The Multiray Model.

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This paper describes an multipath microwave distribution computer program. The program demonstrates that most power in the indoor radio environment is due to reflections. The program demonstrates that indoor cellular distribution systems will be fractal with limiting dimension 1/4 wavelength. Fast handoff algorithms will be needed to make effective use of this. The program is written in C and runs on a Silicon Graphics Personal Iris 4D25T with RGB videolink 1400AX. Hardcopy was produced using a Digital LJ250 (a modified Hewlett Packard Paint Jet Printer). Computation takes 75 seconds for 63 rays with 4 transmitting antenna and 5589 receive antenna.

Through the looking-glass.

The indoor radio environment can not be understood without considering reflections. With good insight it will then be possible to design distribution and diversity systems that more than compete with wired LAN's.

It is known that the indoor radio channel tends toward Rayliegh[1] fading with spatial correlation less than one wavelength. It follows that the coverage areas of a multiantenna distribution system will be fractal with minimum scale a fraction of a wavelength, not some pattern of squares or hexagons. This can be demonstrated by computer simulation for some simple room geometries.

Brute force ray tracing can be used to calculate field intensity and though that may be the only method that will work for complex rooms, there is another approach. Think of a kaleidoscope with its repeated folded images. At microwave frequencies walls, ceilings, and floors form mirrors (sometimes dirty ones). Imagine standing in a mirrored rectangular room: You will see through the looking glass into endless other rooms. (Imagine that the floor and ceiling are also mirrors!)

Brute force ray tracing works backwards from reality. Rays are sent out in all directions from the receiver, keeping track of distance and reflection loss, until they hit a source (Assuming they ever hit a source!). The product of loss times source intensity gives the intensity in each direction. Finding total level at one receiver location requires the vector sum of all directions. Finding the signal level at all possible receiver locations in the room requires too many calculations. The method is not efficient since most rays do not find sources.

The problem is simplified by replacing the mirrored walls with the "through the looking glass" rooms. The reflection coefficient of the mirrors becomes the transmission coefficient of the looking glass walls. Total signal at a receiver is the vector sum obtained indexing through all sources in all rooms, computing distance to the receiver and the transmission coefficients of walls traversed. The problem is manageable if the required number of rooms can be bounded.

Bounding limit.

The number of rooms needed is bounded by the event horizon and by attenuation. The time per symbol and speed of light defines the event horizon the radius of a sphere centered on the receiver that contains all rooms that can participate in the symbol. Intersymbol interference or partial response may require event horizons greater than the time per symbol. Attenuation also limits the number or rooms needed. Surprisingly enough only the reflection loss is important, attenuation with distance is not.

Imagine a room containing a source that delivers 1 watt per square meter to the walls of the room. Imagine that the walls reflect 90% of the incident power, 1/10 watt is absorbed. Energy balance requires that power level in the room increases to 10 watts per square meter at the walls, at which point energy emitted equals energy absorbed. If p is the field reflection coefficient, then power density increases to $1/(1-p)$. Power density approaches infinity as p approaches 1.

A room has 6 nearest (first order) neighbors, East North West South Down and Up, written E N W S D U. A room has 18 second order neighbors, EE NE NN NW WW SW SS SE UU UE UN UW US DE DN DW DS DD. There are 38 third order neighbors, EEE NEE NNE NNN NNW NWW WWW SWW SSW SSS SSE SEE UEE UNE UNN UNW UWW USW USS USE UUU UUE UUN UUW UUS DEE DNE DNN DNW DWW DSW DSS DSE DDE DDN DDW DDS DDD.

[1]Edward C. Jordan and Keith G. Balmain, "Electromagnetic Waves and Radiating Systems" Prentice-Hall, Inc. 1968. p 664.

The number of rooms of order n is $4n^2+2$. The order of a looking glass room is the number of looking glasses that must be crossed to reach it. It is equivalent to the number of times a ray has bounced. The zero order room is real, and represents the so called line of sight or optical path.

Assume for the moment that all walls have the same reflection coefficient, and the rooms are cubical with radius(?) R. Then the distance to the center of an nth order room is n2R. The power contributed by all rooms of nth order is transmission loss through walls times number of nth order rooms divided by distance squared, or $p^n(4n^2+2)/(n2R)^2$. This is approximately equal to p^n/R^2 for values of n larger than 2. Total power for rooms order 0 through n is:

$$P(n) = \frac{1}{R^2} \sum_{m=0}^{n} p^n$$

Notice that the R^2 term is a constant related to power level at the walls of the room. In the limit as n becomes very large P(inf) becomes:

$$P(\inf) = \frac{1}{R^2} 1/(1-p)$$

Since $p^n = e^{\ln(p)n}$ and the summation is approximately equal to an integral:

$$P(n) = \frac{1}{R^2}(e^{\ln(p)n}-1)/\ln(p)$$

The bounding limit (BL) is the value of n such that P(n) is close to the value P(inf). It is convenient to say that close means 63.21% of the final value or $(1-e^{-1})$ in which case:

$$BL = -1/\ln(p)$$

If the reflection coefficient is .9, the bounding limit is 9.5, reflections out to at least the 9th order must be taken into account. How many rooms (rays) is that?

