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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Approved by John Zimmer
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 ($Z$). 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 $l = 2h$ 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, $l \ll \lambda$ (or $l_{\text{max}} \approx \lambda/10$), 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 $\lambda$. 
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 suggest a configuration consisting of an elementary dipole (1/10 $\lambda$) for the transmitting antenna and either a short vertical whip antenna ($\lambda/10$ for $f = 30 \text{ mc}$) 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 1a shows that the input impedance for a short vertical whip antenna is $(4 + j350)$ ohms for both 30 mc and 100 mc, whereas, Table 1b 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:

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

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

$$ \sigma = \text{surface conductivity} $$
Required transmitter power $P_t$ (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, $d_o = 1$ km
- Case II: Elementary dipole transmitting antenna, /4 wave antenna, receiving antenna, $d_o = 1$ km
- Case III: Same as Case I except $d_o = 1/2$ km
- Case IV: Same as Case I except $d_o = 1 1/2$ km

Figure 1. Required transmitter power as a function of frequency for several distances and antenna configurations.
Figure 2. - Geometric Relationship Between Dipole and Monopole to Determine Monopole Input Impedance

Short Whip Antenna

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Input Impedance</th>
<th>Antenna Length (%)</th>
<th>Required Transmitter Pwr</th>
<th>Ground Screen (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 mc</td>
<td>4+j350</td>
<td>3</td>
<td>-3.5 dbm</td>
<td>15'</td>
</tr>
<tr>
<td>100 mc</td>
<td>4+j350</td>
<td>1'</td>
<td>+14.5 dbm</td>
<td>5'</td>
</tr>
</tbody>
</table>

\( \frac{1}{4} \) Wave Antenna (End Fed)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Input Impedance</th>
<th>Antenna Length (%)</th>
<th>Required Transmitter Pwr ( P_t )</th>
<th>Ground Screen (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 mc</td>
<td>36.5 ohms</td>
<td>8'</td>
<td>-45 dbm</td>
<td>30'</td>
</tr>
<tr>
<td>100 mc</td>
<td>36.5 ohms</td>
<td>2.5'</td>
<td>-2 dbm</td>
<td>10'</td>
</tr>
</tbody>
</table>

Table I. - Comparison of Two Receiving Antenna Configuration for 30 Mc and 100 Mc
The basic relationship to be solved is

\[ P_t = 32.45 + 20 \log d_0 \text{ (km)} + 20 \log f_{mc} + A_t + L_C + L_R + L_t - (G_t + G_r) + \]
\[ R + F + B + 10 \log (K_b t_o) \]  

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. \( L_c \approx L_r \)
2. Vertical Polarization
3. \( B = 10 \text{ Kc} \) (40 db)
4. \( R = 10 \text{ db} \)
5. \( G_t = 1.76 \text{ db} \) for short dipole antenna
6. \( G_r = 1.25 \text{ db} \) for short vertical whip antenna
7. \( H_r \) is determined from (1) for \( \lambda/4 \) wave antenna

Then equation (1) can be written as follows

\[
P_t - (R + B) = 32.45 + 20 \log f \text{mc} + A_t + L_t - 0.51 + F - 204
\]
\[
P_t - (R - B) = -172.07 + 20 \log f \text{mc} + A_t + L_t + F
\]

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 \( \varepsilon_r = 2 \).

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

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 1 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 \( (\approx 10 \text{ mc}) \), 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 $l$ in free space. The parameter for the curve is

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

and the abscissa is

$$\beta_{oh} = \frac{2 \pi P}{\lambda} h$$

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

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

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

and

$$\beta_{oh} = \frac{2 \pi P}{\lambda} \frac{\lambda}{10} = 0.628$$

From Figure 30.5a (1)

