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THE TERRAIN SHIELDING ALGORITHM USED IN THE MASR AIRBORNE SURVE--ETC(U)

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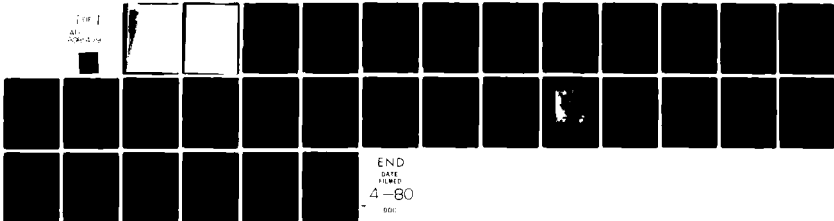
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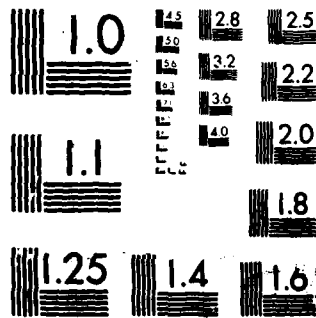
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THE TERRAIN SHIELDING ALGORITHM USED IN THE MASR  
AIRBORNE SURVEILLANCE RADAR PROGRAM

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Group 46

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ABSTRACT

The Terrain Shielding Algorithm

Used in The MASR Airborne Surveillance Radar Program

The algorithm described herein quickly determines if a point on the surface of the earth is visible or not from a remote aircraft due to masking by nearby terrain features. It was designed to work in an airborne radar surveillance system, updating a 16 x 16 km area every 4 seconds with a resolution of 250 x 250 m.

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## I. INTRODUCTION

The MASR<sup>1</sup> was an agile beam standoff airborne surveillance radar (ASR) system that used a wide-band data link to send target reports to a Ground Processing Center (GPC)<sup>2</sup> for tracking and display. Typically, the MASR would be flying at an altitude of 10,000 feet 30 km from the target and would be examining several independent 2 x 2 km Areas of Interest (AOI) that could be placed anywhere inside a fixed 16 x 16 km area by using an interactive graphics display

In such a situation, it is desirable to know whether the AOI's are visible from the aircraft so that one would not waste the ASR's resources examining shielded areas, and to optimize the flight path in the mission planning stage, or to anticipate track dropouts and/or how long a track will coast. An AOI can become invisible because it is in a valley, or an intervening mountain masks it, or it is shielded by trees, foliage, buildings, etc.

In order to calculate the terrain shielding, one must have a hipsographic data base. Fortunately, we were able to obtain from the Defense Mapping Agency's Topographic Center in Washington, DC, a magnetic tape containing the elevation of Eastern Massachusetts for an array of points spaced 63.5 meters apart. These data include only the hipsographic (elevation) data, nothing for trees or cultural details, but these could be added to the data base if desired. Appendix 1 describes in more detail the character of this hipsographic data base.

Since the aircraft is moving, the terrain that is shielded changes as the aspect from the aircraft changes, consequently, a real-time computation of this effect is required. With the MASR aircraft flying at speeds of about 100 knots over Central Massachusetts, the terrain that is shielded remains essentially constant for a few tens of seconds using an elemental area (or precision) of 250 x 250 m. This time constant would be less for more mountainous terrain, greater for flatter terrain.

One of the functions of the GPC was to provide this terrain shielding information in real time. This was done by devoting a background task to this job. The GPC, using a Fortran task in a DEC PDP 11/70 computer, was able to refresh a 16 x 16 km display in 4 seconds\* with 250 m resolution. Since this was fast enough for the MASR requirements, no effort was spent trying to speed up the program by writing it in machine language etc.

The resolution and/or the total area could have been increased at the expense of more storage for the hipsographic data. The PDP 11, being a 16 bit computer with 32 k words of address space, is hard pressed to increase the core resident hipsographic data beyond the 16 k words that were used. A larger hipsographic data base could be stored on a disk and selective portions read in as required, but this would complicate the program and slow it down so it would not be suitable for our real time application. A 32 bit computer would ameliorate this problem.

## II. ALGORITHMS

### A. Basic Algorithms

The basic algorithm is a ray tracking approach developed by RADC<sup>3</sup>. It starts with a point on the surface of the earth and constructs a straight line (ray) to the aircraft. The program "moves up" this ray in constant increments (200 meters)\*\*. At each increment, the ray altitude is computed and compared with altitude of the surface directly beneath it. If the surface altitude exceeds the ray's altitude, the initial point is considered blocked. If not, the next point up the ray is examined, etc., until the ray becomes higher than the highest point in the hipsographic data base. In this case, the initial point is considered to be in the clear. The program then moves along the earth's surface a constant increment (250 meters)\*\* to start a new initial point and the process is repeated. When the entire AOI has been scanned, 250 meters at a time, the algorithm terminates.

---

\*The time required is directly proportional to the area and inversely proportional to the square of the resolution.

\*\*These constants were chosen to be commensurate with the resolution of the hipsographic data base.

