BENDIX SYSTEMS DIVISION ANN ARBOR, MICH.

6-23-66

Evaluation of Parameters Effecting
Operating Frequency for the Active
Seismic Experiment (Mortar)

NO.
ATM-332

REV. NO.

PAGE ___1___ OF ___16___ PAGES

Abstract: The analytical study was performed to determine the
tradeoffs effecting the selection of the optimum operating frequency
for the lunar based Active Seismic Mortar Experiment. With constraints
on the receiver sensitivity and receiving antenna and transmitting
antenna physical dimensions, an operating frequency of 100 mc is
recommended on the basis of the best required transmitter power and
impedance match combination.

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Summary:

To evaluate the parameters effecting the required transmitted power P_t for the grenade transmitter in the Active Seismic experiment, two antenna configurations were considered for a range of frequencies of 1-100 mc. The first antenna configuration considered a short dipole antenna for the grenade transmitter and a short vertical whip antenna for the receiver. Curves were generated for this configuration for distances of 1/2 km, 1 km and 1 1/2 km. The second antenna configuration consisted of a short dipole at the transmitter and a 1/4 wave-end fed vertical antenna at the receiver. For the latter case, curves were generated for a distance of 1 km only. See Figure 1 for the curves of the four cases described above.

The second part of the study was to determine the input impedance of the receiving antenna (2). The assumption was made that the input impedance of a monopole of length h, mounted vertically over a perfectly conducting ground plate*, is one-half the input impedance of a dipole of length $1 = 2h$ in free space. Therefore, to analytically determine the input impedance of the monopole, the more readily obtainable quantity of the dipole impedance in free space can be used, see Figure 2.

Table I summarizes the results for two frequencies, 30 Mhz and 100 Mhz. The table shows that for a short dipole, $1 << \lambda$ (or $1_{max} = \lambda/10$), a transmitter power 18 db greater is required for an operating frequency of 100 Mhz compared to the transmitter power required at 30 Mhz. The antenna input impedance is a function of the antenna dimensions and will be the same for any frequency if the antenna has the same length and radius measurements, relative to a wave length.

* NOTE: To approximate a perfectly conducting ground plane for a short antenna, a ground screen with dimensions $\lambda/2$ can be used. For the 1/4 wave antenna, the ground screen dimensions should be λ.

BENDIX SYSTEMS DIVISION ANN ARBOR, MICH.
6-23-66
Evaluation of Parameters Effecting
the Operating Frequency for the
Active Seismic Experiment (Mortar)

NO. ATM-332   REV. NO.

PAGE ___2___ OF ___16___ PAGES

Discussion:

To obtain seismic data from a mortar launched grenade on the lunar surface, it is necessary to perform a link analysis to determine the required transmitter power and operating frequency with constraints on the antenna size and receiver sensitivity. The antenna physical lengths are three feet for the receiving antenna and less than 4 inches for the transmitting antenna. The physical lengths of the antennas suggests a configuration consisting of an elementary dipole ($1 \leq \lambda/10$) for the transmitting antenna and either a short vertical whip antenna ($\lambda/10$ for $f = 30$ mc) or a $\lambda/4$ end-fed wave antenna operating at 100 mc, for the receiving antenna.

A second consideration in determining the proper antenna configuration is the antenna input impedance. For antenna dimensions, length and radius of the element, that are comparable with respect to a wavelength, the input impedance of the antenna is the same regardless of the operating frequency. For example, Table Ia shows that the input impedance for a short vertical whip antenna is $(4 + j350)$ ohms for both 30 mc and 100 mc, whereas, Table Ib indicates that for a quarter wave antenna, the input impedance is 36.5 ohms for both frequencies. However, a $\lambda/4$ antenna operating at 30 mc is eight feet long compared to a 3 foot length for a quarterwave antenna operating at 100 mc. Since the physical length of the antenna is constrained to 3 feet, a short whip antenna can be used for an operating frequency of 30 mc or a $\lambda/4$ monopole can be used operating at a frequency of 100 mc.

As shown in Figure 1, the required transmitter power P_t decreases as the operating frequency decreases. However, the optimum antenna length for proper impedance matching is $\lambda/4$, which is prohibitive for low frequencies e.g. less than 100 mc. Therefore, the optimum link configuration would be a $\lambda/4$ wave monopole, mounted on a ground screen, with an operating frequency of 100 mc.

