standard partitioning)

PROGRAM DESCRIPTION

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_a and phase angle $\angle^H_E$ at arbitrary frequencies input by user. Alternately, an MT sounding from frequencies f_{min} to f_{max}, having n points per log cycle may be calculated. This program is a translation of Ray Watt's HP67 program.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Load side 1 and side 2, then initialize:				f_1	
2	To work with resistivities ... (In this case, all symbols σ below are to be interpreted as resistivity values, not conductivities. If flag 1 not set, default case of conductivity is assumed.)		2nd	St flg	1	
3	Input layers, working from shallow to deep. Last layer entered is taken to be half-space, and program does not use h value for it.	σ_i [mho/m]			x⇌t	
		h_i [m]			B	
4	To calculate $\sigma_a, \angle^H_E$ at frequency f	f (Hz)			C	σ_a
	(Use this option when printer not available)				x⇌t	$\angle^H_E$
5	To calculate an MT sounding with n points per log cycle...	n		STO	35	
		f_{min}			x⇌t	
	(Use this option only with PC-100A printer.)	f_{max}			E	$\sigma_a, \angle^H_E$
6	For next case, press "2nd CMs" and go to step 2.					

USER DEFINED KEYS	
A	START
B	σ, h
C	f
D	—
E	f_{min}, f_{max}
A'	—
B'	—
C'	—
D'	—
E'	—

DATA REGISTERS (INV Lst)

0	$\omega\mu_0$	10	(n)
1	Re E↑ (Used with ML-4, ML-5)	11 – 20	σ_i
2	Im E↑ (Used with ML-4, ML-5)	21 – 30	h_i
3	(Used with ML-4, ML-5)	30	
4	(Used with ML-4, ML-5)	31	
5	Re E↓	32	σ_a
6	Im E↓	6	
7	i = layer no.	7	
8	σ index	8	
9	h index	9	

LABELS (Op 08)

FLAGS	0	1	2	3	4	5	6	7	8	9
		Resistivity								

Comments

1. Error conditions:
   a. At Step 4, a flashing "-1.00 00" in display means no layers were entered.
   b. At Step 3, a flashing "11." in display means an attempt was made to enter too many ($\geq$ 11) layers.
   c. If only a single layer has been entered, the program stops at Step 4 with "0.00 00" in display. (To calculate soundings over an infinite half-space, fool the program by entering 2 layers with identical conductivities.)

2. This program is a translation by Dave Campbell of Ray Watts' HP program (Campbell and Watts, 1978). The algorithm used involves the special case of equations (2) through (15) in which k_x vanishes (Watts, 1978). For an alternate treatment, see Ward (1967).

3. Users who don't have access to a PC-100 print cradle may omit quite a few steps in this program which merely handle print-out. These steps are marked by a double vertical bar on the listing on pages 3, 4, and 5.

References:

Campbell, D. L., and Watts, R. D., 1978, Exploration geophysics calculator programs for use on Hewlett-Packard models 67 and 97 programmable calculators: U.S. Geological Survey Open-File Report 78-815, p. 56-60.

Nekut, A., Connerney, J. E. P., and Kuckes, A. F., 1977, Deep crustal electric conductivity: evidence for water in the lower crust: Geophysical Research Letters, v. 4, no. 6, p. 239-242.

Ward, S. H., 1967, Electromagnetic theory for geophysical application, in Ward, S. H., ed.: Mining Geophysics II, Society of Exploration Geophysicists, Tulsa, p. 107-124.

Watts, R. D., 1978, Electromagnetic scattering from buried wires: Geophysics, v. 43, p. 767-781.

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PROGRAMMER *Dave Campbell* DATE