### B. RADC Implementation

The code that RADC developed to implement this algorithm started with geodetic spherical coordinates (longitude, latitude, altitude above mean sea level -  $\lambda$ ,  $\theta$ ,  $h$ ) for the aircraft and first surface point. These would be converted to a geocentric rectangular coordinate system ( $x$ ,  $y$ ,  $z$  from the center of the earth) so that the ray and increments along the ray are trivial to calculate. For each increment up the ray, the  $x$ ,  $y$ ,  $z$  position would be converted to  $\lambda$ ,  $\theta$ ,  $h$  and the resultant "h" would be compared first to the maximum, then to the surface altitude. This second coordinate conversion was necessary because the hipsographic data were stored as of function of  $\lambda$ ,  $\theta$ .

After the ray is shown to be blocked or in the clear, the next surface point ( $\lambda$ ,  $\theta$ ) is found (by adding a constant  $\Delta\lambda$  and  $\Delta\theta$  converted to  $x$ ,  $y$ ,  $z$  and the process repeated until the desired areas has been scanned. The two conversions from  $\lambda$ ,  $\theta$  to  $x$   $y$   $z$  and back again  $\lambda$ ,  $\theta$ , were done to take the curvature to the earth into account.

4096 surface points are required to scan 16 x 16 km with a precision of 250 meters; each surface point required one conversion from spherical to rectangular coordinates and generated one ray. On the average, there might be 10 increments along each ray to be examined, so some  $4 \times 10^4$  conversions from rectangular to spherical coordinates were required in all.

The conversion from rectangular to spherical coordinates (requiring at least 2 arc tangents and 2 square roots) is clearly the limiting factor in this implementation for any real time application.

### C. MASR Implementation

The MASR Implementation of the terrain shielding algorithm substitutes for the coordinate conversion an expression that is much faster to calculate. In addition, it not only stays in one coordinate system for all the terrain shielding calculations, but keeps it throughout all aspects of the MASR software. The output display showing roads, political boundaries, etc., the position of the aircraft and its flight path, and the targets and beam prints were all shown on the same projection.

The obvious choice for this projection is a gnomonic projection to a plane tangent to the earth at the center of the 16 x 16 km area. The chief attribute of this projection is that all straight lines are great circles and vice versa, so that one can follow the path a radio wave takes by adding a constant  $\Delta x$ ,  $\Delta y$  to the starting point.

The gnomonic projection\* obviates the need for back and forth coordinate conversions for the calculations involving positions on the ray in the x-y plane. However, the curvature of the earth introduces a complication in determining the height of the ray above mean sea level. Figure II.1 shows a plane passing through the aircraft, center of the earth, and the starting point of the ray on the ground. From the law of cosines:

$$(a + r)^2 = d^2 + (r + h_0)^2 - 2d(r + h_0) \cos \alpha$$

$$(h + r)^2 = y^2 + (r + h_0)^2 - 2y(r + h_0) \cos \alpha$$

where:  $a$  is the altitude of the aircraft;

$h_0$  is the altitude of the terrain at the rays starting point;

$h$  is the altitude of the ray a distance of  $y$  from the starting point;

$d$  is the distance along the ray from the aircraft to the starting point;

$\alpha$  is the angle APO;

$r$  is the local radius of the earth.

---

\*For small enough areas, where the difference between projection is less than the precision of the hipsographic data one can use a projection that is more convenient from other respects. In MASR, for example, the largest area of concern for terrain shielding was 16 x 16 km and the hipsographic precision (quantization) was 125 meters. Consequently, we used a modified cylindrical equal-spaced projection (linear in latitude and longitude) since the output of the program that converted distance and angle from the aircraft to ground coordinates was latitude and longitude.<sup>4</sup> If the output were in rectangular cartesian coordinates, one would use an orthographic projection, or if military use demanded, one could use Universal Transverse Mercator.

