A method is presented for the determination of radar frequency radiation power densities that the PAVE PAWS radar system could produce in its air and ground environment. The effort was prompted by the concern of the people in the vicinity of OTIS AFB MA and SEAL AFB CA about the possible radar frequency radiation hazard of the PAVE PAWS radar. The method is based on the following main assumptions that: a) the total field can be computed as the vector summation of the individual fields due to each (over)
antenna element, b) the individual field can be calculated using distances for which the field point is in the far field of the antenna element. An RFR computer program was coded for the RADC HE 6180 digital computer and exercised to calculate the radiation levels in the air and ground space for the present baseline and the possible SIX DB and 10 DB growth systems of the PAVE PAWS radar system at OTIS AFB MA. The average radiation levels due to the surveillance fence were computed for three regions: in the air space in front of the radar, at the radar hazard fence at OTIS AFB MA and at representative ground points in the OTIS AFB vicinity. For the air space, the cases considered were: along the main beam axis with the beam radiating on-boresight and off-boresight, along the edge of the beam and elevation pattern densities at various azimuths and elevations. Numerous power density plots are presented. For example, the baseline system power density boresight beam axis power density plots show near field (from a 10 foot distance from the antenna to 500 feet), the transition region (from 500 feet to 4646 feet) and the far field region without discontinuities between regions. An air hazard zone where the power density levels, on a conservative boresight spotlight beam basis, could be 10 milliwatts/centimeter squared or higher is defined as a zone extending over an azimuth sector of 120 degrees per face with a radius of approximately 3035 feet for the baseline system, 6140 feet for the SIX DB system and 8710 feet for the 10 DB system. The calculated average power densities for the hazard fence periphery are well below the OSHA hazard level. Power density levels calculated for seven off-base ground points are in the safe low microwatts/centimeter squared region. The RFR computer program calculated values of power density for four ground points when the radar is operating according to its beam position, frequency, and timing schedule, were within 3.5 dB of measured field data.

It is concluded that the radar frequency radiation of PAVE PAWS does not present a hazard to personnel provided there is no entry to the air hazard zone or to the area within the hazard fence. The method developed offers a cost effective way to determine radiation levels from a phased array radar especially in the near field and transition regions.
Preface

Research described in this report was accomplished in-house at RADC under Job Order Number 20590101.

Appreciation is expressed to Mr. George Vogel, IRAE for the impetus he gave to this effort by his original work on the Time Scanned Array Radar and by the many productive discussions, to Capt Jimmie Boyd, OCSP for his coding of the RFR computer program, and to Mr. Donald Stebbins, OCSP for his debugging of the computer program, running the program and helping in the analysis of the results.
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1.0 Introduction: In the late 1970's period there was a great deal of concern expressed by the people living in the area of OTIS Air Force Base Massachusetts and BEALE Air Force Base California about the possible radar frequency radiation hazard that might be caused by the large phased array radar of PAVE PAWS system. In order to determine whether or not PAVE PAWS could present a radiation hazard to personnel, RADC developed and exercised an RFR (Radar Frequency Radiation) computer program.

The prime mission of the PAVE PAWS radar system is to detect and track sea launched ballistic missiles and to provide the National Military Command Center, the North American Air Defense Command Center and the Strategic Air Command with warning and attack characterization data. The secondary mission is to support satellite surveillance and tracking. The PAVE PAWS radar system consists of two radars -- one located on the east coast at OTIS AFB Massachusetts and one located on the west coast at BEALE AFB California. Figure 1.1 shows the PAVE PAWS radar located at BEALE AFB. The radar is housed in a five story building 105 feet high. The building is shaped approximately like a truncated pyramid with a triangular base 105 feet on a side. The PAVE PAWS radar is a dual-faced radar system with two radiating radar antennas -- Faces A and B which are visible in Figure 1.1 and with one passive antenna -- Face C which is located at the rear of the building. At present, in the baseline system, each radar face is a spatially thinned array with an active area diameter of 72.5 feet. Each radar face can radiate independently in the 420 to 450 MHz frequency band with a peak power of approximately 580 kilowatts at a duty cycle of 0.25. Faces A and B operate in a surveillance and tracking mode. The surveillance fence is maintained at a nominal 3 degrees elevation over an azimuth sector of 120 degrees per face. Each radar face has 1792 active elements which can transmit and receive and 885 "dummy" elements which neither transmit nor receive. Each active element has a solid
state transmit/receive module. In addition to the two radiating faces, the PAVE PAWS radar has a receive only Face C linear array which has 21 elements and is used for interference monitoring purposes. In the future, either of two growth systems -- a SIX DB system or a 10 DB system could be implemented. The SIX DB system would have an active array diameter of 102.5 feet with 3584 active elements and 1770 "dummy" elements and with a peak transmitted power double that of the baseline system at the same duty cycle for each face A and B. Figures 1.2 and 1.3 show the active element layout for the baseline and the SIX DB systems, respectively. The 10 DB system would have an active array diameter of 102.5 feet with uniform illumination, a total of 5354 active elements and no "dummy" elements with a peak transmitted power approximately three times that of the baseline system at the same duty cycle for each face A and B.

All three systems were considered in the RADC field intensity calculations with the emphasis placed on the baseline and the SIX DB systems. The calculations were performed using the RADC RFR computer program. This computer program was developed by RADC and coded for the RADC Honeywell HE 6180 digital computer. The RFR computer program has the capability of calculating the field intensity levels that a phased array would produce anywhere in its environment. This method applies to any phased array, facilitates the antenna design stage and reduces the need for expensive field measurements. The radiation levels due to the operation of the PAVE PAWS surveillance fence were computed for three regions using the slightly higher design value of 344 transmit peak watts/module. The particular radar treated in this report is the PAVE PAWS radar at OTIS AFB. First, in order to determine the exposure levels to airborne personnel, the radiation levels were computed in the air space in front of the radar. Second, in order to evaluate the effectiveness of the radar hazard fence, the radiation levels were computed at and near the radar hazard fence. Third, in order to determine the exposure levels to personnel outside the base itself, the radiation levels were computed at
representative points of interest in the OTIS AFB vicinity.

2.0 Method:

2.1 Assumptions: The field intensity algorithm development is based on the following assumptions and constraints:

a. Two isotropic radiators with suitable phasing and separation can represent an antenna array element mounted in front of the array plane.

b. The total field can be computed as the vector summation of the individual fields due to each array antenna element.

c. The individual field due to an array antenna element is calculated using distances for which the field point is in the far field of the antenna array element.

d. The mutual coupling effects between antenna array elements can be ignored. A negligible error (less than 6 percent -- Appendix A) results in the calculation of the field intensity. But there results a significant lessening of the computational complexity.

e. Refraction effects are neglected.

f. The beam steering phases are not quantized and consequently no random/parabolic corrections for phase step errors are applied. Rather correct steering phases are usually assumed. The effect of errors in the steering phase can be considered and is treated in Appendix B.

2.2 Element Pattern: The PAVE PAWS element was represented in the RFR computer program by a pattern due to two isotropic radiators spaced one half of the wavelength at the midband frequency of 435 MHz along the array normal with each radiator spaced 0.25 \( \lambda \) (wavelength) from the plane which would contain the array face. The phasing between the radiators was taken as 180 degrees at the band center. Equation (2.1) represents this pattern.
where \( \vec{E} \) is the electric field intensity at a field point normalized to a unity excitation

\( k \) is the wavenumber

180 is the phasing between the radiators at the midband frequency in degrees

\( r_1 \) is the distance from the field point to the radiator in front of the array plane

\( r_2 \) is the distance from the field point to the radiator in back of the array plane

Figure 2.1 shows the midband (435 MHz) element patterns measured by Raytheon in four different planes. The "rapid" variations are measurement effects due to the rotation of the linear sampling antenna of the circularly polarized actual antenna element. The "slow" variations are due to the edge effects of the partial array (320 elements) used as a test array. The beamwidth is on the order of 60 degrees. There are some undulations in the pattern (less than 1 dB); the measured gain is 5.77 dB. Figure 2.2 shows the midband (435 MHz) element patterns computed by the RADC RFR computer program for the vertical plane. Figure 2.2A is a rectangular power plot, and Figure 2.2B is a polar voltage plot. The beamwidth is 60 degrees. Figure 2.2 is without the undulations evident in the Raytheon plot. The gain is 6 dB. It is considered that this pattern is a good representation of the actual PAVE PAWS element pattern.