Calculations:

For determining the system losses for a lunar based point-to-point communications system, the following effects were considered, (1) ground wave attenuation due to a homogeneous ground or a stratified ground, (2) change in permittivity and conductivity, (3) antenna effects, (4) noise effects and (5) distance.

The temperature in each case is assumed to be 288° K, which corresponds to 62.5°F or a little below room temperature. The parameters that were used to determine the various system losses, see reference (1), are defined as follows:

$$S = 60\lambda\sigma \; \text{Mhos}/\text{m}$$

$$\lambda = \text{wavelength}$$

$$\sigma = \text{surface conductivity}$$

Required transmitter power Pt (dbw) as a function of frequency assuming homogeneous ground, vertical polarization, $\sigma = 10^{-4}$, $\epsilon_r = 2$, $h = \lambda/16$

Legend:

Case I: Elementary dipole transmitting antenna, short monopole receiving antenna, $d_0 = 1$ km

Case II: Elementary dipole transmitting antenna, $\lambda/4$ wave antenna receiving antenna, $d_0 = 1$ km

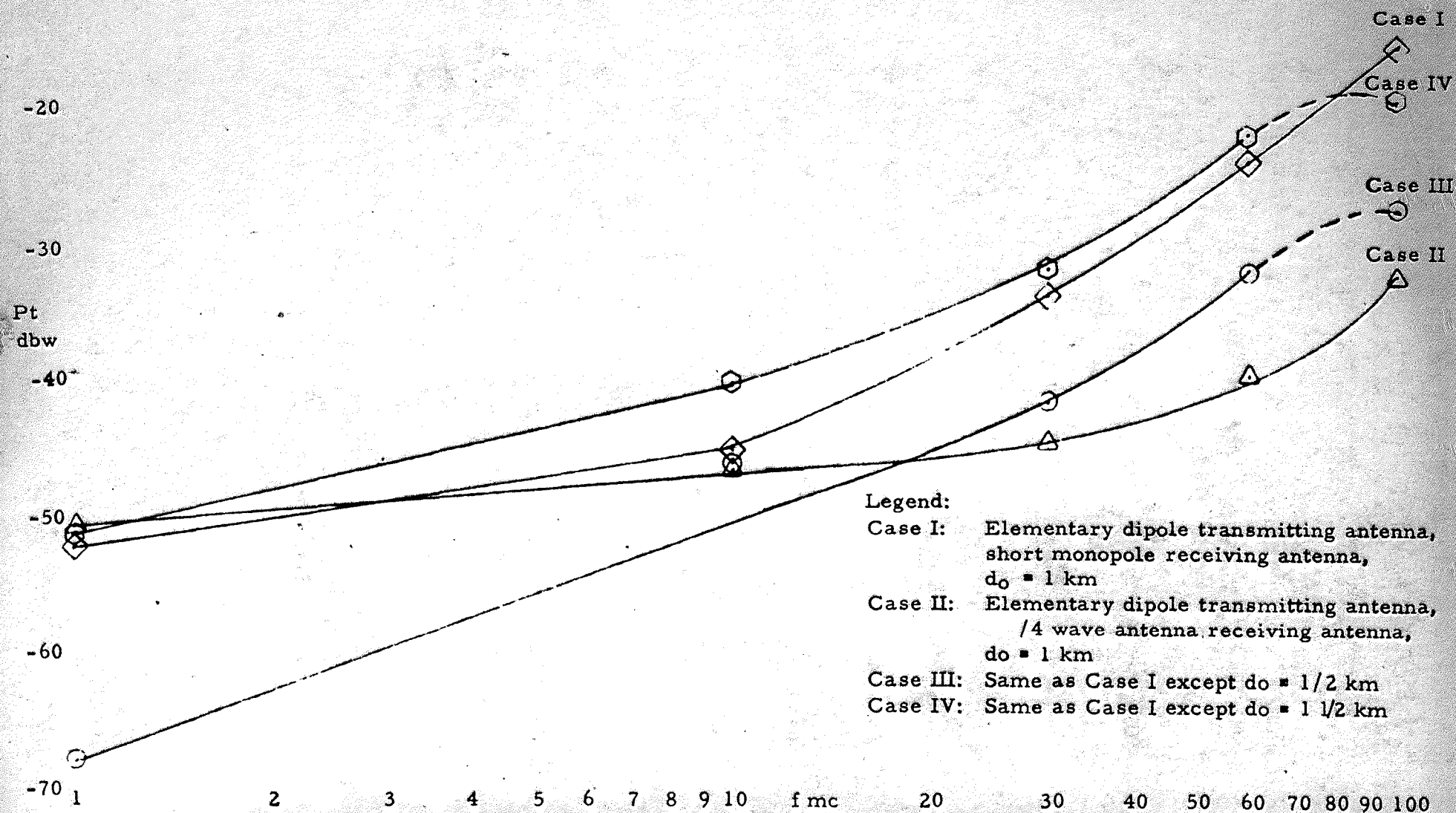Case III: Same as Case I except $d_0 = 1/2$ km