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
000	76	LBL	A: START
001	11	A	
002	47	CMS	Clear Mem.
003	01	1	&
004	00	0	set layer
005	42	STO	indexing.
006	08	08	
007	42	STO	
008	35	35	
009	02	2	
010	00	0	
011	42	STO	
012	09	09	
013	52	EE	
014	22	INV	
015	52	EE	
016	69	OP	
017	00	00	
018	03	3	
019	00	0	
020	03	3	
021	07	7	
022	00	0	
023	00	0	"MT_PL"
024	03	3	
025	03	3	
026	02	2	
027	07	7	
028	69	OP	
029	01	01	
030	01	1	
031	03	3	
032	03	3	
033	01	1	"ANEWA"
034	01	1	
035	07	7	
036	04	4	
037	03	3	
038	01	1	
039	03	3	
040	69	OP	
041	02	02	
042	04	4	
043	02	2	"VE___"
044	01	1	
045	07	7	
046	00	0	
047	00	0	
048	00	0	
049	00	0	
050	00	0	
051	00	0	
052	69	OP	
053	03	03	
054	69	OP	
055	05	05	
056	98	ADV	
057	00	0	
058	92	RTN	
059	76	LBL	B:
060	12	B	
061	69	OP	
062	27	27	Increment
063	69	OP	layer
064	28	28	indexes.
065	69	OP	
066	29	29	
067	32	X⇄T	σ
068	87	IFF	
069	01	01	Resistivity?
070	35	1/X	
071	71	SBR	
072	76	LBL	
073	76	LBL	
074	34	√X	√x:
075	72	ST*	
076	08	08	Store σ
077	22	INV	
078	52	EE	
079	32	X⇄T	Thickness h
080	42	STO	store h
081	32	32	
082	03	3	"M"
083	00	0	
084	69	OP	
085	04	04	
086	43	RCL	
087	32	32	
088	69	OP	
089	06	06	
090	72	ST*	
091	09	09	Store h
092	01	1	
093	01	1	
094	32	X⇄T	
095	43	RCL	
096	07	07	too many
097	77	GE	layers?
098	10	E'	
099	42	STO	
100	10	10	
101	98	ADV	
102	92	RTN	
103	76	LBL	
104	35	1/X	1/x:
105	71	SBR	
106	88	DMS	
107	35	1/X	
108	61	GTO	
109	34	√X	
110	76	LBL	C:
111	13	C	
112	70	RAD	
113	22	INV	
114	52	EE	
115	22	INV	
116	58	FIX	
117	42	STO	
118	00	00	
119	02	2	
120	03	3	"HZ"
121	04	4	
122	06	6	
123	69	OP	
124	04	04	
125	43	RCL	
126	00	00	
127	57	ENG	
128	58	FIX	
129	02	02	
130	69	OP	prepare for iteration:
131	06	06	
132	89	π	
133	33	X²	
134	65	×	
135	08	8	
136	52	EE	
137	94	+/-	
138	07	7	
139	95	=	
140	49	PRD	μ₀ω
141	00	00	
142	00	0	Zero:
143	42	STO	
144	01	01	Re E↑
145	42	STO	
146	02	02	Im E↑
147	42	STO	
148	06	06	Im E↓
149	32	X⇄T	
150	01	1	
151	42	STO	
152	05	05	Re E↓ = 1
153	43	RCL	
154	10	10	
155	75	−	
156	01	1	
157	95	=	if n-1<1,
158	22	INV	GTO INT
159	77	GE	

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

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TITLE *MT Planewave* PAGE *3* OF *6*

TI Programmable Coding Form

PROGRAMMER ______ DATE ______

LOC	CODE	KEY	COMMENTS
000	76	LBL	*Pgm A:*
001	11	A	
002	47	CMS	*Start*
003	01	1	
004	00	0	*Clear mem.*
005	42	STO	*& set layer*
006	08	08	*indexes.*
007	42	STO	
008	35	35	
009	02	2	
010	00	0	
011	42	STO	
012	09	09	
013	52	EE	
014	22	INV	
015	52	EE	
016	69	OP	
017	00	00	
018	03	3	
019	00	0	
020	03	3	
021	07	7	
022	00	0	*"MT_PL"*
023	00	0	
024	03	3	
025	03	3	
026	02	2	
027	07	7	
028	69	OP	
029	01	01	
030	01	1	
031	03	3	
032	03	3	
033	01	1	*"ANEWA"*
034	01	1	
035	07	7	
036	04	4	
037	03	3	
038	01	1	
039	03	3	
040	69	OP	
041	02	02	
042	04	4	
043	02	2	
044	01	1	*"VE___"*
045	07	7	
046	00	0	
047	00	0	
048	00	0	
049	00	0	
050	00	0	
051	00	0	
052	69	OP	
053	03	03	
054	69	OP	

LOC	CODE	KEY	COMMENTS
055	05	05	
056	98	ADV	
057	00	0	
058	92	RTN	
059	76	LBL	
060	12	B	*Pgm B:*
061	69	OP	
062	27	27	
063	69	OP	*Increment layer indexes.*
064	28	28	
065	69	OP	
066	29	29	
067	32	X⇄T	
068	87	IFF	σ_i
069	01	01	
070	35	1/X	*Resistivity?*
071	71	SBR	
072	76	LBL	
073	76	LBL	
074	34	√X	*√x: store* σ_i
075	72	ST*	
076	08	08	
077	22	INV	
078	52	EE	
079	32	X⇄T	
080	42	STO	*Store* h_i *in temp. location*
081	32	32	
082	03	3	
083	00	0	
084	69	OP	*"H" for print-out*
085	04	04	
086	43	RCL	
087	32	32	
088	69	OP	
089	06	06	
090	22	INV	
091	58	FIX	
092	72	ST*	*Store* h_i
093	09	09	
094	01	1	
095	01	1	
096	32	X⇄T	
097	43	RCL	*Too many layers?*
098	07	07	
099	77	GE	
100	10	E'	
101	42	STO	
102	10	10	
103	98	ADV	
104	92	RTN	
105	76	LBL	*Sub 1/x:*
106	35	1/X	
107	71	SBR	*Invert* σ *to get* ρ.
108	88	DMS	
109	35	1/X	