2.3 **Total Field:** Since the array antenna element is small and has short dimensions (in the order of 16 inches) it has a far field distance of approximately 1.6 feet. Thus it can be considered that the field density
calculations for the element can be performed for points at distances greater than 10 feet from the element on the basis of far field conditions where the energy propagates according to the inverse distance squared law. Equation (2.2) applies:

\[ P = \frac{W}{4\pi r^2} \]  

(2.2)

where

- \( P \): power density at the field point
- \( W \): power radiated by the radiator in watts
- \( r \): distance from the radiator to the field point

The power density can also be expressed by equation (2.3).

\[ P = \frac{1}{2Z} \left| \mathbf{E} \right|^2 \]  

(2.3)

where

- \( \mathbf{E} \): electric field intensity vector
- \( Z \): free space resistance of 120\( \pi \)

Combining equations (2.2) and (2.3), one obtains

\[ \left| \mathbf{E} \right| = \frac{\sqrt{60W}}{r} \]  

(2.4)

which leads to

\[ \overrightarrow{E_1} = \frac{\sqrt{60W}}{r_1} e^{-jkr_1} \]  

(2.5)

and to

\[ \overrightarrow{E_2} = \frac{\sqrt{60W}}{r_2} e^{-j(kr_2 + 180)} \]  

(2.6)

where the subscripts 1 and 2 refer to the front and rear radiators, respectively, and where the exponential terms account for the phases accumulated due to the
distances and the phase of the radiator position in front or rear of the plane containing the array face. From equation (2.3), it is evident that the total power density \( P \) for \( i \) isotropic radiators is given by

\[
P = \frac{1}{2Z} \sum E_i^2
\]

(2.7)

where the summation is summed for 1792 front radiators and for 1792 rear radiators for the case of the baseline system which has 1792 radiating antenna elements. These numbers double for the case of the SIX DB system and increase to 5354 for the 10 DB system. Equation (2.7) leads to

\[
P = \frac{30 W}{Z} \left[ \sum_{i=1}^{2} \frac{e^{-j(\mathbf{k}r_i + \mathcal{G}_i)}}{r_i^2} \right]
\]

(2.8)

where \( \mathcal{G}_i \) is the phase at the \( i \)-th radiator. This phase term includes the 180 degree phase at the midband frequency for the rear element and the beam steering phases.

Based on equations (2.5), (2.6), and (2.8) and based on the PAVE PAWS geometry of Figure 2.3, an RFR computer program was coded for the RADC HE 6180 computer. The pair of points \( F \) and \( R \) of Figure 2.3 depicting the location of the front and rear isotropic radiators, respectively, for one antenna array element are located in the \( x',y',z' \) radar face cartesian coordinate (RFCC) system. The field sample point \( Q \) is located in the radar topocentric system. The orientation of the \( x,y,z \) coordinate system was chosen to simplify the calculations of \( r \) the distance from a radiator (\( R \) or \( F \)) to the field point \( Q \). This distance \( r \) was calculated from

\[
r = \left( \Delta x^2 + \Delta y^2 + \Delta z^2 \right)^{1/2}
\]

(2.9)
where

\[ \Delta x = x + x' \]
\[ \Delta y = y + y' \cos T \pm d \sin T \]
\[ \Delta z = z - y' \sin T \pm d \cos T - h \]

and where

\( x, y, z \) are the topocentric coordinates of the point Q
\( x', y', z' \) are the RFCC coordinates of the isotropic radiators
\( T \) is the array face tilt angle from the horizontal xy plane
\( h \) is the array face center height above the xy plane

the \(+d\) term applies to front radiator
the \(-d\) term applies to the rear radiator
Fig. 2.1 RAYTHEON ELEMENT PATTERN
a. Rectangular plot

b. Polar plot

Fig 2.2 Midband Element Pattern
FIG. 2.3 PAVE PAWS GEOMETRY

NOT TO SCALE
3.0 Air Space Densities: To determine the radiation hazard to personnel, average power density levels were calculated for various samples of space in front of the array. Cases considered were: a) along the main beam axis with the beam radiating on-boresight and off-boresight, b) along the edge of the main beam and c) elevation antenna pattern densities at various azimuths and distances. Spotlight beams i.e. the worst case of a beam fixed in space were considered. It is to be noted that in actual operation the spotlight beam densities would be decreased by the beam motion factor.

3.1 Beam Axial Densities: Figure 3.1 shows the baseline system power density levels along the main beam axis when the radar transmit beam is fixed on array boresight i.e. at 20 degrees elevation and zero degrees azimuth, where azimuth is taken with respect to array boresight. There are three regions apparent: a near field or Fresnel region, a transition region, and a far field or Fraunhofer region. The power density undergoes rapid changes in the near field - the region between the antenna array and the last peak. The last peak with a power density level of 145 milliwatts/centimeter squared is located at a distance $R_2$ of 500 feet away from the antenna. There are many different power density peaks and nulls in the near field with some peaks higher than the last peak. The highest peak in the near field has a value of 137 milliwatts/centimeter squared and occurs at a distance of $R_1$ of 79 feet away from the antenna. In the transition region which exists for distances greater than $R_2$ and lesser than, say, the far field distance of $20\sqrt{\lambda}$ (here - 4646 feet), the power density levels decrease monotonically with distance. A power density level of 10 milliwatts/centimeter squared exists at a distance of 3030 feet. In the far field region the power density levels decrease pretty much with the
distance squared. Figure 3.2 shows the variation of the range exponent $n$ where the the power density is taken to vary as the distance raised to the exponent $n$. The exponent $n$ undergoes rapid changes in sign and magnitude in the near field and monotonically decreases in the transition region. Figure 3.3 is an expanded plot of the previous Figure 3.2. The range exponent approaches an asymptotic value of minus 2, the range exponent value normally used in far field calculations. Figure 3.4 shows the SIX DB system power density levels along the main beam axis for the beam on boresight. Figure 3.4 is similar to Figure 3.1 but the near field is larger and extends to $R_2$ equal to 976 feet where the last peak is 151 milliwatts/centimeter squared. The near field highest peak is higher, has a value of 248 milliwatts/centimeter squared and occurs at a distance $R_1$ of 50 feet. Figures 3.5, 3.5, and 3.7 show the power density levels along the main beam axis with the radar beam in the mid position of the surveillance fence i.e. at 3 degrees elevation and zero degrees azimuth with respect to boresight for the baseline system, the SIX DB system and the 10 DB system, respectively. It is to be noted that even in the 10 DB system case (where the antenna aperture is filled and with uniform excitation) the near field exhibits many different power density peaks and valleys. Figures 3.8 and 3.9 show the power density levels along the main beam axis when the radar transmit beam is off boresight at 50 degrees azimuth and 20 degrees elevation and 3 degrees elevation, respectively. As the beam axis moves away from the boresight position, the last power density peak, the start of the transition region, moves in closer to the array and increases in magnitude. As the antenna radiating aperture increases the extent of the near field increases. Table 3.1 shows the beam axis power density levels for the fixed beam at different azimuths and
elevations. The peaks in the near field which are higher than the last peak are designated P1. The P1 peaks occur at distances of R1. The peaks designated P2 occur at the distance R2, the start of the transition region. The distances at which the power density levels of 10 milliwatts/centimeter squared occur are indicated by R3. Dashes in Table 3.1 indicate no P1 peaks and indicate no data in the R3 column.

Table 3.1. Beam Axial Density

<table>
<thead>
<tr>
<th>System</th>
<th>Azimuth</th>
<th>Elevation</th>
<th>R1</th>
<th>P1</th>
<th>R2</th>
<th>P2</th>
<th>R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees</td>
<td>Degrees</td>
<td>Feet</td>
<td>Mw/cm</td>
<td>Feet</td>
<td>Mw/cm</td>
<td>Feet</td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>0</td>
<td>20</td>
<td>79</td>
<td>197</td>
<td>500</td>
<td>145</td>
<td>3038</td>
</tr>
<tr>
<td>Baseline</td>
<td>0</td>
<td>3</td>
<td>24</td>
<td>175</td>
<td>478</td>
<td>157</td>
<td>3035</td>
</tr>
<tr>
<td>Baseline</td>
<td>40</td>
<td>20</td>
<td>28</td>
<td>231</td>
<td>398</td>
<td>187</td>
<td>2994</td>
</tr>
<tr>
<td>Baseline</td>
<td>60</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>199</td>
<td>218</td>
<td>2333</td>
</tr>
<tr>
<td>Six DB</td>
<td>0</td>
<td>20</td>
<td>50</td>
<td>248</td>
<td>976</td>
<td>151</td>
<td>-</td>
</tr>
<tr>
<td>Six DB</td>
<td>0</td>
<td>3</td>
<td>67</td>
<td>174</td>
<td>936</td>
<td>164</td>
<td>-</td>
</tr>
<tr>
<td>Six DB</td>
<td>60</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>378</td>
<td>228</td>
<td>4673</td>
</tr>
<tr>
<td>10 DB</td>
<td>0</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>1124</td>
<td>270</td>
<td>8707</td>
</tr>
</tbody>
</table>

3.2 Edge of Beam Densities: Figures 3.10, 3.11, and 3.12 show the edge of beam power density variation with distance for the baseline, SIX DB, and 10 DB systems, respectively. The beam was defined here as in T.O 31Z-10-4 "Radiation Hazards" which defines the beam as a cylinder with about the same size as the projected area of the aperture. The edge of the beam considered here is the top edge of the beam. The power density does not remain constant in any of the regions but changes rapidly with
many peaks and valleys showing the effects of the constructive and destructive interference from the individual radiating antenna element sources. The edge of the beam densities for the baseline and SIX 65 systems change most rapidly within the first 60 feet (approximately) distance from the antenna reaching a highest peak of 67.6 milliwatts/centimeter squared at a distance of 31.5 feet from the antenna for the baseline system and a highest peak of 72.2 milliwatts/centimeter squared at a distance of 25 feet from the antenna for the SIX 08 system. The 10 DB system edge of beam densities vary less violently with distance with the highest peak of 26 milliwatts/centimeter squared occurring at a distance of 14.5 feet from the antenna. The density level of 10 milliwatts/centimeter squared occurs at a distance of 2540 feet from the antenna for the baseline system and 5050 feet for the SIX DB system.