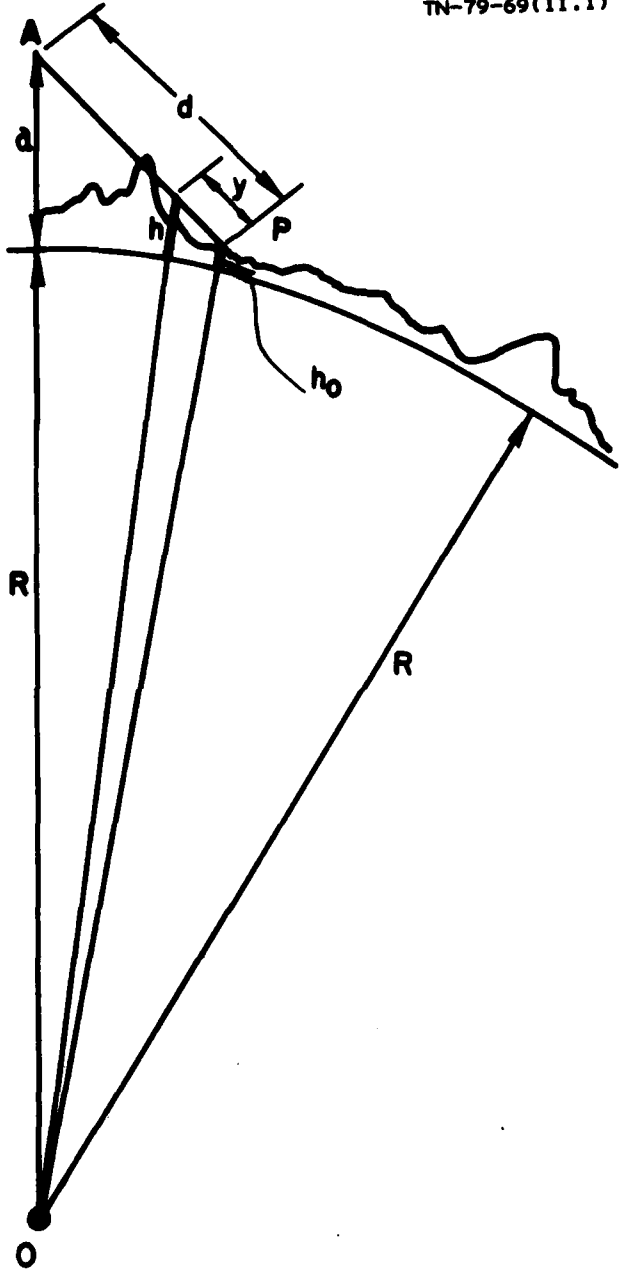


Fig. II-1. Terrain geometry.

Simplifying, this becomes:

$$(h + r)^2 = y^2 + (r + h_o)^2 + Ay$$

where:

$$A = \frac{(a + r)^2 - d^2 - (r + h_o)^2}{d}$$

Solving for h, we have:

$$\begin{aligned} h &= -r + \sqrt{(r + h_o)^2 + y^2 + Ay} \\ &= -r + h_o + 1/2 \frac{y^2 + Ay}{r + h_o} + O\left(\frac{1}{r^3}\right) \end{aligned}$$

Dropping the last term causes error less than 1 foot, so we have:

$$h = h_o + \frac{y^2 + Ay}{2(r + h_o)}$$

As y goes from 0 to d, h goes quadratically from  $h_o$  to a. If the ray's starting point is beyond the horizon ( $\alpha < 90^\circ$ ),  $A < 0$  and h will start off decreasing as we move up along the ray. Such a point will be blocked unless the terrain altitude falls off at a greater slope.

An approximate correction for the curvature of the ray due to refraction can be made by making r larger than the actual earth's radius by a factor of 1.0 to 1.5 depending on the actual index of refraction (4/3 is a very good nominal value to use). More accurate corrections for refraction or the ellipticity of the earth are not worthwhile because the hipsographic data base is so coarsely quantized.

In effect, we have replaced the conversion from rectangular to spherical coordinates by the much simpler quadratic expression given above.

#### D. Other Implementations

The other two methods of implementing terrain shielding will be briefly discussed. Neither of these methods was used in the MASR experiments.

### 1. Perspective Projection

This algorithm<sup>5,6</sup> constructs a continuous three dimensional function from the hipsographic data which is viewed from the aspect of the aircraft. A hidden line algorithm marks the area that is shielded. In addition to giving a visible-invisible plot, this method also gives a perspective projection of the topographic data, which might be very useful in the mission planning stages. Reference 7 gives a detailed discussion of this method.

### 2. Fixed Scenes

This scheme uses one of the above methods to generate shadow plots for several candidate aircraft positions. These plots are discretely switched as the aircraft moves about. This method is satisfactory for fixed flight paths and/or not too hilly terrain. Potentially, this is the fastest method for real time use from a computational point of view (presumably a library of fixed scenes would be prepared and stored on a disk and a simple look up algorithm based on the aircraft's location would requisition the closest one), but it lacks generality and is not an aesthetically satisfactory solution.

## III. THE TERRAIN SHIELDING PROGRAM

A tutorial version of the terrain sheilding program has been prepared with the interactive graphics display removed so that only the essentials remain. A flow chart of this program is shown in Figure III.1. A complete listing is given in Appendix 2. All that is required to make it a working program on any installation is to have a subroutine to fill up the MAP array with the hipsographic data in the format described in Appendix 1. This would go in place of statements 0029 to 0031.

The innermost loop (statements 0071 to 0080) is the area where the program spends most of its time, so the code has been arranged to try to speed up the calculations in this area. That is why there is an "odd" system of units used -- height in contour intervals, and distance in units of the scope display instead of meters or feet.