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

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

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

$$f_{oh} = 2\pi \sqrt{a} \times \lambda/4 = 1.57$$

Then,

$$R_0 = 73 \text{ ohms}$$

$$|x_e| = 0$$

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.
For an antenna length of 3\lambda, 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) | $\lambda$ (m) | $h_1$ (\$/16 ft) | Fmc$^{1/3}$ | S (mhos/m) | $\chi_0^1$ | $|\Gamma v|$ | Kv | $\theta$ (deg) | At (dbw) | Lr (dbw) | F (dbw) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 300 | 61.5 | 1 | 1.8 | 1 | 0.53 | 0.057 | 80° | 10 | 7 | 53 |
| 10 | 30 | 6.15 | 2.154 | 0.18 | 2.154 | 0.51 | 0.0275 | 90° | 25 | 3 | 29 |
| 30 | 10 | 2.05 | 3.107 | 0.06 | 3.107 | 0.5 | 0.0194 | 90° | 38 | 2 | 19 |
| 60 | 5 | 1.03 | 3.914 | 0.03 | 3.914 | 0.5 | 0.0154 | 90° | 48 | 2 | 13 |
| 100 | 3 | 0.59 | 4.641 | 0.018 | 4.641 | 0.5 | 0.013 | 90° | 50 | 2 | 10 |

Table 2a: System losses for $d_o$ (Km) = 1, $\sigma = 10^{-4}$, $\epsilon_r = 2$, $\chi = 0.786$, $h = \lambda /16$, vertical polarization and homogeneous ground.
### Table 2b: Systems losses for homogeneous ground, vertical polarization, $\sigma = 10^{-3}$, $\varepsilon_r = 2$, $d_0 (km) = 1$, $\alpha = 786$, $h = \lambda / 16$

<table>
<thead>
<tr>
<th>$f$ (mc)</th>
<th>$S$ (mhos/m)</th>
<th>$K_v$</th>
<th>$b_\theta$ (deg)</th>
<th>$A_t$ (dbw)</th>
<th>$L_r$ (dbw)</th>
<th>$F$ (dbw)</th>
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<td>1</td>
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<td>.14</td>
<td>80°</td>
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<td>7</td>
<td>53</td>
</tr>
<tr>
<td>10</td>
<td>1.8</td>
<td>.0265</td>
<td>90°</td>
<td>25</td>
<td>7</td>
<td>29</td>
</tr>
<tr>
<td>30</td>
<td>.6</td>
<td>.0187</td>
<td>90°</td>
<td>38</td>
<td>5</td>
<td>19</td>
</tr>
<tr>
<td>60</td>
<td>.3</td>
<td>.0153</td>
<td>90°</td>
<td>48</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>100</td>
<td>.18</td>
<td>.0128</td>
<td>90°</td>
<td>50</td>
<td>2</td>
<td>10</td>
</tr>
</tbody>
</table>

### Table 2c: Systems losses for homogeneous ground, vertical polarization, $\sigma = 10^{-4}$, $\varepsilon_r = 1.1$, $\alpha = 786$, $d_0 (km) = 1$, $h = \lambda / 16$

<table>
<thead>
<tr>
<th>$f$ (mc)</th>
<th>$S$ (mhos/m)</th>
<th>$K_v$</th>
<th>$b_\theta$ (deg)</th>
<th>$A_t$ (dbw)</th>
<th>$L_r$ (dbw)</th>
<th>$F$ (dbw)</th>
</tr>
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<tbody>
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<td>1</td>
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<td>.057</td>
<td>80°</td>
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<td>8.5</td>
<td>53</td>
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<tr>
<td>10</td>
<td>.18</td>
<td>.0275</td>
<td>90°</td>
<td>25</td>
<td>3.5</td>
<td>29</td>
</tr>
<tr>
<td>30</td>
<td>.06</td>
<td>.0194</td>
<td>90°</td>
<td>38</td>
<td>2.0</td>
<td>19</td>
</tr>
<tr>
<td>60</td>
<td>.03</td>
<td>.0154</td>
<td>90°</td>
<td>48</td>
<td>1.0</td>
<td>13</td>
</tr>
<tr>
<td>100</td>
<td>.018</td>
<td>.013</td>
<td>90°</td>
<td>50</td>
<td>1.0</td>
<td>10</td>
</tr>
</tbody>
</table>