3.3 Elevation Antenna Pattern Densities: Figures 3.13 through 3.22 show the baseline system elevation antenna pattern average power densities at the midband frequency for various distances from the antenna and for the transmit beam at zero degrees azimuth and 3 degrees elevation. Figures 3.23 through 3.29 and figures 3.30 through 3.35 are similar plots for the SIX DB and 10 DB systems, respectively. The beam formation is evident as one progresses through the near field, the transition region into the far field. In the near field region the beam is not yet formed, the beam is much wider than the far field beamwidth and the pattern has higher sidelobes. The upper limit of the elevation angular extent over which the power density is greater than or equal to 10 milliwatts/centimeter squared is plotted as a function of distance from the antenna in figures 3.36, 3.37 and 3.38 for the baseline, SIX 65 and the 10 DB systems, respectively. This elevation angular extent varies
inversely with distance. Thus the baseline system upper elevation limit is 15 degrees for the 145 feet distance, 9 degrees for the 290 feet distance and 6 degrees for the 580 feet distance. A similar effect occurs for the case of the azimuth patterns where e.g. the azimuth angular extent over which the baseline power density is equal to greater than 10 milliwatts/centimeter squared occurs between plus and minus 6.5 degrees for the distance of 290 feet, 3.4 degrees for the distance of 580 feet and 1.8 degrees for the distance of 1161 feet when the beam is at zero degrees azimuth and 20 degrees elevation. For the same distances from the antenna the elevation angular extent widens as the aperture increases in size and in number of radiators.

3.4 Air Hazard: Based on a worst case assumption (spotlight boresight beam), the air hazard zone in front of the radar for airborne personnel is a zone extending over an azimuth sector of 240 degrees (120 degrees per Face) and with a radius equal to approximately 3035 feet for the present baseline PAVE PAWS radar system, 6140 feet for the SIX DB system, if implemented, and 8710 feet for the possible 10 DB system. This worst case assumes a stationary boresight radar beam and makes no allowance for off-boresight losses and no allowance for the possible shielding effect of the aircraft.
Figure 3.1
Boreight Beam Density vs Beam Axis Distance
Baseline System 135 MHz Peak Watts/Module Beam at 20 Deg Elevation 0 Deg Azimuth

Density in MW/cm Squared

Distance in Feet

300 200 100

0 10 100 1000 10000
FIG 3.2 BEAM AXIS RANGE EXPONENT

BASELINE SYSTEM
435 MHZ
344 PEAK WATTS/MODULE
BEAM AT 20 DEG ELEVATION
0 DEG AZIMUTH

DISTANCE IN FEET

19 IV 1978
FIG 3.3 BEAM AXIS RANGE EXPONENT

BASELINE SYSTEM
435 MHZ
344 PEAK WATTS/MODULE
BEAM AT 20 DEG ELEVATION
0 DEG AZIMUTH

DISTANCE IN FEET

19 IV 1978
FIG. 3.5 BEAM AXIS POWER DENSITY
BASELINE SYSTEM
FREQUENCY 435 MHZ
86 WATTS/MODULE
BEAM AT 3 DEG ELEVATION
0 DEG AZIMUTH

DISTANCE IN FEET

DENSITY IN MW/CM SQUARED
FIG. 3.6  BEAM AXIS POWER DENSITY
SIX DB SYSTEM
FREQUENCY 435 MHZ
86 WATTS/MODULE
BEAM AT 3 DEG ELEVATION
0 DEG AZIMUTH

DENSITY IN MW/CM SQUARED

DISTANCE IN FEET
FIG. 3.7  BEAM AXIS POWER DENSITY

10 DB SYSTEM
FREQUENCY 435 MHZ
86 WATTS/MODULE
BEAM AT 3 DEG ELEVATION
BEAM AT 0 DEG AZIMUTH
FIG. 3.8 BEAM AXIS POWER DENSITY
BASELINE SYSTEM
435 MHZ
344 PEAK WATTS/MODULE
BEAM AT 20 DEG ELEVATION
60 DEG AZIMUTH
FIG. 3.10  EDGE BEAM DENSITY VS DISTANCE

BASELINE SYSTEM
435 MHz
344 PEAK WATTS/MODULE
BEAM AT 3 DEG ELEVATION
0 DEG AZIMUTH

DENSITY IN MW/CM SQUARED

DISTANCE IN FEET
FIG. 3.12  EDGE BEAM DENSITY VS DISTANCE

10 DB SYSTEM
435 MHZ
344 PEAK WATTS/MODULE
BEAM AT 3 DEG ELEVATION
0 DEG AZIMUTH

DENSITY IN MV/CM SQUARED

DISTANCE IN FEET
Fig. 3.13 Baseline Elevation Pattern
Beam at 0 deg Azimuth
3 deg Elevation
Frequency 435 MHz
Distance 145 Feet

Elevation in Degrees

10 20 30 40 50
FIG. 3.11 BASELINE ELEVATION PATTERN
BEAM AT 0 DEG AZIMUTH
3 DEG ELEVATION
FREQUENCY 435 MHZ
DISTANCE 290 FEET

DB LEVEL
-20
-30
-40
-50
-60

ELEVATION IN DEGREES
10 20 30 40 50
FIG. 3.13 BASELINE ELEVATION PATTERN

BEAM AT 0 DEG. AZIMUTH
3 DEG. ELEVATION

FREQUENCY 435 MHZ
DISTANCE 560 FEET

LEVEL

10

0

-20

-40

-60

-80

ELEVATION IN DEGREES
FIG. 3-16 BASELINE ELEVATION PATTERN

BEAM AT 0 DEG AZIMUTH
3 DEG ELEVATION

FREQUENCY 435 MHZ
DISTANCE 1151 FEET

DB LEVEL
-10
-20
-30
-40
-50
-60

0 20 40 60 80
ELEVATION IN DEGREES
FIG. 3.17 BASELINE ELEVATION PATTERN

BEAM AT 0 DEG AZIMUTH

3 DEG ELEVATION

FREQUENCY 435 MHZ

DISTANCE 1600 FEET

ELEVATION IN DEGREES
FIG. 3.1A BASELINE ELEVATION PATTERN

BEAM AT 0 DEG AZIMUTH

3 DEG ELEVATION

FREQUENCY 435 MHZ

DISTANCE 1800 FEET

ELEVATION IN DEGREES
FIG 3.10 BASELINE ELEVATION PATTERN

BEAM AT 0 DEG AZIMUTH

3 DEG ELEVATION

FREQUENCY 435 MHZ

DISTANCE 2323 FEET

ELEVATION IN DEGREES
FIG. 3.20 BASELINE ELEVATION PATTERN
BEAM AT 0 DEG AZIMUTH
3 DEG ELEVATION
FREQUENCY 435 MHZ
DISTANCE 300 FEET

ELEVATION IN DEGREES
FIG. 5.21 BASELINE ELEVATION PATTERN
BEAM AT 0 DEG AZIMUTH
3 DEG ELEVATION
FREQUENCY 435 MHZ
DISTANCE 3300 FEET

LEVEL

ELEVATION IN DBRFTS
FIG. 3.22 BASELINE ELEVATION PATTERN
BEAM AT 0 DEG AZIMUTH
3 DEG ELEVATION
FREQUENCY 435 MHZ
DISTANCE 4046 FEET
FIG. 3.23  ELEVATION PATTERN

- 50-5 DB SYSTEM
- BEAM ELEVATION 3 DEG
- BEAM AZIMUTH 2 DEG
- FREQUENCY 235 MHz
- DISTANCE 145 FEET

ELEVATION IN DEGREES
FIG. 3.24 ELEVATION PATTERN
SIX DB SYSTEM
BEAM ELEVATION 3 DEG
BEAM AZIMUTH 2 DEG
FREQUENCY 436 MHZ
DISTANCE 245 FEET
FIG. 3-25  ELEVATION PATTERN
SIX DB SYSTEM
BEAM ELEVATION 3 DEG
BEAM AZIMUTH 2 DEG
FREQUENCY 435 MHZ
DISTANCE 292 FEET
FIG. 3.26 ELEVATION PATTERN
SIX-PA SYSTEM
BEAM ELEVATION 3 DEG
BEAM AZIMUTH 2 DEG
FREQUENCY 435 MHZ
DISTANCE 500 FEET
FIG. 3.27   ELEVATION PATTERN