Case IV: Same as Case I except $d_0 = 1 1/2$ km

Figure 1. Required transmitter power as a function of frequency for several distances and antenna configurations.

dipole in free
space

monopole over a perfectly
conducting ground plane
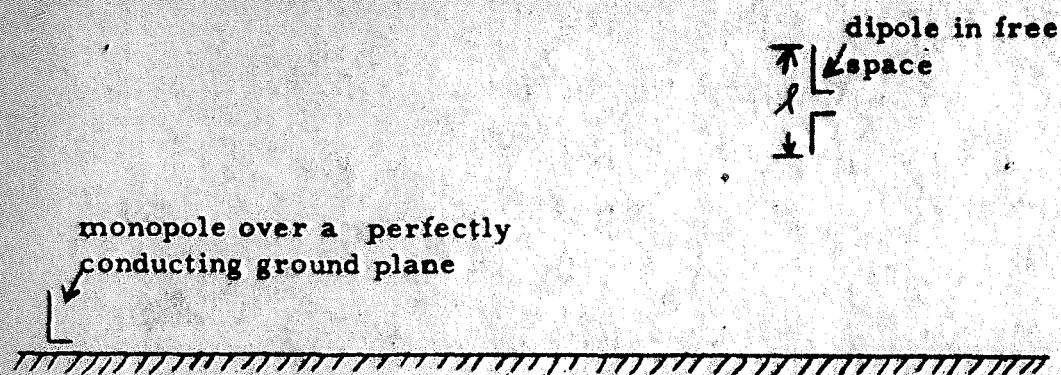
Figure 2. - Geometric Relationship Between Dipole and Monopole to
Determine Monopole Input Impedance

Short Whip Antenna

Frequency	Input Impedance	Antenna Length $(\%_0)$	Required Trnasmitter Pwr	Ground Screen $(\frac{d}{a})$
30 mc	4+j350	3	-3. 5 dbm	15'
100 mc	4+j350	1'	+14. 5 dbm	5'

(a)

$\lambda/4$ Wave Antenna (End Fed)

Frequency	Input Impedance	Antenna Length $(\%_4)$	Required Transmitter Pwr P_t	Ground Screen (λ)
30 mc	36. 5 ohms	8'	-15 dbm	30'
100 mc	36, 5 ohms	2. 5'	- 2 dbm	10'

(b)

Table I. - Comparison of Two Receiving Antenna Configuration
for 30 Mc and 100 Mc

BENDIX SYSTEMS DIVISION ANN ARBOR, MICH.

Evaluation of Parameters Effecting
the Operating Frequency for the
Active Seismic Experiment (Mortar)

NO. ATM-332   REV. NO.

6-23-66

PAGE 5 OF 16 PAGES

$$= f_{mc}^{1/3} \ d_o \ (km)$$

f_{mc} = operating frequency in megacycles

d_o (km) = propagation distance in kilometers

$$K_v = \frac{3.02(10^{-2})}{|tv| \ f_{mc}^{1/3}}$$

$$T_v = \left[\frac{\sqrt{(\epsilon_r - 1)^2 \ S^2}}{\epsilon_r^2 + S^2} \right]^{\frac{1}{2}}$$

$$b_v^o = 2 \tan^{-1} \frac{\epsilon_r}{S} - \tan^{-1} \left(\frac{\epsilon_r - 1}{S} \right)$$

h = height of the receiving antenna above the ground

$$\alpha = \frac{2\pi h}{\lambda}$$

The basic relationship to be solved is

$$P_t = 32.45 + 20 \log d_o \ (km) + 20 \log \ f_{mc} + A_t + L_c + L_r + L_t - (G_t + G_r) +$$

$$R + F + B + 10 \log (K_b \ t_o) \qquad (1)$$

where

A_t = Ground wave attenuation and assumes that both antennas are approximately zero feet above the ground.