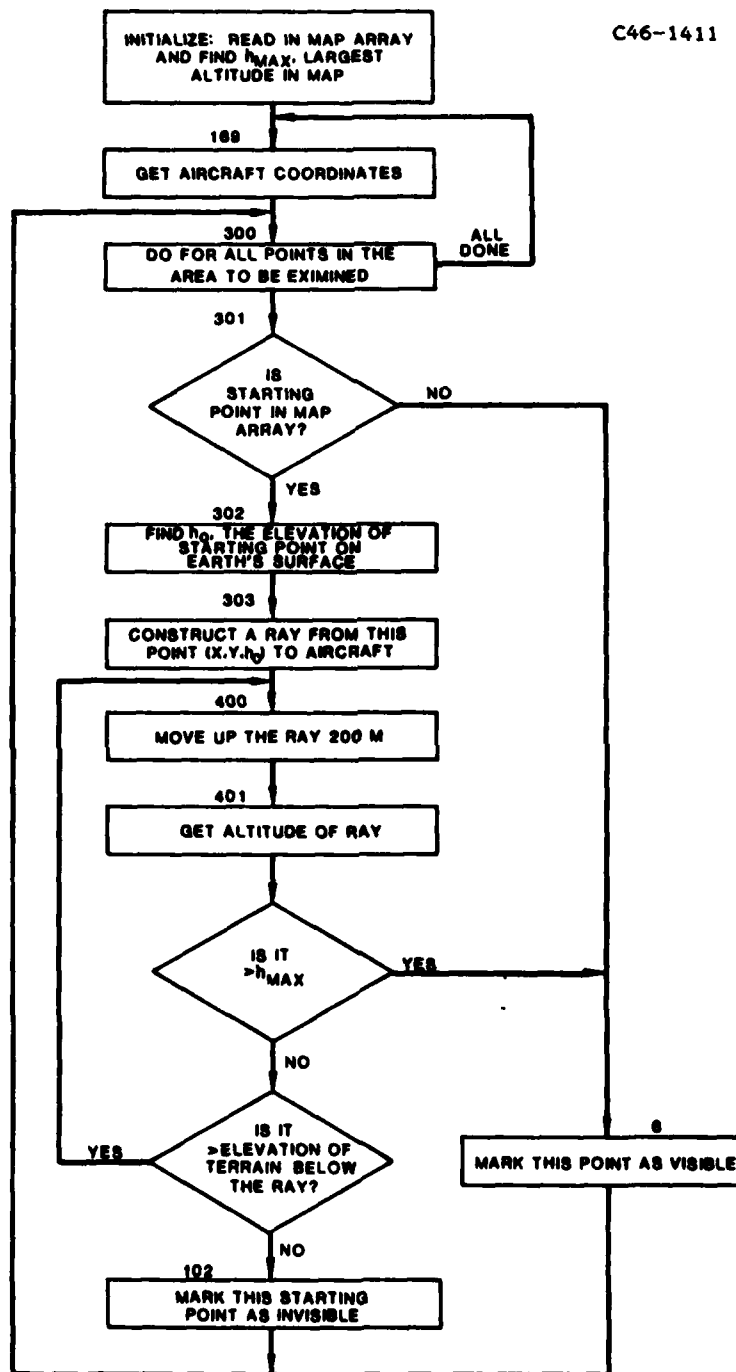


Fig. III-1. : Flow chart.

Two examples of the output of this program are shown in Figures III.2 and III.3. Both figures show the terrain that is shielded (as an asterisk) from an aircraft 50 km due east of the center with a depression angle of 2.3°. The resolution is 250 m in Figure III.2 and 125 km in Figure III.3. The center of the figure corresponds to 42° 30' N, 71° 37.5' W. West is up, north is the right due to the way the scanning raster was set up in the program.

In Figure III.4 the aircraft has been moved 1 km north of its position in Figure III.3. This position is where the MASR aircraft would be 16 seconds later if flying at 120 knots. Sixteen seconds is the time it takes the program to completely calculate the shadowing with 125 meters resolution. A close examination of these two figures reveals essentially no difference showing that this program runs fast enough for real time application to the MASR aircraft in the Eastern Massachusetts environment. This satisfactory situation is made even better (by a factor of 4) when 250 meters resolution is used.

If this program is run with a "Ø" as the logical unit for the output device, there will be no shadow map generated. The program was used in this manner to generate the data shown in Figure III.5 which is an average of the percentage visible from an aircraft flying in the four cardinal directions from the center.