SIX DB SYSTEM

BEAM ELEVATION 0-20°

BEAM AZIMUTH 0-20°

FREQUENCY 450 MHz

DISTANCE 1161 FEET

ELEVATION IN DEGREES
FIG 3.28  ELEVATION PATTERN

SIX DB SYSTEM
BEAM ELEVATION 3 DEG
BEAM AZIMUTH 3 DEG
FREQUENCY  435 MHz
DISTANCE  1500 FEET
FIG. 3.29 ELEVATION PATTERN

SIX DB SYSTEM

BEAM ELEVATION 3 DEG

BEAM AZIMUTH 0 DEG

FREQUENCY 435 MHz

DISTANCE 1200 FEET

ELEVATION IN DEGREES
FIG. 3.30  10 DB SYSTEM ELEVATION PATTERN

BEAM AT 90 Deg AZIMUTH
3 Deg ELEVATION

FREQUENCY 435 MHZ
DISTANCE 143.59 FEET
FIG. 3.31 10 DB SYSTEM ELEVATION PATTERN

BEAM AT 0 DEG AZIMUTH

3 DEG ELEVATION

FREQUENCY 435 MHz

DISTANCE 287.2 FEET

ELEVATION IN DEGREES
FIG. 3.32  10 DEG SYSTEM ELEVATION PATTERN

BEAM AT 0 DEG AZIMUTH
3 DEG ELEVATION

FREQUENCY 435 MHZ
DISTANCE 574 FEET

ELEVATION IN DEGREES
FIG. 5.33 10 DB SYSTEM ELEVATION PATTERN

BEAM AT 0 DEG AZIMUTH

3 DEG ELEVATION

FREQUENCY 435 MHZ

DISTANCE 2299 FEET

RELATIVE

ELEVATION IN DEGREES

N N S S S S S

S

S

--
FIG. 3.34 10 DB SYSTEM ELEVATION PATTERN

BEAM AT 71 DBG 601 MPH

3 DEG ELEVATION

FREQUENCY 435 MHZ

DISTANCE 4599.5 FEET

ELEVATION IN DEGREES
Fig. 3.35 10 dB System Elevation Pattern

Beam at 0 deg Azimuth
3 deg Elevation
Frequency 435 MHz
Distance 9156 Feet

Elevation in Degrees
FIG. 3.36  BASELINE SYSTEM 10 DBM  

ELEVATION LIMITS

ELEVATION ANGLE IN DEGREES

DISTANCE IN FEET
4.0 **Ground Densities:** To determine the possible radiation hazard levels to personnel on the ground, average power densities were calculated for the PAVE PAWS radar fence and for selected various ground points in the OTIS AFB vicinity when illuminated by a continuously moving search beam and a stepped search beam moving in accordance with the PAVE PAWS search algorithm. For the stepped beam case the RFR calculated values were compared with experimental data.

4.1 **Hazard Fence:** The radiation levels for the radar hazard fence were computed based on the geometry of figures 2.3 and 4.1. The fence was placed in the xy topocentric plane of Figure 2.3. Figure 4.1 shows the radar outline projection on the xy plane and the fence boundary starting from point D, proceeding through points L, E, F, I, M and ending at point N. The radiation levels were computed first for the field sample point Q on the linear portion of the fence (line segment LE) and then for the field sample point Q' on the circular portion of the fence illuminated by Face A. Because of the symmetry and the "windshield wiper" mode of the search operation, the levels calculated for the hazard fence portions illuminated by Face A were assumed to pertain also to the hazard fence portions illuminated by Face B when the radar Face B search fence is operating.

4.1.1 **Linear Fence**
The linear fence segment LQ is generated by equations (4.1)

\[ \begin{align*}
  x &= 69.82 + LQ \cos 30 \\
  y &= 19 + LQ \sin 30 \\
  z &= 0
\end{align*} \]  

(4.1)

where the dimensions are in feet.

The increment LQ is a variable distance from the point L along the LE
line to the field sample point Q. The line DE is approximately 912 feet long. Since the power density at the hazard fence depends on the azimuth position of the search beam, the RFR program was used to determine the azimuth at which the power density at a fence point is maximum. The fence point chosen was at a 500 feet distance away from the radar (LQ = 500 feet). Figures 4.2 and 4.3 show the power density at this point versus beam azimuth position for the baseline and the SIX DB systems, respectively. The maximum power density at this point was 53.8 microwatts/centimeter squared with the beam at 56.25 degrees radar azimuth for the baseline system, and 136.5 microwatts/centimeter squared at 57.25 degrees radar azimuth for the Six DB system. Figures 4.4 and 4.5 show the fence power density as the distance (EQ) from the array to the field point increases when the search beam is at its worst azimuth position. The density levels are fairly low. The maximum density levels are 0.183 milliwatts/centimeter squared at a distance of 142 feet for the baseline system and 0.56 milliwatts/centimeter squared at a distance of 40 feet for the Six DB system.

4.1.2 Fence Arc Segment: The fence arc is generated by equations (4.2)
\[
\begin{align*}
x &= 1070 \sin B \\
y &= 1070 \cos B - 55 \\
z &= 0
\end{align*}
\tag{4.2}
\]
where the dimensions are in feet.

The fence central angle B is the angle (angle FCQ') measured from the y axis to the field sample point Q' and is taken positive in the clockwise direction. The extreme fence point E occurs at B = 58.14 degrees or at an azimuth of 60.7 degrees. The conversion of the fence angle B to the radar face of boresight azimuth angle (also taken positive in the clockwise direction) is given by equation (4.3)
A = \arctan \left( \frac{\sin B}{\cos B - \frac{55}{1070}} \right) \quad (4.3)

Power densities were calculated for the fence arc segment extending over a central angle of 86 to 60 degrees. Since the points of maximum power density will occur at different fence points $Q'$ for different azimuth positions, the power densities on the arc illuminated by Face A were computed for 4 representative beam positions of 0, 20, 40 and 60 degrees azimuth angles and at the 3 degree elevation. Figures 4.6 through 4.9 and figures 4.10 through 4.13 show the power density variation along the fence arc segment as a function of the fence angle for fixed beams at 3 degrees elevation and 0, 20, 40, 60 azimuth angles for the baseline and SIX DB systems, respectively. Shown in Table 4.1.1 are the maxima arc segment hazard fence power densities for both the baseline and SIX DB systems for the four fixed beam orientations. Even for the spotlight conditions, the levels are considerably under the OSHA standard.

<table>
<thead>
<tr>
<th>Beam Azimuth Degrees</th>
<th>Fence Angle 1 Degrees</th>
<th>Density 1 uw/cm²</th>
<th>Fence Angle 2 Degrees</th>
<th>Density 2 uw/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>+26.6</td>
<td>54.6</td>
<td>+26</td>
<td>152.1</td>
</tr>
<tr>
<td>20</td>
<td>-30.8</td>
<td>46.7</td>
<td>-11.1</td>
<td>133.5</td>
</tr>
<tr>
<td>40</td>
<td>-6.2</td>
<td>69.1</td>
<td>3.1</td>
<td>91.9</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>42.5</td>
<td>16.2</td>
<td>69.5</td>
</tr>
</tbody>
</table>

4.2 OTIS AFB Vicinity: Power densities were calculated for seven off-base ground points selected as representative points in the OTIS AFB vicinity. Table 4.2.1 gives the physical location parameters for these
points.

Table 4.2.1 Point Locations

<table>
<thead>
<tr>
<th>Point</th>
<th>Height (Feet)</th>
<th>Azimuth (Degrees)</th>
<th>Azimuth (Degrees)</th>
<th>Distance (Feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Proposed Highway 25</td>
<td>220</td>
<td>350</td>
<td>-57</td>
<td>2702</td>
</tr>
<tr>
<td>2. Mid Cape C</td>
<td>180</td>
<td>25</td>
<td>-22</td>
<td>3403</td>
</tr>
<tr>
<td>3. Mid Cape S</td>
<td>140</td>
<td>75</td>
<td>28</td>
<td>4403</td>
</tr>
<tr>
<td>4. Mid Cape N</td>
<td>150</td>
<td>350</td>
<td>-57</td>
<td>4803</td>
</tr>
<tr>
<td>5. Sagamore Town</td>
<td>100</td>
<td>10</td>
<td>-37</td>
<td>6003</td>
</tr>
<tr>
<td>6. Sagamore Bridge</td>
<td>217</td>
<td>350</td>
<td>-57</td>
<td>8601</td>
</tr>
<tr>
<td>7. Smoke Stack</td>
<td>400</td>
<td>49</td>
<td>2</td>
<td>10200</td>
</tr>
</tbody>
</table>

The C, S, and N designators for the Mid Cape Highway pertain to points on the center, southern and northern portions, respectively. The height values are with respect to Mean Sea Level; the azimuth is referenced to true north. The radar azimuth is referenced to the PAVE PAWS face boresight line. Figure 4.14 shows the map locations of these seven points. Figures 4.15 through 4.19 are the height profiles for these points. Some of the points are located in the PAVE PAWS radar shadow. This shadowing effect was disregarded in this study to arrive at conservative (higher) power density values. Figures 4.20 through 4.26 and Figures 4.27 through Figures 4.33 show the calculated power density levels existing at the points of Table 4.2.1 versus beam position with the beam fixed at various off-boresight azimuths and at 3 degrees elevation - the minimum elevation angle allowed for radiation for the baseline and the SIX DB systems, respectively. The arrow on each figure points to the azimuth of a particular Table 4.2.1 point. The power density scales are shown in microwatts/centimeter squared and in.
dBu, decibels above a microwatt/centimeter squared. Table 4.2.2 lists the average midband densities for the seven points for both the baseline and SIX DB systems.