L_c = Antenna circuit loss factor

L_r = Ground proximity loss factor (receiving antenna)

L_t = Ground proximity loss factor (transmitting antenna)

R = Receiver S/N ratio

F = Operating noise factor (external internal noise)

B = Receiver noise bandwidth

For this study the assumptions were made that

1. $L_c \cong L_r$
2. Vertical Polarization
3. $B = 10$ Kc (40 db)
4. $R = 10$ db
5. $G_t = 1.76$ db for short depole antenna
6. $G_r = 1.25$ db for short vertical whip antenna
7. $G_r =$ determined from [1] for $\lambda/4$ wave antenna

Then equation (1) can be written as follows

$$P_t - (R + B) = 32.45 + 20 \log f_{mc} + A_t + L_t - 0.51 + F - 204$$

$$P_t - (R \ B) = -172.07 + 20 \log f_{mc} + A_t + L_t + F \qquad (2)$$

Table 2a shows the variation of system losses as a function of frequency for a short dipole transmitting antenna and a short monopole receiving antenna a height of $\lambda/16$ above the ground, separated by 1 kilometer. The conductivity $\sigma = 10^{-4}$, permittivity $\epsilon = 2$.

Table 2b considers the same case for $\sigma = 10^{-3}, \epsilon_r = 2$. Table 2c considers the same case for $\sigma = 10^{-4}, \epsilon_r = 1.1$. Table 2d is identical to Table 2a with the exception that the antenna is a height $h = \frac{\lambda}{4\pi(100)}$.

The ranges of permittivity and conductivity were chosen based on the data obtained from [1]. It can be seen from Tables 2a, 2b and 2c that the system losses do not vary appreciably with the variation in conductivity and permittivity for a constant receiving antenna height above ground of $h = \lambda/16$. This height is negligible for determining A_t but is significant with respect to L_t. Comparison of Tables 2a and 2d shows a significant difference in loss factors due to the decreasing antenna height above ground. This loss factor is a measure of the increased losses due to the ground proximity factor L_t, in the absence of a ground screen.

Table 3a and 3b show the actual transmitter power required for the system losses shown in Tables 2a and 2d, respectively. The results of Table 3a were plotted as Case I in Figure 1.

Table 4a shows the variation of A_t with frequency as a function of a two layer surface, with the upper layer being one meter and 1000 meters. Table 4b shows the required transmitter power for the stratified layers given in Table 4a. The table shows that an upper layer of 1000 m requires approximately the same transmitter power as a homogeneous ground. If the upper layer depth is only one meter there will be a significant decrease in required transmitter power at the lower frequencies (≈ 10 mc), with the improvement diminishing as the frequency increases.

Tables 5a and 5b show the transmitter power required for antenna separations of 1/2 kilometer and 1 1/2 kilometers respectively. The ground constants and antenna configuration is the same as Table 2a. The above results are plotted on Figure 1. of Case III and Case IV, respectively.

Table 6 shows the variation of required transmitter power with frequency, for a $\lambda/4$ wave antenna (end fed.). The results indicated in the Table are plotted on Figure 1 as Case II.

The input impedance is based on the theoretical relationship between a dipole in free space and a monopole mounted vertically over a perfectly conducting ground plane. The relationship is that the input impedance of a monopole of length h, mounted vertically over a perfectly conducting ground plane, is one-half the input impedance of a dipole of length 2h in free space.

Reference (2) contains curves of input impedance for a dipole of arbitrary length 1 in free space. The parameter for the curve is

$$\Omega = 2 \ln \frac{2h}{a}$$

and the abscissa is

$$\beta_o h = \frac{2\pi}{\lambda} h$$

A free space dipole $h = \frac{\lambda}{5}$ implies a short monopole over a perfectly conducting earth of $\frac{\lambda}{10}$, therefore

$$h = \frac{\lambda}{10}, \quad a = \frac{\lambda}{1500} \quad (\text{fmc} = 30, h = 3')$$

$$\Omega = 2 \ln \frac{\frac{\lambda}{5}}{\frac{\lambda}{1500}} = 2 \ln 300 = 2 (5.7) = 11.4$$