LOC	CODE	KEY	COMMENTS
110	61	GTO	
111	34	√X	
112	76	LBL	*Pgm C:*
113	13	C	
114	70	RAD	
115	22	INV	
116	52	EE	
117	22	INV	
118	58	FIX	
119	42	STO	
120	00	00	
121	02	2	*"HZ"*
122	03	3	
123	04	4	
124	06	6	
125	69	OP	
126	04	04	
127	43	RCL	
128	00	00	
129	57	ENG	
130	58	FIX	
131	02	02	
132	69	OP	
133	06	06	
134	89	π	
135	33	X²	*Prepare for iteration, downward thru layers.*
136	65	×	
137	08	8	
138	52	EE	
139	94	+/-	
140	07	7	
141	95	=	
142	49	PRD	
143	00	00	*Now*
144	00	0	*zero:*
145	42	STO	*Re E↑*
146	01	01	
147	42	STO	
148	02	02	*Im E↑*
149	42	STO	
150	06	06	*Im E↓*
151	32	X⇄T	
152	01	1	
153	42	STO	
154	05	05	*Re E↓ ← 1*
155	43	RCL	
156	10	10	
157	75	−	*if n−1<1 GTO Int*
158	01	1	
159	95	=	

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

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PROGRAMMER ______ DATE ______

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
160	22	INV	
161	77	GE	
162	24	CE	
163	76	LBL	
164	30	TAN	*Lbl tan:*
165	67	EQ	
166	10	E'	*Error exit.*
167	42	STO	
168	07	07	*i*
169	85	+	
170	01	1	
171	00	0	
172	95	=	
173	42	STO	
174	08	08	*σ index*
175	85	+	
176	01	1	
177	00	0	
178	95	=	
179	42	STO	
180	09	09	*h index*
181	76	LBL	
182	78	Σ+	*Lbl Σ+:*
183	71	SBR	*loop entry*
184	59	INT	
185	69	OP	
186	28	28	
187	73	RC*	
188	08	08	σ_{i+1}
189	69	OP	
190	38	38	
191	55	÷	
192	73	RC*	
193	08	08	σ_i
194	95	=	
195	34	√X	$\sqrt{\sigma_{i+1}/\sigma_i}$
196	49	PRD	
197	05	05	*New Re Et*
198	49	PRD	
199	06	06	*New Im Et*
200	71	SBR	
201	59	INT	
202	73	RC*	
203	08	08	σ_i
204	65	×	
205	43	RCL	
206	00	00	$\omega\mu_0$
207	65	×	
208	02	2	
209	95	=	
210	34	√X	
211	65	×	
212	73	RC*	
213	09	09	h_i
214	95	=	

LOC	CODE	KEY	COMMENTS
215	42	STO	
216	04	04	$h\sqrt{2\sigma\mu_0\omega}$
217	94	+/-	
218	22	INV	
219	23	LNX	e^x
220	32	X⇄T	
221	43	RCL	
222	04	04	
223	37	P/R	
224	42	STO	
225	04	04	
226	32	X⇄T	
227	42	STO	
228	03	03	
229	36	PGM	
230	04	04	*Cx mult.*
231	13	C	
232	69	OP	
233	37	37	*Decrement*
234	69	OP	*all*
235	38	38	*indexes*
236	69	OP	
237	39	39	
238	01	1	
239	32	X⇄T	
240	43	RCL	
241	07	07	
242	77	GE	
243	78	Σ+	
244	71	SBR	
245	59	INT	
246	43	RCL	
247	05	05	
248	48	EXC	
249	01	01	
250	42	STO	
251	03	03	
252	43	RCL	
253	06	06	
254	48	EXC	
255	02	02	
256	42	STO	
257	04	04	
258	36	PGM	
259	04	04	
260	18	C'	*Complex*
261	36	PGM	*divide*
262	05	05	
263	12	B	*→ Polar*
264	33	X²	
265	65	×	
266	43	RCL	
267	11	11	
268	95	=	
269	87	IFF	