Table 4.2.2 Average Point Densities for 435 MHz

<table>
<thead>
<tr>
<th>Point</th>
<th>Baseline System</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Azimuth</td>
<td>Maximum Sector</td>
<td>Average</td>
<td>Azimuth</td>
<td>Maximum Sector</td>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Proposed</td>
<td>Degrees</td>
<td>uw/cm²</td>
<td>uw/cm²</td>
<td>Degrees</td>
<td>uw/cm²</td>
<td>uw/cm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highway 25</td>
<td>-54.25</td>
<td>10.57</td>
<td>1.52</td>
<td>-47.5</td>
<td>8.74</td>
<td>1.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Mid Cape C</td>
<td>-15.75</td>
<td>3.55</td>
<td>0.62</td>
<td>-26.25</td>
<td>6.99</td>
<td>1.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Mid Cape S</td>
<td>21.5</td>
<td>2.64</td>
<td>0.45</td>
<td>32.5</td>
<td>4.86</td>
<td>1.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Mid Cape N</td>
<td>-54.25</td>
<td>3.74</td>
<td>0.48</td>
<td>-47.5</td>
<td>2.98</td>
<td>0.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Sagamore Town</td>
<td>-32.5</td>
<td>1.48</td>
<td>0.23</td>
<td>-48</td>
<td>3.91</td>
<td>0.57</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Sagamore Bridge</td>
<td>-56.5</td>
<td>4.66</td>
<td>0.91</td>
<td>-54.75</td>
<td>3.55</td>
<td>0.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Smoke Stack</td>
<td>4.25</td>
<td>6.44</td>
<td>0.62</td>
<td>1.25</td>
<td>25.86</td>
<td>2.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The maximum columns list the spotlight upper bound values. More realistic in practice are the sector average values obtained by considering uniform beam motion over a 40 degree azimuth sector. Since some of the PAVE PAWS radar energy resources must be allocated to the tracking function, the sector average power density values would be further reduced by multiplying these values by the search duty factor of about 11/25. The densities at the off-base points considered are very low —— well under 10 microwatts/centimeter squared and very comfortably under the OSHA standard of 10 milliwatts/centimeter squared.
4.3 **Verification:** Using the RADC RFR computer program, field intensities were calculated at four of the OTIS AFB site south face ground points for which field intensities were measured with the radar in the surveillance fence mode, i.e. the scanned mode. The calculations were performed on the basis of the PAVE PAWS CPCI-2 undithered beam schedule versus time and at the radar transmit frequencies varying from frequency No. 1 to frequency No. 24, inclusive. The doublet and triplet edge beam frequencies were offset from the center frequencies by the CPCI-2 specified frequency differences. The beam schedule template considered short range pulse schedules, long range pulse schedules, Aurora transmissions, calibration and free resource periods for the total 41.04 second search beam template period. Table 4.3.1 shows the locations of the ground points and their field intensities as measured by the field team, and as calculated by Raytheon and by RADC using the RFR computer program.

<table>
<thead>
<tr>
<th>Point</th>
<th>Azimuth</th>
<th>Elevation</th>
<th>Range</th>
<th>Raytheon</th>
<th>RADC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Degrees</td>
<td>Degrees</td>
<td>Feet</td>
<td>uw/cm²</td>
<td>uw/cm²</td>
</tr>
<tr>
<td>A</td>
<td>258</td>
<td>-2.03</td>
<td>1600</td>
<td>0.64</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>104</td>
<td>-2.68</td>
<td>1800</td>
<td>0.10</td>
<td>4.2</td>
</tr>
<tr>
<td>C</td>
<td>155</td>
<td>-0.75</td>
<td>3100</td>
<td>0.50</td>
<td>1.3</td>
</tr>
<tr>
<td>D</td>
<td>167</td>
<td>-0.01</td>
<td>3900</td>
<td>0.01</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The field measured values are 10 second averages; the RADC RFR computer program calculated values are 41.04 second averages. The Raytheon values are higher than the measured values; by 8.9 dB for point A, 16.2
dB for point B, 3 dB for point C and 21 dB for point D. The RADC calculated values vary either side of the measured values and differ from them by -1.0 dB for point A, +3.4 dB for point B, -3.4 dB for point C and +13.2 dB for point D. Since the geometries for points C and D are comparable, one would expect comparable intensities. A decimal error is suspected in the stated point D measured intensity; the measured value is more likely 0.10 instead of 0.01.

Figures 4.34 through 4.45 show the search fence individual beam short term intensities i.e., intensities averaged over a radar resource period (54 milliseconds). The maximum short term averages are low and are 6.6 microwatts/centimeter squared at point A, 1.22 microwatts/centimeter squared at point B, 4.8 microwatts/centimeter squared at point C and 5.12 microwatts/centimeter squared at point D. The variations are due to a combination of the factors of distance, off-boresight losses and beam sidelobe structures due to the varying frequencies of transmission.

Data similar to that in Figures 4.34 through 4.45 were also obtained for a surveillance fence but with a constant frequency of transmission (435 MHz) for the same search beam template period. The resulting maximum short term averages were 0.453 microwatts/centimeter at point A, 1.59 microwatts/centimeter squared at point B, 4.89 microwatts/centimeter squared at point C and 4.33 microwatts/centimeter squared at point D. The resulting 41.14 second search beam template averages are 0.453 microwatts/centimeter squared at point A, 0.239 microwatts/centimeter squared at point B, 0.245 microwatts/centimeter squared at point C and 0.231 microwatts/centimeter squared at point D. Relative to the varying frequency search beam template, the constant frequency beam template yields short term averages that are -1.6 dB at point A, +1.2 dB at point B, 0.08 dB at point C and -0.73 dB at point D; and long term (41.04
seconds) averages that are -0.47 dB at point A, -0.37 dB at point B, +0.29 dB at point C and +0.46 dB at point D. Relative to the varying search beam template the constant frequency beam template yields short term averages within roughly ±1.5 dB and long term averages (41.04 seconds) within +0.5 dB. Therefore, if one is concerned over the long term averages, the data for these geometries suggest that the simpler constant frequency search beam template be used for the calculation of intensity. Table 4.3.2 compares the measured (by Raytheon) midband frequency vertical and horizontal beamwidth data with the far field values calculated by the RADC RFR computer program.

<table>
<thead>
<tr>
<th>Beamwidth Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beamwidth</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Vertical Degrees</td>
</tr>
<tr>
<td>Horizontal Degrees</td>
</tr>
<tr>
<td>Measured</td>
</tr>
<tr>
<td>Calculated</td>
</tr>
<tr>
<td>Percent of Measured</td>
</tr>
</tbody>
</table>

The agreement between the measured and calculated data for the ground point densities and for the beamwidth is good.

4.4 Ground Hazard: The radar hazard fence is well placed with the result that the radiation levels at its periphery are very low and safe levels — below a milliwatt/centimeter squared. For the present baseline system, the highest power density levels are 0.183 milliwatts/centimeter squared on the linear portion of the fence and 0.069 milliwatts/centimeter squared on the arc segment of the fence. For the SIX DB system the highest power density levels are 0.56 milliwatts/centimeter squared on the linear portion of the fence and 0.15 milliwatts/centimeter squared on the arc segment of the fence. For
the ground points considered in the OTIS AFB vicinity, the calculations show that there is no hazard to personnel. For the worst case of a stationary beam, the densities are in the order of microwatts/centimeter squared. The power density values calculated by the RFR computer program agree with measured power density values within approximately 3.5 dB.
FIG. 4.1 HAZARD FENCE GEOMETRY

"A" = FACE A
"B" = FACE B
NOT TO SCALE
FIG. 4.2 HAZARD FENCE POINT DENSITY VS. BEAM POSITION

BASELINE SYSTEM

BEAM ELEVATION 3 DEG

AZIMUTH OFF-BORESIGHT DEGREES
FIG. 4.3 HAZARD FENCE POINT DENSITY
VS BEAM POSITION

SIX DB SYSTEM

BEAM ELEVATION 3 DEG

AZIMUTH OFF-BORESIGHT DEGREES
FIG 4.10 HAZARD FENCE DENSITY VS FENCE ANGLE
SIX DB SYSTEM - BEAM 0 DEG AZ 30 DEG E
FIG. 12. HAZARD FENCE DENSITY VS FENCE ANGLE