and

$$\beta_o h = \frac{2\pi}{\lambda} \frac{\lambda}{10} = 0.628$$

From Figure 30.5a (1)

$$Ro = 8 \text{ ohms}$$

From Figure 30.5b (1)

$$|X_o| = 700 \text{ ohms}$$

Therefore, the input impedance of the monopole of length $\lambda/10$ is

$$Z_m' = 4 + j\,350$$

For a $\lambda/4$ antenna, $a = \lambda/500$, ($f_{mc} = 100$, $h = 2.5'$)

$$\Omega_\lambda = 2 \ln \frac{\frac{\lambda}{2}}{\frac{\lambda}{500}} = 2 \ln 250 = 2 \times 5.5 = 11.0$$

$$\beta \text{oh} = \frac{2\pi}{\lambda} \times \lambda/4 = 1.57$$

Then,

$$R_o = 73 \text{ ohms}$$

$$|X_c| = 0$$

Conclusions:

Because of the input impedance mismatch between the short monopole and the receiver, the best operating frequency is 100 mc. With this frequency, a 3 foot quarter wave antenna can be built with a purely resistive input impedance of 36.5 ohms. Selecting any other length antenna (implying a different operating frequency) will result in an appreciable reactive part for the input impedance and consequently increase the system overall losses due to additional impedance match circuitry.

For the case of the $\lambda/4$ antenna, less power is required for either frequency because of the increased antenna gain. However, there is a tremendous improvement in the input impedance match because for a $\lambda/4$ it is seen that the input impedance for a $\lambda/4$ monopole is 36.5 ohms. Again, with equivalent length and radius measurements relative to a wavelength, the input impedance is the same for both frequencies.

In this case, 13 db more power is needed for 100 mc as compared to the power requirement for 30 mc. However, the length of the $\lambda/4$ antenna is 8' for a frequency of 30 mc and 3' for a frequency of 100 mc.

BENDIX SYSTEMS DIVISION ANN ARBOR, MICH.

6-23-66

Evaluation of Parameters Effecting
Operating Frequency for the Active
Seismic Experiment (Mortar)

NO.

ATM-332

REV. NO.

PAGE 9 OF 16 PAGE

For an antenna length of 3', a frequency of 30 mc is required for a short whip antenna and 100 mc is required for $\lambda/4$ end fed wave antenna. The transmitted power for a receiver sensitivity of -121 dbm is -3.5 dbm and -2 dbm, respectively. However, the mismatch loss between the antenna and the receiver input of 50 ohms will be large for the 30 mc short whip antenna case and will be close, to optimum for the 100 mc $\lambda/4$ wave antenna.

Therefore, on the basis of required transmitter power and input impedance match, a $\lambda/4$ wave antenna operating at a frequency of 100 mc is the best selection for the Active Seismic Experiment.

Reference:

(1) NBS Monograph 85, "A Study of Lunar Surface Radio Communications"
   14 September 1964

(2) King, RWP, "The Theory of Linear Antennas pp 158, 159 Harvard University
   Priss, 1956

Freq. (Mc)	λ (m)	h_1 ($\lambda/16$ ft)	$Fmc^{1/3}$	S (mhos/m)	Xo'	$|Tv|$	Kv	bv^{o} (deg)	At (dbw)	Lr (dbw)	F (dbw)
1	300	61.5	1	1.8	1	0.53	.057	80°	10	7	53
10	30	6.15	2.154	.18	2.154	0.51	.0275	90°	25	3	29
30	10	2.05	3.107	.06	3.107	0.5	.0194	90°	38	2	19
60	5	1.03	3.914	.03	3.914	0.5	.0154	90°	48	2	13
100	3	0.59	4.641	.018	4.641	0.5	.013	90°	50	2	10

Table 2a: System losses for d_o (Km) = 1, $\sigma = 10^{-4}$, $\epsilon r = 2$, $\alpha = 0.786$, $h = \lambda/16$, vertical polarization and homogeneous ground

BENDIX SYSTEMS DIVISION ANN ARBOR, MICH.

Evaluation of Parameters Effecting
Operating Frequency for the Active
Seismic Experiment   (Mortar)

6-23-66

NO. ATM-332   REV. NO.