LOC	CODE	KEY	COMMENTS
270	01	01	
271	39	COS	
272	71	SBR	
273	76	LBL	
274	76	LBL	*Lbl sin:*
275	38	SIN	
276	32	X⇄T	
277	65	×	
278	01	1	
279	08	8	
280	00	0	
281	55	÷	
282	89	π	
283	95	=	
284	75	-	
285	01	1	
286	03	3	
287	05	5	
288	95	=	
289	42	STO	
290	33	33	
291	22	INV	
292	57	ENG	
293	22	INV	
294	58	FIX	
295	01	1	
296	06	6	
297	01	1	*"DEG"*
298	07	7	
299	02	2	
300	02	2	
301	69	OP	
302	04	04	
303	58	FIX	
304	01	01	
305	43	RCL	
306	33	33	
307	32	X⇄T	
308	00	0	
309	77	GE	
310	50	IXI	
311	32	X⇄T	
312	76	LBL	
313	55	÷	*Lbl ÷:*
314	69	OP	
315	06	06	
316	22	INV	
317	58	FIX	
318	32	X⇄T	
319	43	RCL	

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

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TI Programmable Coding Form

PROGRAMMER ______ DATE ______

LOC	CODE	KEY	COMMENTS
320	32	32	
321	98	ADV	‖
322	92	RTN	
323	76	LBL	Lbl Int:
324	59	INT	
325	43	RCL	B
326	01	01	
327	85	+	
328	43	RCL	
329	05	05	D
330	95	=	
331	48	EXC	B+D→B
332	01	01	
333	75	-	
334	43	RCL	
335	05	05	
336	95	=	
337	42	STO	B−D→D
338	05	05	
339	43	RCL	
340	02	02	
341	85	+	
342	43	RCL	
343	06	06	
344	95	=	
345	48	EXC	C+E→C
346	02	02	
347	75	-	
348	43	RCL	
349	06	06	
350	95	=	
351	42	STO	C−E→E
352	06	06	
353	92	RTN	
354	76	LBL	Lbl cos:
355	39	COS	
356	35	1/X	Invert
357	71	SBR	
358	88	DMS	
359	61	GTO	
360	38	SIN	
361	76	LBL	Lbl |x|:
362	50	I×I	
363	32	X:T	
364	85	+	
365	03	3	
366	06	6	
367	00	0	
368	95	=	
369	61	GTO	
370	55	÷	
371	76	LBL	
372	15	E	
373	42	STO	
374	34	34	

LOC	CODE	KEY	COMMENTS
375	32	X:T	
376	76	LBL	
377	48	EXC	
378	42	STO	
379	31	31	
380	71	SBR	
381	13	C	
382	01	1	
383	00	0	
384	45	YX	
385	43	RCL	
386	35	35	
387	35	1/X	
388	95	=	
389	49	PRD	
390	31	31	
391	43	RCL	
392	34	34	
393	32	X:T	
394	43	RCL	
395	31	31	
396	22	INV	
397	77	GE	
398	48	EXC	
399	92	RTN	
400	76	LBL	Lbl Lbl:
401	76	LBL	
402	42	STO	Print-out
403	32	32	subroutine
404	22	INV	
405	58	FIX	
406	03	3	
407	00	0	
408	02	2	
409	03	3	"MHO"
410	03	3	
411	02	2	
412	69	OP	
413	04	04	
414	52	EE	
415	58	FIX	
416	02	02	
417	43	RCL	
418	32	32	
419	69	OP	
420	06	06	
421	92	RTN	
422	76	LBL	Lbl DMS:
423	88	DMS	
424	42	STO	Print-out
425	32	32	subroutine
426	22	INV	
427	57	ENG	
428	22	INV	
429	58	FIX	

LOC	CODE	KEY	COMMENTS
430	03	3	
431	02	2	
432	02	2	"OHM"
433	03	3	
434	03	3	
435	00	0	
436	69	OP	
437	04	04	
438	43	RCL	
439	32	32	
440	57	ENG	
441	58	FIX	
442	02	02	
443	69	OP	
444	06	06	
445	22	INV	
446	57	ENG	
447	92	RTN	
448	76	LBL	Sub E':
449	10	E'	
450	33	X²	Error
451	94	+/-	
452	34	√X	
453	91	R/S	
454	00	0	
455	00	0	
456	00	0	
457	00	0	
458	00	0	
459	00	0	
460	00	0	
461	00	0	
462	00	0	
463	00	0	
464	00	0	
465	00	0	
466	00	0	
467	00	0	
468	00	0	
469	00	0	
470	00	0	
471	00	0	
472	00	0	
473	00	0	
474	00	0	
475	00	0	
476	00	0	