BIX DB SYSTEM - BEAM 20 DEG FZ 30 DEG EL

FENCE ANGLE IN DEGREES
FIG. 4. HAZARD FENCE DENSITY VS FENCE ANGLE
SIX DB SYSTEM - BEAM HP 300, AZ 30 Deg EL

FENCE ANGLE IN DEGREES

DENSITY IN HAZARD SQUARED
FIG. 4.20 HIGHWAY 25 POINT DENSITY

VS BEAM POSITION

BASELINE SYSTEM

BEAM ELEVATION 3 DEG

AZIMUTH OFF-BORESIGHT DEGREES
FIG. A.21: MIDCAPE C POINT DENSITY
VS BEAM POSITION

BASELINE SYSTEM

BEAM ELEVATION 3 DEG

MICROWATTS/KM SQUARED

AZIMUTH OFF-BORESIGHT DEGREES
FIG. A.4
6910Cape 5 Point Density
Vs Beam Position

Baseline System

Beam Elevation 3 deg

MICROWATT/C2 SQUARED

θ = 30

MUTH OFF-BORESIGHT DEGREES

10 20 30 40
FIG 4.7 MID-CAPE N POINT DENSITY
VS BEAM POSITION

BASELINE SYSTEM

BEAM ELEVATION 3 DEG

AZIMUTH OFF-BORESIGHT DEGREES
FIG. 25 SEGMORE BRIDGE POINT DENSITY VS BEAM POSITION

BASELINE SYSTEM

BEAM ELEVATION ±3 DEG

E90 MUTH OFF-BORESIGHT DEGREES
Fig 4.26 Smoke Stack Point Density vs Beam Position

Baseline System

Beam Elevation 3 deg

<table>
<thead>
<tr>
<th>Azimuth Off-BoreSight Degrees</th>
<th>20</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

-20 0 20 -50 200
FIG. 4.27 HIGHWAY 25 POINT DENSITY VS BEAM POSITION

SIX DB SYSTEM

BEAM ELEVATION 3 DEG

AZIMUTH OFF-BORESIGHT DEGREES

-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60

-20 -10 0 10
FIG. 4.29 MID:SNR PE 5 POINT DENSITY vs BEAM POSITION

SIX DB SYSTEM

BEAM ELEVATION 3 DEG

10 10

-10

3

-20

20 1 -30

10 30 30 40

AZIMUTH OFF-BORESIGHT DEGREES
FIG. 13 M10 CEPF N POINT DENSITY
VS BEAM POSITION
SIX DE SYSTEM
BEAM ELEVATION 3 DEG
AZIMUTH OFF-BORESIGHT DEGREES
FIG 4.15:

SHORE POINT DENSITY

VS BEAM POSITION

SIX DEG SYSTEM

BEAM ELEVATION 3 DEG

10 10

AZIMUTH OFF-BORESIGHT DEGREES

-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
FIG. 4.32 SAGEMORE BRIDGE POINT DENSITY
VS BEAM POSITION
SIX DB SYSTEM
BEAM ELEVATION 3 DEG

AZIMUTH OFF-BORESIGHT DEGREES
FIG 4.33 SMOKE STACK POINT DENSITY

VS BEAM POSITION

SIX DE SYSTEM

BEAM ELEVATION: 3 DEG

AZIMUTH OFF-BORESIGHT DEGREES
F1G. 1.38 SEARCH DENSITY

POINT RT
AZIMUTH 104 DEG
ELEVATION -2.63 DEG
RANGE 1800 FEET
FIG. 4.14 SEARCH DENSITY

POINT AT
AZIMUTH 167 DEG
ELEVATION - 01 DEG
RANGE 3900 FEET
FIG. 4.10 SEARCH DENSITY

POINT AT
AZIMUTH 167 DEG
ELEVATION -.01 DEG
RANGE 3900 FEET

DENSITY IN WORKED SQUARED

30 32 34 36 38 40
TIME IN SECONDS

110
5.0 Subarray Failures: This section addresses the question of the effect of subarray outages on the far field elevation pattern power density of the PAVE PAWS baseline radar. Of major interest is the lower elevation region and this is where the emphasis is placed.

5.1 Method: Elevation patterns were generated at a 4646 foot distance from the radar for a transmit radar beam at zero degrees azimuth with respect to boresight and three degrees elevation for multiple subarray total failures. The number of failed subarrays was varied from zero (to provide a reference) to a maximum of 28 subarrays. There are 36 subarrays in the baseline system. Some of the number of failures considered are extreme. It is unlikely that the PAVE PAWS radar would operate with more than 6 failed subarrays (failed in the transmit mode only) because of e.g., the one dB degradation alert to the operators and maintenance personnel when 6 or more subarrays fail on transmit. A failed subarray was considered totally failed on transmit in that a failed subarray did not radiate at all but could continue to receive. The frequency was held constant at 445 MHz. The failed subarrays were chosen rather arbitrarily in the upper half of the array, maintaining the same vertical array dimension except for the 28 subarray failure case where the vertical dimension shrunk in half. The upper half was chosen because of its expected greater impact on the lower elevation angle region.

5.2 Results: The odd numbered Figures 5.1 through 5.19 show the particular subarrays failed. The failed subarray area is shown encircled in heavy outline. Figure 5.1 shows the normal baseline array for the limiting case of no subarray failures i.e., for all 36 subarrays functioning normally on transmit. The even numbered Figures 5.2 through 5.20 show the resulting elevation patterns. Figure 5.2 shows the
transmit elevation pattern for the array of Figure 5.1. Table 5.1 summarizes the main effects of the subarray failures on the transmit elevation pattern.

5.3 Analysis: The subarray failures degrade the transmit elevation pattern by decreasing the main beam peak level, increasing sidelobe levels, changing the beamwidth and increasing the power density level at a ground point considered here to be at zero degrees azimuth with respect to radar boresight, at zero degrees elevation and at a distance of 4646 feet. See even numbered Figures 5.2 through 5.20 and Table 5.1. The situation portrayed by Figures 5.1 through 5.10 and by Table 5.1 entries above the horizontal line could exist operationally when the system degradation does not exceed the one dB criterion.

5.3.1 Beam Peak: The boresight beam peak level varies with the square of the ratio of the number of active subarrays to the normal baseline array complement of 56 active subarrays. The agreement is within 0.1 dB except for the case where the entire upper half of the array is failed and is not transmitting. For this case the agreement is still good and is within 0.3 dB. The disagreement is attributed to the fact that, as the subarrays fail, the transmit array spatial (and equivalent amplitude) taper is changing. For the extreme case of the 28 failed subarrays, the normally evenly symmetrical array taper in the vertical dimension becomes asymmetrical.

5.3.2 Sidelobe Level: As the number of failed subarrays rises, the sidelobe level also rises. The sidelobe level increases faster than the main beam level decreases. As a result, the difference between the main beam level and the sidelobe level decreases rapidly. This difference which is 21.4 dB for the full array becomes 20, 18.6, 16.1, 10.6, 9.7, 7.8 dB as 1, 2, 4, 12, 16, 20 subarrays fail, respectively. It should
be noted that even with 6 subarrays failed (which is within the one dB system degradation criterion) the sidelobe level is only approximately 14 dB below the peak of the main beam. The lower elevation angle sidelobes plotted on Figures 5.12 through 5.20 are usually higher than the upper elevation sidelobes for the same number of subarray failures by a small amount — under one dB.

5.3.3 **Beamwidth:** The beamwidth of the transmitted pattern changes with subarray failures. For the case of 6 subarray failures or less, the beamwidth decreases with the number of subarray failures. The decrease is slight — less than 5 percent of the normal (no failed subarrays) beamwidth. For the case of 12 subarray failures and more, the 1.9 degree beamwidth for 12 subarray failures shows a decrease from the normal beamwidth of almost 10 percent, with the 1.9 degree beamwidth increasing as more than 12 subarrays fail to beamwidths wider than the normal beamwidth. For the extreme case of 28 subarray failures, the array vertical dimension shrinks in half and the resulting beamwidth is 3.9 degrees. This beamwidth is not quite double the normal beamwidth since the effective array dimension does not remain constant. It should be noted that the beamwidth numbers of Table 5.1 cannot be readily quantitatively extrapolated for different scenarios of subarray failures. This is due to the fact the elevation beamwidth depends on the effective array height and taper in the vertical dimension for the same frequency. The height and taper depend on the array positions of the failed subarrays.

5.3.4 **Field Strength:** Table 5.1 also shows the field strengths that exist at a point at a distance of 4646 feet, zero degrees azimuth and elevation for the various cases of subarray failures. Note that these field strength values are for the spotlight beam cases. The PAVE PAWS
radar system has built-in safeguards against beam spotlighting. In operation with the moving surveillance fence beams, the spotlight beam would be reduced by the beam motion factor. This factor depends on the relative geometry of the field point with respect to the radar. It should be noted that with proper maintenance it is unlikely that more than 2 subarrays would fail and stay failed for more than a short time due to the subarray test which occurs every 30 seconds, due to the element test which is routinely done every day and which can be commanded at any time, due to the low transmit transistor failure rates and finally due to the radar modular construction which permits rapid replacement of a defective module with interruption of the radar operation.