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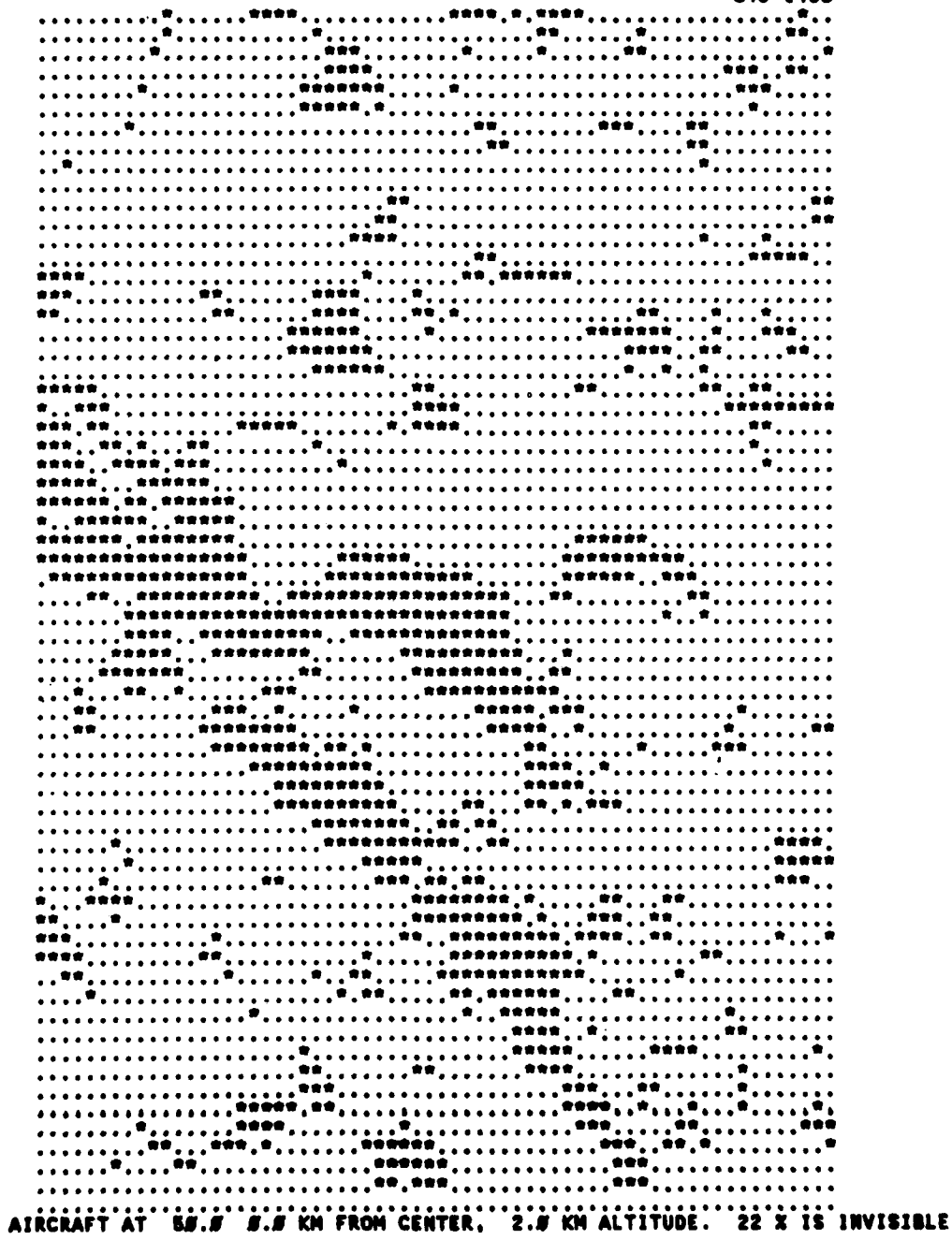


Fig. III-2. 250 m resolution.



Fig. III-3. Same as Fig. III-2 except resolution is 125 m.



Fig. III-4. Same as Fig. III-3, with aircraft moved 1 km.

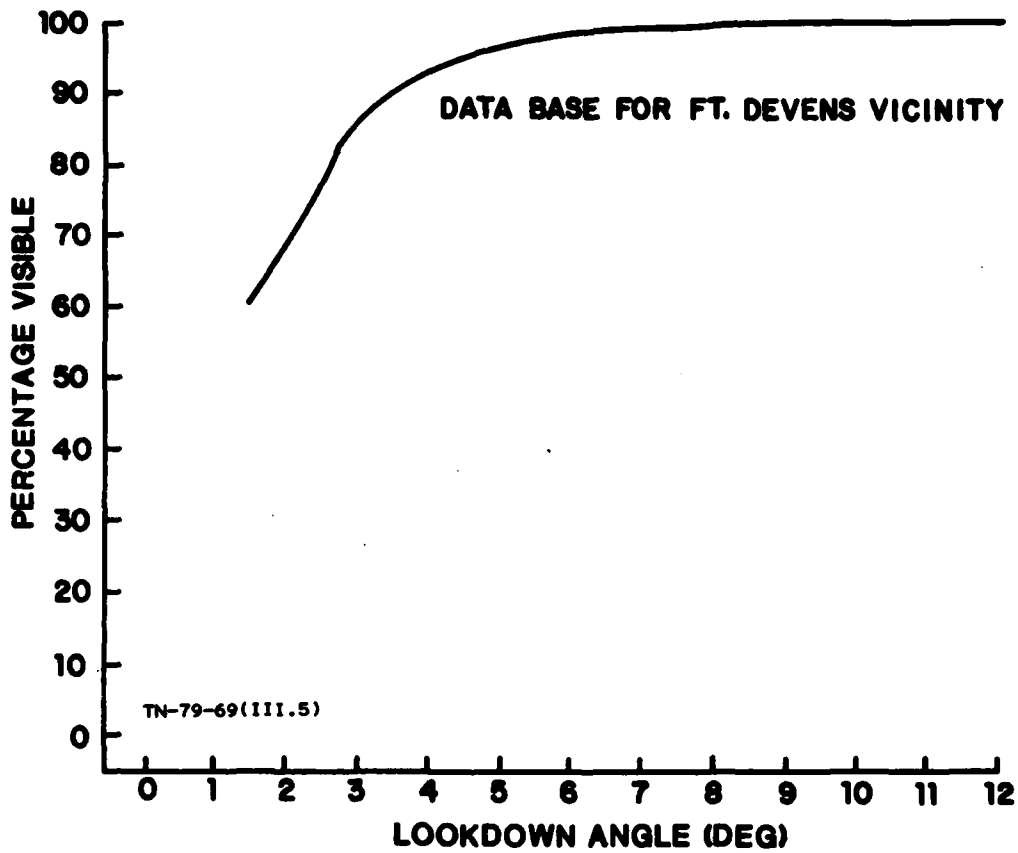


Fig. III-5. Terrain shielded vs. lookdown angle.