Order	Number of Rooms in this order	Total Number	p for BL(p)=n
0	1	1	0.000
1	6	7	0.368
2	18	25	0.607
3	38	63	0.717
4	66	129	0.779
5	102	231	0.819
6	146	377	0.846
7	198	575	0.867
8	258	833	0.882
9	326	1159	0.895
10	402	1561	0.905
11	486	2047	0.913
n	$4n^2+2$	$(2n+1)(2n(n+1)+3)/3$	

The multiray model up to order n forms a tetrahedron of looking glass rooms arranged about the real (order 0) room. Some of the rooms are mirror images, some backwards, some the same. The following represents a slice through order 0 of a 5th order tetrahedron.

```
                             5
                            /
                          *UUUUU*
                        / W \   E   /
                       5  W  4  E  5
                          W     E
                    *DDDDD*DDDDD*DDDDD*
                    E     W     E     W
                 5  E  4  W  3  E  4  W  5
                /   E   \ W /   E   \ W /
              *UUUUU*UUUUU*UUUUU*UUUUU*UUUUU*
            / W \   E   / W \   E   / W \   E   /
           5  W  4  E  3  W  2  E  3  W  4  E  5
              W     E     W     E     W     E
         *DDDDD*DDDDD*DDDDD*DDDDD*DDDDD*DDDDD*DDDDD*
         E     W     E     W     E     W     E     W
      5  E  4  W  3  E  2  W  1  E  2  W  3  E  4  W  5
     /   E   \ W /   E   \ W /   E   \ W /   E   \ W /
   *UUUUU*UUUUU*UUUUU*UUUUU*UUUUU*UUUUU*UUUUU*UUUUU*UUUUU*
 / W \   E   / W \   E   / W \   E   / W \   E   / W \   E   /
5  W  4  E  3  W  2  E  1  W  0  E  1  W  2  E  3  W  4  E  5
   W     E     W     E     W     E     W     E     W     E
  *DDDDD*DDDDD*DDDDD*DDDDD*DDDDD*DDDDD*DDDDD*DDDDD*DDDDD*
         E     W     E     W     E     W     E     W
      5  E  4  W  3  E  2  W  1  E  2  W  3  E  4  W  5
     /   E   \ W /   E   \ W /   E   \ W /   E   \ W /
         *UUUUU*UUUUU*UUUUU*UUUUU*UUUUU*UUUUU*UUUUU*
             / W \   E   / W \   E   / W \   E   /
            5  W  4  E  3  W  2  E  3  W  4  E  5
               W     E     W     E     W     E
               *DDDDD*DDDDD*DDDDD*DDDDD*DDDDD*
                     E     W     E     W
                  5  E  4  W  3  E  4  W  5
                 /   E   \ W /   E   \ W /
                     *UUUUU*UUUUU*UUUUU*
                         / W \   E   /
                        5  W  4  E  5
                           W     E
                           *DDDDD*
                              5
                             /
```

A computer program was written that models propagation in a windowless room with no furnishings. The room measures 6 meters wide (x) by 5.1 meters depth (y) by 2.438 meters (8 feet) high (z). The receive antenna height is 0.4 meters from the floor at any location on an 81 x 69 point lattice. Lattice spacing is 1/4 wavelength, tests indicate that closer spacing is superfluous. The measurement system origin is the center of the floor. Transmit antenna identified by color are placed as follows:

```
green (0.4, 0.5, 1.1)
red   (-1.9, -1.7, 1.0)
blue  (-2.215, 2.385, 1.285)
white (1.3, -2.3, 1.145)
```

Transmit and receive antenna are infinitesimal[2] vertically polarized dipoles; antenna gain (voltage) varies with the cosine of the ascension angle. E field varies as 1/r. Near field is not used. Reflections are real (no imaginary component) no polarization effects are considered.

Transmitters are coherent at 1 GHz. The program computes the vertical E field at the receive antenna plane for each transmitter, and colors it appropriately. Hidden line removal is used so only the strongest E field at each point is shown. The program runs as an animation so that the wavefronts can be tracked. This can be confusing to watch because the wavefronts are spherical, they propagate through and have phase velocities > c in the receive plane.