5.4 Failure Effects: Subarray transmit failures degrade the normal transmit elevation beam by decreasing the beam peak level, increasing the sidelobe levels, changing the transmitted beamwidth and increasing the power densities for the cases examined in this section. See Table 5.1. The increase in sidelobe levels with increasing numbers of failed subarrays is rapid and results in rapid deterioration and decrease of the sidelobe levels with respect to the peak of the failed beam. Prolonged subarray transmit failures of more than 2 are unlikely if proper maintenance procedures are followed. For the case of 2 subarray failures, the decrease in this main beam peak is small (0.32 dB), the upper sidelobe level with respect to the failed beam is 18.6 dB which is worse (higher) than the desired level of 20 dB, the beamwidth slightly decreases from 2.1 to 2.07 degrees and the field density increases by almost 2.5 times the normal case for the particular point considered to 24 microwatts/centimeter squared -- a value still considerably below the OSHA standard.
<table>
<thead>
<tr>
<th>FAILED SUBARRAYS</th>
<th>BEAM PEAK</th>
<th>UPPER SIDELOBES</th>
<th>BEAMWIDTH</th>
<th>0° ELEVATION POINT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>dbm</td>
<td>dbm</td>
<td>db</td>
<td>degrees</td>
</tr>
<tr>
<td>0</td>
<td>6.03</td>
<td>-15.4</td>
<td>21.4</td>
<td>2.10</td>
</tr>
<tr>
<td>1</td>
<td>5.87</td>
<td>-14.17</td>
<td>20</td>
<td>2.09</td>
</tr>
<tr>
<td>2</td>
<td>5.71</td>
<td>-12.85</td>
<td>18.6</td>
<td>2.07</td>
</tr>
<tr>
<td>4</td>
<td>5.38</td>
<td>-10.72</td>
<td>16.1</td>
<td>2.03</td>
</tr>
<tr>
<td>6</td>
<td>5.04</td>
<td>-9</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>3.94</td>
<td>-6.64</td>
<td>10.6</td>
<td>1.90</td>
</tr>
<tr>
<td>16</td>
<td>3.11</td>
<td>-6.6</td>
<td>9.7</td>
<td>1.91</td>
</tr>
<tr>
<td>20</td>
<td>2.19</td>
<td>-5.56</td>
<td>7.8</td>
<td>1.95</td>
</tr>
<tr>
<td>24</td>
<td>1.17</td>
<td>*</td>
<td>*</td>
<td>2.24</td>
</tr>
<tr>
<td>28</td>
<td>0</td>
<td>*</td>
<td>*</td>
<td>3.9</td>
</tr>
</tbody>
</table>

* = sidelobe not defined.

Note 1: The situations portrayed above the horizontal line could exist operationally within the 1 db system degradation bound criterion. Prolonged failures of more than 2 subarrays are unlikely due to the subarray tests.
FIG. 5.2 BASELINE ELEVATION PATTERN

BEAM AT 0 DEG AZIMUTH

3 DEG ELEVATION

FREQUENCY 455 MHZ

DISTANCE 4646 FEET

INACTIVE SUBARRAYS

NONE

ELEVATION IN DEGREES
FIG. 5.4 BASELINE ELEVATION PATTERN

BEAM AT 0 DEG AZIMUTH
3 DEG ELEVATION
FT. '76 CEN 445 MHZ
DISTANCE 4849 FEET

INACTIVE SUBARRAYS
NR 22

ELEVATION IN DEGREES

LEVEL
-27
-40
-57
-70
-80
-90
FIG. 5.6 BASELINE ELEVATION PATTERN
BEAM AT 0 DEG AZ. MUTH
2 DEG ELEVATION
FREQUENCY 445 MHZ
DISTANCE 4646 FEET

INACTIVE SUBARRAYS
NR 22, NR 43

ELEVATION IN DEGREES

LEVEL

-67
FIG. 5.7 ARRAY WITH 4 FAILED SUBARRAYS
FIG. 5.8 BASELINE ELEVATION PATTERN

BEAM AT 0 DEG AZIMUTH

3 DEG ELEVATION

FREQUENCY 445 MZH

DISTANCE 4646 FEET

INACTIVE SUBARRAYS

NR 19 / NR 22 / NR 23 / NR 25

0 10 20 30 40 50

ELEVATION IN DEGREES
FIG 5.10 BASELINE ELEVATION PATTERN
BEAM AT 0 DEG AZIMUTH
3 DEG ELEVATION
FREQUENCY 445 MHZ
DISTANCE 4846 FEET
INACTIVE SUBARRAYS
NR 17, NR 19, NR 22
NR 23, NR 26, NR 28
ELEVATION IN DEGREES
Fig. 6.12 Baseline Elevation Pattern
12 inactive subarrays

Beam at 0 deg azimuth
3 deg elevation
Frequency 448 MHz
Distance 4646 feet

Elevation in degrees
FIG. 5.14  BASELINE ELEVATION PATTERN
16 INACTIVE SUBARRAYS

BEAM AT 0 DEG AZIMUTH
3 DEG ELEVATION

FREQUENCY 445 MHZ
DISTANCE 4548 FEET

ELEVATION IN DEGREES
FIG. 5.16  BASELINE ELEVATION PATTERN
20 INACTIVE SUBARRAYS

Beam at 0 deg Azimuth
7 deg Elevation
Frequency 4.5 MHz
Distance 4546 Feet

Elevation in Degrees
Fig. 5.13  Baseline Elevation Pattern
24 Inactive Subarrays

Beam at 0 deg azimut
3 deg elevation
Frequency 445 MHz
Distance 4846 feet

Elevation in degrees
FIG. 5.20 BASELINE ELEVATION PATTERN

28 INACTIVE SUBARRAYS

BEAM AT Z: DES 570 MTH
3 DEG ELEVATION
FREQUENCY WVE MTH
DISTANCE 4646 FEET

ELEVATION IN DEGREES
6.0 **Conclusions:** It is concluded that the radar frequency radiation (RFR) by the PAVE PAWS radar system does not present a radiation hazard to personnel provided that there is no entry to the hazard zones. These zones are the air hazard zone (section 3) and the ground hazard zone within the hazard fence (section 4). The air hazard zone as conservatively defined in this report is a zone extending over an azimuth sector of 240 degrees (120 degrees per radar face) with a radius of approximately 3035 feet for the present baseline system, 6140 feet for the SIX 08 system and 8710 feet for the 10DB system. Radiation levels calculated for various off-base ground points of interest are well below the OSHA standard of 10 milliwatts/centimeter squared and indicate no radiation hazard to personnel.

The RADC RFR computer program was verified by comparing the RFR computer program calculated values for four ground points with actual measured data obtained when the PAVE PAWS radar was operating in the surveillance fence mode. The agreement between the measured and calculated data is within plus or minus 3.5 dB. The disagreement may be due to multipath effects which were not considered in this report.

The RADC RFR computer program calculates the radiation levels in the near field, the transition region and the far field with no discontinuities between regions and offers a cost-effective method to determine radiation levels from a phased array radar especially in the near and transition regions. It is also useful in determining the effects of array anomalies such as partial array outages, steering phase errors and in determining the effect of changes in aperture taper.
References

15. NAS, Radiation Intensity of the PAVE PAWS Radar System, National Academy.
of Sciences, Washington D.C., 1979


Appendix A

Mutual Coupling

1.0 Introduction: The mutual coupling was determined on a partial array (320 elements) by exciting element (1,1) [see Figure A1] at the horizontal polarization H-port and measuring $C_{\text{HH}}$ the resulting coupling at the horizontal polarization H-port of an element $(m,n)$, and measuring $C_{\text{HV}}$ the resulting coupling at the vertical polarization V-port of an element $(m,n)$. This procedure was repeated for the vertical polarization port of the element (1,1).

2.0 Results: Figure A2 shows the magnitudes of $C_{\text{HH}}$ and $C_{\text{VV}}$ out to the element (1,29), i.e. the fourteenth neighbor element at 430 MHz. The $C_{\text{HH}}$ coupling is approximately minus 27 dB at the nearest neighbor and, in general, decreases with increasing distance. The cross-polarized coupling $C_{\text{HV}}$ is on the order of 13 dB lower than $C_{\text{HH}}$. Figure A3 shows the magnitudes of $C_{\text{VV}}$ and $C_{\text{HV}}$ out to element (1,29). The $C_{\text{VV}}$ coupling is approximately minus 30 dB at the neighbor element and, in general, also decreases with distance. The cross-polarized coupling $C_{\text{HV}}$ is on the order of 23 dB lower than $C_{\text{VV}}$. Table A1 shows the couplings from half of the first ring of elements closest to the center element, e., elements (1,3), (2,2), (-2,2) for 420 MHz the low end of the band and for 435 MHz the midband frequency. Table A2 shows the effect of frequency on the coupling from all the elements of the first ring of elements of the element (1,1) for the $C_{\text{VV}}$ and $C_{\text{HH}}$ couplings. As expected, the strongest degree of coupling exists at 420 MHz, the lowest frequency, and decreases monotonically with frequency. Table A3 shows the couplings from half of the second ring of elements, i.e., elements (1,5), (2,4), (3,3), (-3,3) and (3,1) at 420 MHz. Table A4 shows the second ring couplings at 435 MHz. Table A5 shows the resulting coupling
into the element (1,1) from the first ring of 6 elements, from the second ring of 12 elements, and from both of these two rings of elements for 420 and 435 MHz. The total coupling is low in the order of 12 dB for the $C_{VV}$ and $C_{HH}$ cases. The energy coupled into the antenna element will be partially absorbed by the element source impedance, partially reflected from the element source impedance and radiated depending on the element VSWR. The element highest VSWR over the total scan volume was measured as 2.1 at 450 MHz, the high edge of the band. This VSWR would reduce the coupled energy available for radiation by an element by about 14 dB.