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

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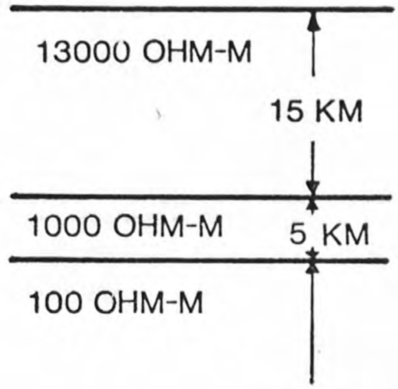
EXAMPLE: NEKUT AND OTHERS (1977) GIVE THE SOLUTION SKETCHED AT RIGHT FOR RESISTIVITY STRUCTURE UNDER THE ADIRONDACK DOME. CALCULATE A 3-POINT-PER-DECADE MT SOUNDING WHICH WOULD BE SEEN OVER SUCH A STRUCTURE FOR FREQUENCIES FROM 0.001 HZ TO 1 HZ.



SOLUTION:

VARIABLE	KEY	DISPLAY
	A	0.
	2nd St flg 1	(0.)
$\rho = 13000$ ohm-m	x⇆t	(0.)
$h_1 = 15000$ m	B	1.
$\rho_2 = 1000$ ohm-m	x⇆t	(11.)
$h_2 = 5000$ m	B	2.
$\rho_3 = 100$ ohm-m	x⇆t	(11.)
* $h_3 = 100000$ (arbitrary)	B	3.
For display output		
$f = .001$ Hz.	C	$\rho_a = 127.3187294$ ohm-m
	x⇆t	$\phi = 51.17599521$ deg
$f = .00215$ Hz.	C	$\rho_a = 142.0727971$ ohm-m
	x⇆t	$\phi = 53.57424851$ deg
$f = .00464$ Hz.	C	$\rho_a = 166.1621533$ ohm-m
	x⇆t	$\phi = 56.65565392$ deg
$f = .01$ Hz.	C	$\rho_a = 206.4591395$ ohm-m
	x⇆t	$\phi = 60.37161281$ deg
etc....		
For printed output		
3 (points/decade)	Sto 35	3.
$f_{min} = .001$ Hz	x⇆t	
$f_{max} = 1$ Hz	E	(Printed output as shown)

PRINT-OUT

MT PLANEWAVE	
13.00 03	OHM†
15000.00	M
1.00 03	OHM
5000.00	M
100.00 00	OHM
100000.00	M
1.00-03	HZ
127.32 00	OHM
51.2	DEG
2.15-03	HZ
142.12 00	OHM
53.6	DEG
4.64-03	HZ
166.18 00	OHM
56.7	DEG
10.00-03	HZ
206.46 00	OHM
60.4	DEG
21.54-03	HZ
276.22 00	OHM
64.5	DEG
46.42-03	HZ
401.23 00	OHM
68.8	DEG
100.00-03	HZ
632.46 00	OHM
72.7	DEG
215.44-03	HZ
1.07 03	OHM
75.7	DEG
464.16-03	HZ
1.92 03	OHM
77.3	DEG
1.00 00	HZ
3.52 03	OHM
76.8	DEG

MT PLANEWAVE ++	
7.69-05	MHO
15000.00	M
1.00-03	MHO
5000.00	M
1.00-02	MHO
10000000.00	M
1.00-03	HZ
7.85-03	MHO
51.2	DEG
2.15-03	HZ
7.04-03	MHO
53.6	DEG
4.64-03	HZ
6.02-03	MHO
56.7	DEG
10.00-03	HZ
4.84-03	MHO
60.4	DEG
21.54-03	HZ
3.62-03	MHO
64.5	DEG
46.42-03	HZ
2.49-03	MHO
68.8	DEG
100.00-03	HZ
1.58-03	MHO
72.7	DEG
215.44-03	HZ
933.55-06	MHO
75.7	DEG
464.16-03	HZ
522.12-06	MHO
77.3	DEG
1.00 00	HZ
283.86-06	MHO
76.8	DEG

* Note any value of h_3 may be supplied at this step, since the program doesn't actually use the input h value for the bottom half-space.

† The correct unit is "ohm-m", of course, rather than the abbreviation "OHM" seen on print-out tapes. Similarly, for conductivity calculations, the tag says "MHO" to indicate "mho/m".

++ Similar print-out for conductivity calculations, same problem, is given at right.