## APPENDIX 1

### Hypsographic Data Base

The Defense Mapping Agency has transformations of elevation information from maps or photos to x, y, z digital coordinates available on 1/2 inch magnetic tape. Approximately two 2400 ft reels of tape are required to record the elevation data corresponding to one 1:250,000 scale topographic map (ten thousand elevation points are produced per square inch).

The elevation data are derived from topographic maps by manually tracing contour lines on a Digital Graphics Recorder (DGR) which digitizes points at which the contour line crosses superimposed grid lines. The grid system is an integral part of the DGR and consists of lines etched on a glass plate at intervals of 0.01 inch in both x and y axes. The result of the DGR operation is a series of coordinates which define a contour line. After arranging the data into an x-y sequence, the next step is known as the Planar process, a name derived from the basic procedure which uses points on contour lines to define a plane on which the elevation of a point between contours must fall. The end result is an elevation at each 0.01-inch grid point from edge to edge of the source map.

The resolution of the elevation data has an absolute and a relative aspect. The resolution of the device which converts line (graphics) information to digital forms is 0.01 absolute inch. The resolution of the "absolute" information is relative to the scale of the source map. For example, a digital record of the elevations obtained from a 1:250,000 scale map would have an absolute resolution of 0.01 inch which is a relative resolution of about 63.5 meters on the ground because of the source map scale. The accuracy of the elevation data is purely relative to the accuracy of the source. Data obtained from a Class A 1:250,000 scale topographic map are neither more nor less accurate than the data which could be obtained by careful scaling and interpretation of the reproduction material which has not been distorted by the printing process. Also, the computer process which interpolates the normal contours on a topographic map to produce a matrix of equally spaced elevations is more consistent than a manual process.

The elevation data are organized in an x-y matrix with only the elevation value, z recorded. The x and y coordinates are implied by the position of the z within the record. The relation of the x-y coordinates to geographic position is included in the file for each map sheet. The horizontal and vertical datums are the same as those on the source map.

The first step in using these data is to convert the data from x-y coordinates to latitude-longitude. This was done by using the two expressions:

$$\theta = a + bx + cy + dxy$$

$$\lambda = e + fx + gy + hxy$$

These expressions account for the skew in the original topographic map (a Transverse Mercator projection for the Boston map).

The first file on the tape contains the x-y coordinates and corresponding latitude and longitude for the four corners of the area that is digitized on the tape (a 1° by 1° region). These can be substituted in the above equations to give 8 equations with 8 unknowns, a through h. These can easily be solved. For the western half of the Boston map, these constants were:

$$a = 41.98486136$$

$$b = 3.062634379 \times 10^{-6}$$

$$c = 5.710621830 \times 10^{-4}$$

$$d = 2,848018909 \times 10^{-11}$$

$$e = -72.07252640$$

$$f = 7.660974315 \times 10^{-4}$$

$$g = -1.002041361 \times 10^{-5}$$

$$h = 7.157438295 \times 10^{-9}$$

The second step is to get the desired data off the tape that covers the area of interest. These data can be converted from x-y to  $\lambda$ - $\theta$  by the above relations.

The third step is to convert these data back into an x'-y' using the projection that the terrain shielding algorithm is to use - e.g., Gnostic.

Lastly, these data are scaled to be the desired resolution (in the MASR experiment, every other point was decimated to give 125 meters resolution - a compromise between the storage requirements and execution time vs. precision) and put in a two dimensional Fortran array MAP (I,J) where MAP (0,0) is the southwest corner's elevation, MAP (NMAP,0) is the northwest corner's elevation (MAP(NMAP, NMAP) is the dimension of the array MAP).

In the MASR program, this array was written onto the disk and a special subroutine (using QIO) was used to retrieve it directly and quickly without going through the DEC disk files management software.

Figure A.1 shows the output of the Hipsographic data base for 20 x 20 km centered on 42°30'N, 71°41.25'W. The density becomes darker as the terrain altitude exceeds three fixed thresholds. This figure illustrates the type of terrain used to generate the data for this report. The altitude varied from 200 to 600 ft for the MASR AOI.

Although the data base contains no foliage information, provision was made in the program to include a very rough correction for the effect of foliage. The approximation was that all trees are a constant height<sup>\*</sup>, and uniformly surround every ray-starting point. In other words, the starting altitude is decreased by the height of the trees (line 0059 in Appendix 2).

For the MASR AOI, a densely forested area, this approximation was fairly good except for points on an interstate highway when the aircraft was directly in line with the road. Unfortunately, this was the situation that existed in the MASR experiments, so this feature was not used.

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\* An input parameter (line 0024 in Appendix 2). The value "0" was used for the MASR experiments.