PAGE 11 OF 16 PAGES

f mc (mc)	S mhos/m	Kv	bv° (deg)	At (dbw)	Lr (dbw)	F (dbw)
1	18	.14	80°	0	7	53
10	1.8	.0265	90°	25	7	29
30	.6	.0187	90°	38	5	19
60	.3	.0153	90°	48	4	13
100	.18	.0128	90°	50	2	10

Table 2b: Systems losses for homogeneous ground, vertical polarization, $\sigma = 10^{-3}$, $\epsilon_r = 2$, do (km) = 1, $\alpha = .786$, h = $\lambda/16$

f mc (mc)	S mhos/m	Kv	bv° (deg)	At (dbw)	Lr (dbw)	F (dbw)
1	1.8	.057	80°	10	8.5	53
10	.18	.0275	90°	25	3.5	29
30	.06	.0194	90°	38	2.0	19
60	.03	.0154	90°	48	1.0	13
100	.018	.013	90°	50	1.0	10

Table 2c: System losses for homogeneous ground, vertical polarization, $\sigma = 10^{-4}$, $\epsilon_r = 1.1$, $\alpha = 78$ do(km) = 1, h = $\lambda/16$

f mc (mc)	S mhos/m	Kv	bv° (deg)	At (dbw)	Lr (dbw)	F (dbw)
1	1.8	.057	80°	10	59	67.18
10	.18	.0275	90°	25	51	51
30	.06	.0194	90°	38	46	46
60	.03	.0154	90°	48	43	43
100	.018	.013	90°	50	41	41

Table 2d: System losses for homogeneous ground, vertical polarization, $\sigma = 10^{-4}$, $\alpha = 0.01$, do(km) = 1, h = $\lambda/4\pi(100)$

* $f = fe + 4 lr - 1$ and $F \triangleq 10 \log f$, i.e. the $\log_{10}$ of each quantity is given in capital letters.

	1 Mhz	10 Mhz	30 Mhz	60 Mhz	100 Mhz
Constant	-172.07	-172.07	-172.07	-172.07	-172.07
Fmc	0.0	20.0	29.52	35.56	40.0
At	10.0	25.0	38.0	48.0	50.0
Lt	7.0	3.0	2.0	2.0	2.0
F	53.0	29.0	19.0	13.0	10.0
Pt - (R- B)	-102.07	-95.07	-83.55	-73.51	-70.07
R	10	10	10	10	10
B	40	40	40	40	40
Pt	-52.07 dbw	-45.07 dbw	-33.55 dbw	-23.51 dbw	-20.07 dbw

Table 3a: Required transmitter power for the system losses indicated in Table 2a.

	1 Mhz	10 Mhz	30 Mhz	60 Mhz	100 Mhz
Constant	-172.07	-172.07	-172.07	-172.07	-172.07
Fmc	0.0	20.0	29.52	35.56	40.0
At	10.0	25.0	38.0	48.0	50.0
Lt	59.0	51.0	46.0	43.0	41.0
F	67.0	51.0	46.0	43.0	41.0
Pt - (R B)	-36.07	-25.07	-13.55	-3.51	-.07
R	10.0	10	10	10	10
B	40.0	40	40	40	40
Pt	13.93 dbw	24.93 dbw	36.45 dbw	47.49 dbw	49.93 dbw

Table 3b: Required transmitter power for the system losses indicated in Table 2d.

		Upper Layer depth (1m)			Upper Layer Depth (1000 m)		
Fmc	X_0	b_v^o	K_v	At	b_v^o	K_v	At
1	1	-20°	0.8	---	65°	0.055	10
10	2.1	-45°	0.08	0	90°	0.034	30
30	3.1	-45°	0.025	30	90°	0.02	38
60	3.9	0	0.01	50	90°	0.015	50
100	4.6	---	---	---	90°	0.014	52

Table 4a: Ground wave attenuation losses At, for a two layer stratification, with the upper having depths of 1m and 1000m and assuming a conductivity of the lower layer of $\sigma_2 = 10^{-1}$ (poor conductivity) and conductivity of the upper layer $\sigma_1 = 10^{-4}$.

BENDIX SYSTEMS DIVISION ANN ARBOR, MICH.