3.0 Error: To bound the error in the field density calculation caused by neglecting the mutual coupling, let us assume that, since the actual antenna array is large (1792 elements), the edge elements partial coupling can be neglected and the coupling is the same for each element. Let us further assume that each element VSWR is 2.1. Then the antenna pattern

$$E = \sum_{n=1}^{N} \left( a_n e^{j\phi_n} + p a_n e^{j\phi_n} \right)$$

(A1)

where $N$ is the total number of elements
- $a_n$ is the amplitude at each element
- $\phi_n$ is the element phase
- $p$ is the element reflection coefficient magnitude of 0.35 for a VSWR of 2.1
- $a_c$ is the total coupling amplitude
- $\phi_c$ is the total coupling phase

Since the second term in equation (A1) is assumed to be the same for each element.
\[ E = \sum a \cdot e + Np_a e \]  

The error magnitude \( \text{er} \) in the field pattern calculation due to omitting mutual coupling coupling effect is

\[ \text{er} = \frac{Np_a}{\sum j\phi a \cdot e + \sum a \cdot e} \]  

For the boresight case and for unity excitations \( a \cdot e \)

\[ \text{er} = \frac{p_a}{|p_a e^{-j\phi} + 1|} \]  

Taking the worst case (420 MHz) highest value of minus 12 dB at an angle of 15.7 degrees for the coupling, the error is 0.074. The error in the field density calculation due to omitting the mutual coupling effect is negligible -- less than minus 22 dB or less than 0.6 percent on a power basis.
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**FREQUENCY 430 MHZ**
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-70

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TABLE A3--SECOND RING COUPLING AT 420 MHZ

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**TABLE A4---SECOND RING COUPLING AT 435 MHz**

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Appendix B

PAVE PAWS Face C Element Failure

1.0 Introduction: This section concerns itself with the effect of Face C element failures on the signal strength seen by Face C when illuminated by the Face C NFE (Near Field Element). Here, the term Face C element denotes the combination of the Face C antenna element and its corresponding SSM (Solid State Module). Failures considered included total element failures where the failed element provided no signal output at all and element single bit failures where the beam steering phase of 180, 90, 45, or 22.5 degrees was not provided when required.

2.0 Geometry: Figure B1 shows the Face C/NFE geometry used in this analysis. The NFE beam center is taken to point to the Face C array center. The dimensions are given in feet.

3.0 Method: The RADC RFR computer program was used to calculate the signal levels. The Face C array was amplitude tapered in accordance with Table B1.

Table B1  Face C Amplitude Taper

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<td>7,15</td>
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<td>9,13</td>
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<td>10,11,12</td>
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4.0 Results

4.1 Total Failures: Figures B2 through B6 show the effect of single element total outages in Face C on the signal level at the Face C output in this failed mode when illuminated by only a test signal from the Face C NFE. The failed element is identified by a number from 1 to 21 corresponding to the failed element position in the Face C array. Note that the failed 0 coordinate indicates indicates no failed element and is used to provide a reference. In Figure B2 this reference is with respect to the signal level existing at the Face C output for no element failures and no beam steering in azimuth. In Figures B3, B4, B5 and B6 this reference is with respect to the signal existing at the Face C output for no element failures and with the beam steered in azimuth to 7, 17, 37, and 57 degrees, respectively. For the case where the beam position is on the Face C boresight (zero degrees relative azimuth), the Face C signal level change is fairly insensitive to single total element failures and could not be used to identify the failed element on a maintenance oscilloscope or spectrum analyzer (assuming a one dB granularity). As the beam is steered off boresight, the signal level changes are more pronounced when an element fails. For the case where the beam is steered to 7 degrees (Figure B3) relative azimuth, the Face C signal level changes are greater than the boresight beam case and are within plus one dB and minus 2 dB, respectively. These amplitude changes can be measured and used to detect a failed element condition for some elements. Unfortunately, the failed element variable is not a single valued function of the signal level change throughout most of the range of the element variable. This together with the small changes in the signal level from neighboring element failures does not allow a unique identification of the failed element. For the case where the
beam is steered to 17 degrees (Figure B4) relative azimuth, the signal amplitude changes are large and are easily measured. But, again the failed element variable is not a single valued function for most of the failed elements. Again, a unique determination of the failed element is not possible for most of the elements. Where the function is single valued i.e. for failed element Number 12, the identification of this failed element is possible. Similar conclusions can be drawn for the cases where the beam is steered to 37 degrees relative azimuth (Figure B5) and 57 degrees relative azimuth (Figure B6). Figure B5 shows that for the failed elements 1 and 11 the failed element variable is a single valued function and would identify either of these failed elements. For the case where the beam is steered to 57 degrees relative azimuth (Figure B6) the failed element variable is single valued when element Number 11 fails. But, since the signal level change between failed element Number 11 and failed element Number 9 is 0.1 dB, it would be better to identify this failed element Number 11 by steering the beam to 37 degrees (Figure B5) where the relative signal level change between failed element Number 11 and failed element Number 8 is 0.86 dB.

4.2 Steering Bit Failures: Figures B7 through B10 show the effect on the signal strength at Face C when a steering bit failure occurs for various elements of the Face C array and for various bit failures. The steering bit failures considered here are those bit failures, occurring one at a time, that fail to provide the phase steering bit when it is required by a commanded azimuth. The signal level is referred to that existing for no bit failures at a particular beam. As evident from Figures B7 through B10, there are element bit failures which can be identified by measuring the Face C signal levels for various commanded beam azimuth positions.
4.3 **Far Field:** The Face C signal levels change sometimes rather drastically when element errors occur. Largely, this is due to the fact that these signal levels are a result of Face C illumination by the Face C NFE which is at more than minus 47 degrees below the Face C and is in the near field of Face C. The Face C NFE is at about $0.3 \frac{d}{\lambda}$ distance from the Face C array. Figures B11 and B12 depicting the near field azimuth pattern through the NFE for no failed element and element Number 1 totally failed clearly show the sidelobe region effect and the drastic change in Face C signal level as a result of sidelobe mobility due to element Number 1 failure even though this particular element has a severe 12.5 dB amplitude taper. Figures B13, B14, B15 and B16 compare the far field patterns for zero and 57 degrees azimuth and for no failures vs element totally failed. The changes in signal amplitude due to element Number 1 failures are slight for far field illumination, as expected.

5.0 **Conclusions:** It is concluded that injecting a known interference signal into Face C NFE test antenna provides some limited capability to identify totally Face C elements and Face C steering bit failures when a maintenance oscilloscope or spectum analyzer is used and when there is no external interference. This capability will be degraded when other external interference is present. This external interference usually varies in intensity and frequency.
Fig. B.1 FACE C/NFE GEOMETRY

FACE CENTER AT (0, 0.785)
NFE CENTER AT (0, 48.253)

NOT TO SCALE
FIG. 53   FACE C ELEMENT FAILURE = 7 DEG AZ MUTH BEAM
FIG. B5  FACE ELEMENT FAILURE - 37 DEG. AZIMUTH BERM

FAILED ELEMENT
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- 5 FAILED ELEMENT NUMBER

- 10
<table>
<thead>
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<th>FIG. 89</th>
<th>FACE C STEERING BIT FAILURES</th>
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</thead>
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<tr>
<td>30</td>
<td>37 DEG BEAM AZIMUTH</td>
</tr>
<tr>
<td></td>
<td>X 180 DEG BIT</td>
</tr>
<tr>
<td>40</td>
<td>Y 90 DEG BIT</td>
</tr>
<tr>
<td>50</td>
<td>O 45 DEG BIT</td>
</tr>
<tr>
<td>60</td>
<td>X 22.5 DEG BIT</td>
</tr>
</tbody>
</table>

- Failed Element Number

- L
FIG. B10  FACE C STEERING BIT FAILURES

<table>
<thead>
<tr>
<th>57 DEG BEAM AZIMUTH</th>
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</thead>
<tbody>
<tr>
<td>180 DEG BIT</td>
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<tr>
<td>90 DEG BIT</td>
</tr>
<tr>
<td>45 DEG BIT</td>
</tr>
<tr>
<td>22.5 DEG BIT</td>
</tr>
</tbody>
</table>

Failed Element Number

-10
FIG. 8.3  FACE C AZIMUTH PATTERN

0 DEG AZ  435 MHZ  2000 FEET
FIG. 8-14  FACE C AZIMUTH PATTERN
0 DEG. AZ  435 MHZ  2000 FEET

SIGNAL IN DB
0  20  40

AZIMUTH IN DEGREES
-75  -60  -45  -30  -15  0  15  30  45  60  75

NOTE: ELEMENT FAILING

AW. L. 1978
FIG 8.15
FACE C AZIMUTH PATTERN
87 DEG 47 475 MHZ 2000 FEET

NO ELEMENT FAILED

AZIMUTH IN DEGREES