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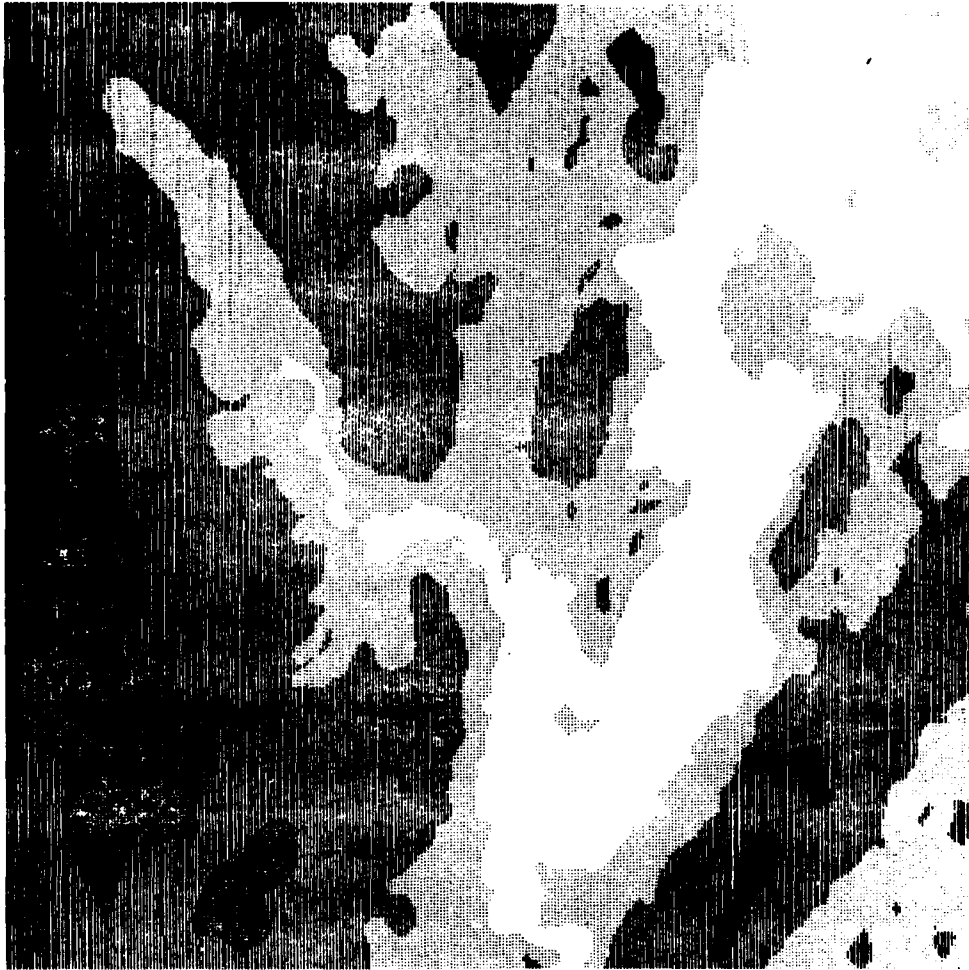


Fig. A-1. Elevation data for 20 x 20 km centered on  $42^{\circ} 30'N$ ,  $71^{\circ} 41.25'W$ . Density changes at 295 ft. 390 ft. and 580 ft.

APPENDIX 2

Program Listing



```

C      IF LUN=0, NO "SHADOW MAP" IS PRODUCED
C
C      DETERMINE RESOLUTION TO BE USED
CANT BE ANY FINER THAN THE INPUT HIPSOGRAHIC DATA BASE
0014 1 TYPE *, ' AND RESOLUTION TO BE USED (1=125 OR 2=250 METERS)'
0015 ACCEPT *, JRES
0016 IF (JRES.LE.0.OR.JRES.GT.2) GO TO 1
0017 RES=125.0*JRES
C
0018 IX1=-1024
0019 IV1=-1024      IDO ENTIRE 16X16 KM ARRAY TOO
C
0020 XINTVL=RES/SUTOM      I=32 OR 16
0021 IDEI=XINTVL      ISCAN INCREMENT IN SCOPE UNITS
0022 NINV=120/JRES      INO OF POINTS TO EXAMINE EACH SCAN (64 OR 128)
C      AND ALSO THE NO OF SCANS AS WE ARE DOING A SQUARE ARRAY
C
0023 CONTUR = 0.3048
0024 TREE = 0. / CONTUR
C      USE 0 METERS FOR TREE HEIGHT
0025 UMAP=SIZMAP/NMAP I=125
0026 XMAPS = SUTOM / UMAP      I=1/16
0027 RAYINC=200.
0028 RINCSU=RAYINC/SUTOM      I=25.6
C
C
C      READ IN MAP ARRAY DATA FROM DISK FILE
C
0029 BLKL4 DISC ADDRESS OF HIPSOGRAHIC DATA
C      BLKL4="056730
0030 MPBYTS NO OF BYTES OF HIPSO DATA ON THE DISC
0031 MPBYTS=32768
C      CALL UDMAP(MAP,MPBYTS,BLKL4,IER)
C
C
C      FIND MAXIMUM HEIGHT OF TERRAIN IN MAP ARRAY
C
0032 HMAX = 0
0033 DO 10 J = 1,NMAP
0034 DO 10 I = 1,NMAP
0035 IF (MAP(J,I) .GT. HMAX) HMAX = MAP(J,I)
0036 10 CONTINUE
0037 TYPE *, ' MAX HEIGHT IN MAP ARRAY IS:',HMAX,MPBYTS,BLKL4,IER
C
C
C      /***** OUTER PROGRAM LOOP *****/
C      DO ONCE FOR EACH 16 BY 16 KM AREA
C
0038 169 TYPE *, ' INPUT A/C X,Y,ALT (IN UNITS OF KM FROM ALPHA,BETA)'
0039 ACCEPT *, XACM,YACM,ZACM
0040 XAC=XACM*1000.0/SUTOM      ICONVERT TO SCOPE UNITS
0041 YAC=YACM*1000.0/SUTOM
0042 ZAC=ZACM*1000.0      ICONVERT ALTITUDE TO METERS
C
C      INITIALIZE STARTING COORDINATES OF SCAN TO LOWER LEFT CORNER