Evaluation of Parameters Effecting
Operating Frequency for the Active
Seismic Experiment (Mortar)

6-23-66

ATM-332

PAGE 14 OF 16 PAGE

Upper Layer: 1 meter

	1 Mhz	10 Mhz	30 Mhz	60 Mhz	100 Mhz
Constant		-172.07	-172.07	-172.07	
Fmc		20.0	29.52	35.56	
At		0	30	50	
Lt		3	2	2	
F		29	19	13	
Pt - (R B)		-120.07	-91.55	-71.51	
R		10	10	10	
B		40	40	40	
Pt		-70.07 dbw	-41.55 dbw	-21.51 dbw	

Upper Layer: 1000 meters

	1 Mhz	10 Mhz	30 Mhz	60 Mhz	100 Mhz
Constant	-172.07	-172.07	-172.07	-172.07	-172.07
Fmc	0	20	29.52	35.56	40
At	10	30	38	50	52
Lt	7	3	2	2	2
F	53	29	19	13	10
Pt - (R B)	-102.07	-90.07	-84.07	-71.51	-68.07
R	10	10	10	10	10
B	40	40	40	40	40
Pt	-52.07	-40.07	-34.07	-21.51	-18.07'

Table 4b: Required Pt for ground conditions specified in Table 4a.

Bendix 6-23-66 | **BENDIX SYSTEMS DIVISION ANN ARBOR, MICH.**
Evaluation of Parameters Effecting
Operating Frequency for the Active
Seismic Experiment (Mortar)

ATM-332

PAGE ___ 15 ___ OF ___ 16 ___ PAGE

	1 Mc	10 Mc	30 Mc	60 Mc	100 Mc
Constant	-172.07	-172.07	-172.07	-172.07	-172.07
Fmc	0.0	20	29.52	35.56	40
At	-6.02	22	30	40	43
Lt	7	3	2	2	2
F	53	29	19	13	10
Pt´- (R B)	-118.09	-98.07	-91.55	-81.51	-77.07
R	10	10	10	10	10
B	40	40	40	40	40
Pt	-68.09 dbw	-48.07 dbw	-41.55 dbw	-37.51 dbw	-27.07 dbw

Table 5a: Required transmitter power for system losses for do = 1 km,
$\sigma = 10^{-4}$, $\epsilon r = 2$, $\alpha = 0.786$, h = $\lambda/16$, vertical polarization
and homogeneous. ground.

	1 Mc	10 Mc	30 Mc	60 Mc	100 Mc
Constant	-172.07	-172.07	-172.07	-172.07	-172.07
Fmc	0.0	20	29.52	35.56	40
At	11	30	40	50	51
Lt	7	3	2	2	2
F	53	29	19	13	10
Pt -(R B)	-101.07	-90.07	-81.55	-71.51	-69.07
R	10	10	10	10	10
B	40	40	40	40	40
Pt	-51.07 dbw	-40.07 dbw	-31.55 dbw	-21.5 dbw	-19.07 dbw

Table 5b: Required transmitted power for the same conditions as indicated
in Table 5a except that do = 1 1/2 km.

* Note: Table 2-5 considered an antenna configuration of a short dipole
transmitting antenna and a short monopole receiving antenna.

BENDIX SYSTEMS DIVISION ANN ARBOR, MICH.

Evaluation of Parameters Effecting
Operating Frequency for the Active
Seismic Experiment   (Mortar)

6-23-66

NO. ATM-332

REV. NO.

PAGE 16 OF 16 PAG

	1 Mc	10 Mc	30 Mc	60 Mc	100 Mc
Constant	32.45	32.45	32.45	32.45	32.45
Fmc	0	10	14.76	14.76	17.78
At	12	30	38	38	46
(Lr-Gr)	8	7.5	7	7	7
F	53	29	19	19	13
	105.45	128.95	111.21	121.21	116.23
10 log Kt	-204	-204	-204	-204	-204
	-98.55	-95.05	-92.89	-92.79	-87.77
Gt	-1.76	-1.76	-1.76	-1.76	-1.76
	-100.31	-96.81	-94.65	-94.55	-89.53
(R+B)	50	50	50	50	50
Pt	-50.3 dbw	-46.81 dbw	-44.55	-44.55	-39.53

Table 6: Transmitter power requirements for a short dipole transmitting
antenna, $\lambda/4$ wave antenna - end fed receiving antenna, vertical
polarization, homogeneous ground, $\sigma = 10^{-4}$, $\epsilon_r = 2$, $h = \lambda/16$,
do = 1 km