### Table 2d: Systems losses for homogeneous ground, vertical polarization, $\sigma = 10^{-4}$, $\alpha = 0.01$, $d_0 (km) = 1$, $h = \lambda / 16$

<table>
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<tr>
<th>$f$ (mc)</th>
<th>$S$ (mhos/m)</th>
<th>$K_v$</th>
<th>$b_\theta$ (deg)</th>
<th>$A_t$ (dbw)</th>
<th>$L_r$ (dbw)</th>
<th>$F$ (dbw)</th>
</tr>
</thead>
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<tr>
<td>1</td>
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<td>80°</td>
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<td>59</td>
<td>67.18</td>
</tr>
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<td>.0275</td>
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<td>25</td>
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<td>60</td>
<td>.03</td>
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<td>48</td>
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<td>43</td>
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<td>100</td>
<td>.018</td>
<td>.013</td>
<td>90°</td>
<td>50</td>
<td>41</td>
<td>41</td>
</tr>
</tbody>
</table>

\* $f = f + 4 \lambda$ and $F = 10 \log f$, i.e. the log10 of each quantity is given in capital letters.
### Table 3a: Required transmitter power for the system losses indicated in Table 2a.

<table>
<thead>
<tr>
<th></th>
<th>1 Mhz</th>
<th>10 Mhz</th>
<th>30 Mhz</th>
<th>60 Mhz</th>
<th>100 Mhz</th>
</tr>
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<tbody>
<tr>
<td>Constant</td>
<td>-172.07</td>
<td>-172.07</td>
<td>-172.07</td>
<td>-172.07</td>
<td>-172.07</td>
</tr>
<tr>
<td>FmC</td>
<td>0.0</td>
<td>20.0</td>
<td>29.52</td>
<td>35.56</td>
<td>40.0</td>
</tr>
<tr>
<td>A</td>
<td>10.0</td>
<td>25.0</td>
<td>38.0</td>
<td>48.0</td>
<td>50.0</td>
</tr>
<tr>
<td>L</td>
<td>7.0</td>
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<td>2.0</td>
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<td>29.0</td>
<td>19.0</td>
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</tr>
<tr>
<td>Pt - (R-B)</td>
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<td>-70.07</td>
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</tr>
<tr>
<td>B</td>
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<td>40</td>
<td>40</td>
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<td>Pt</td>
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<td>-45.07 dbw</td>
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<td>-23.51 dbw</td>
<td>-20.07 dbw</td>
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**Table 3b:** Required transmitter power for the system losses indicated in Table 2d.

<table>
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<tr>
<th></th>
<th>1 Mhz</th>
<th>10 Mhz</th>
<th>30 Mhz</th>
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<td>L</td>
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<td>F</td>
<td>67.0</td>
<td>51.0</td>
<td>46.0</td>
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<td>41.0</td>
</tr>
<tr>
<td>Pt - (R-B)</td>
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<td>B</td>
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<tr>
<td>Pt</td>
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<td>24.93 dbw</td>
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<td>47.49 dbw</td>
<td>49.93 dbw</td>
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Table 4a: Ground wave attenuation losses $A_t$, for a two-layer stratification, with the upper having depths of 1m and 1000m and assuming a conductivity of the lower layer of $\sigma = 10^{-1}$ (poor conductivity) and conductivity of the upper layer $\sigma = 10^{-4}$.

<table>
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<th>$Fmc$</th>
<th>$X_0$</th>
<th>$b_\theta$</th>
<th>$K_\theta$</th>
<th>$A_t$</th>
<th>$b_\theta$</th>
<th>$K_\theta$</th>
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### Upper Layer: 1 meter

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### Upper Layer: 1000 meters

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**Table 4b:** Required Pt for ground conditions specified in Table 4a.
Table 5a: Required transmitter power for system losses for do = 1 km, 
\( \sigma = 10^{-4}, \, \xi r = 2, \, \xi = 0.786, \, h = \lambda/16, \) vertical polarization and homogeneous ground.

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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.
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</table>

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