```

```

0043      IX=IX1-IDEL
C
0044      INVIS=0
C
C      THIS IS THE MAIN PROGRAM LOOP WHICH ITERATES ON THE NUMBER
C      OF VERTICAL SCANS (ROADS) THAT ARE TO BE SEARCHED
C
C
0045      DO 8 NRD=1,NINV
300      GET STARTING COORDINATES FOR BOTTOM OF NEXT SCAN
C      IX=IX+IDEL
0046      IY=IY1
0047      DO 87 JK=1,65  ICLEAR COLUMNS 1 TO 130 IN MARK ARRAY
0048      IMARK(JK)="20040"      IWITH ASCII SPACES
0049      87
C
C      THIS IS THE MIDDLE LOOP WHICH ITERATES ON THE NUMBER OF POINTS
C      ALONG THE GIVEN ROAD THAT ARE TO BE SIGHTED BY THE AIRCRAFT
C
C
0050      DO 7 ITSUM=3,NINV+2
C
C      CONVERT IX,IY INTO UNITS OF MAP MATRIX, AND GET HEIGHT OF ROAD AT
C      THIS POINT IN CONTOUR UNITS
C
0051      301  X1=(IX+1024)*XMAPS+1.5
0052      IXM=X1
0053      Y1=(IY+1024)*XMAPS+1.5
0054      IYM=Y1
C      CHECK TO SEE IF STARTING POINT IS IN MAP ARRAY
C      ASSUME VISIBILITY IF NOT
0055      IF(IXM.LE.0.OR.IXM.GT.NMAP) GO TO 6
0056      IF(IYM.LE.0.OR.IYM.GT.NMAP) GO TO 6
C
0057      302  HO=MAP(IXM,IYM)
0058      RA = RE + HO*CONTUR
0059      HO = HO - TREE
C
C      COMPUTE DISTANCE FROM A/C TO POINT ON GROUND IN SCOPE UNITS
C
0060      303  DX=XAC-IX
0061      DY=YAC-IY
0062      DIST=SQRT(DX*DX+DY*DY)
0063      IF(DIST.LE.0.0) GO TO 6  IAVOID DIVIDE BY 0 WHEN A/C IS OVER THE POINT
C
C      GET INCREMENTS (DX,DY) IN MAP UNITS TO FOLLOW RAY FROM GROUND TO A/C
0064      PORT=XMAPS*RINCSU/DIST
0065      DX=DX*PORT
0066      DY=DY*PORT
C
C      CONVERT DISTANCE TO METERS FROM SCOPE UNITS
C
0067      DIST = DIST * SUTOM
C
C      RA2 AND A ARE FUDGE FACTORS USED TO TAKE INTO ACCOUNT
C      THE FACT THAT THE EARTH IS SPHERICAL
C      RA2 IS IN METERS**2/CONTUR UNIT
C      A IS IN METERS

```



```

      C
0092      IF(LUN.EQ.0) TYPE 236,HVIS,YACN,YACH,ZACH
0093      236      FORMAT (15,' PERCENT IS INVISIBLE AT:',F10.1)
0094      IF(LUN.NE.0) WRITE(LUN,235) YACH,YACH,YACN,HVIS
0095      235      1      FORMAT(' AIRCRAFT AT ',F5.1,' KM FROM CENTER,',F5.1,
      ' KM ALTITUDE.',14,' % IS INVISIBLE')
      C
0096      GO TO 169
      C
      C
      C
0097      END
```



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## GLOSSARY

AOI	Area of Interest
ASR	Airborne Surveillance Radar
DEC	Digital Equipment Corporation
DGR	Digital Graphics Recorder
GPC	Ground Processing Center for the MASR Program
MASR	Multiple Antenna Surveillance Radar
PDP	Programmed Data Processor
QIO	Queued Input Output
RADC	Rome Air Development Center

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The algorithm described herein quickly determines if a point on the surface of the earth is visible or not from a remote aircraft due to masking by nearby terrain features. It was designed to work in an airborne radar surveillance system, updating a 16 x 16 km area every 4 seconds with a resolution of 250 x 250 m.		

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