Stills are included that show a frame from the animation sequence, and top views for completed runs. VSWR 2 corresponds to glass or silicate walls with p=0.333. VSWR 9 is for p=-0.8. VSWR 19 is for p=-0.9. Large VSWR's correspond to conductive or metallic walls.

Conclusions:

The program demonstrates that spatial coherence is on the order of 1/4 wavelength. The program also demonstrates that the cellular telephone model for distribution is grossly incorrect for the indoor environment. These are not square or hexagonal cells, this is a fractal with minimum dimension 1/4 wavelength. This is for a featureless room. A more complex model is not likely to make the radiation pattern less complex.

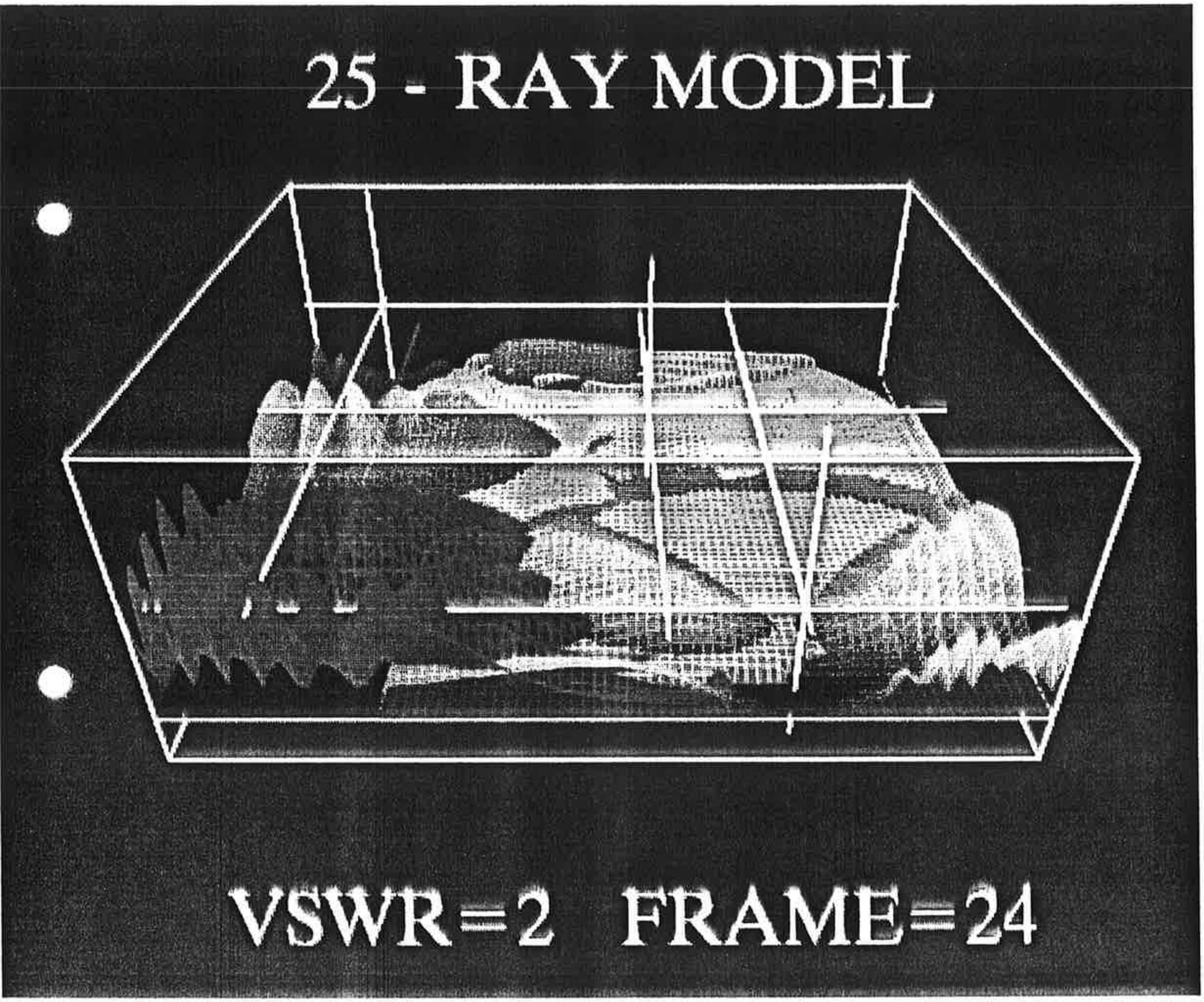
It seems that basic service areas (cells) may be fully interpenetrating (without regard to human wishes). This can be used to advantage in ways similar to antenna diversity. It seems likely that robust and fast handoff algorithms must be looked at with favor.

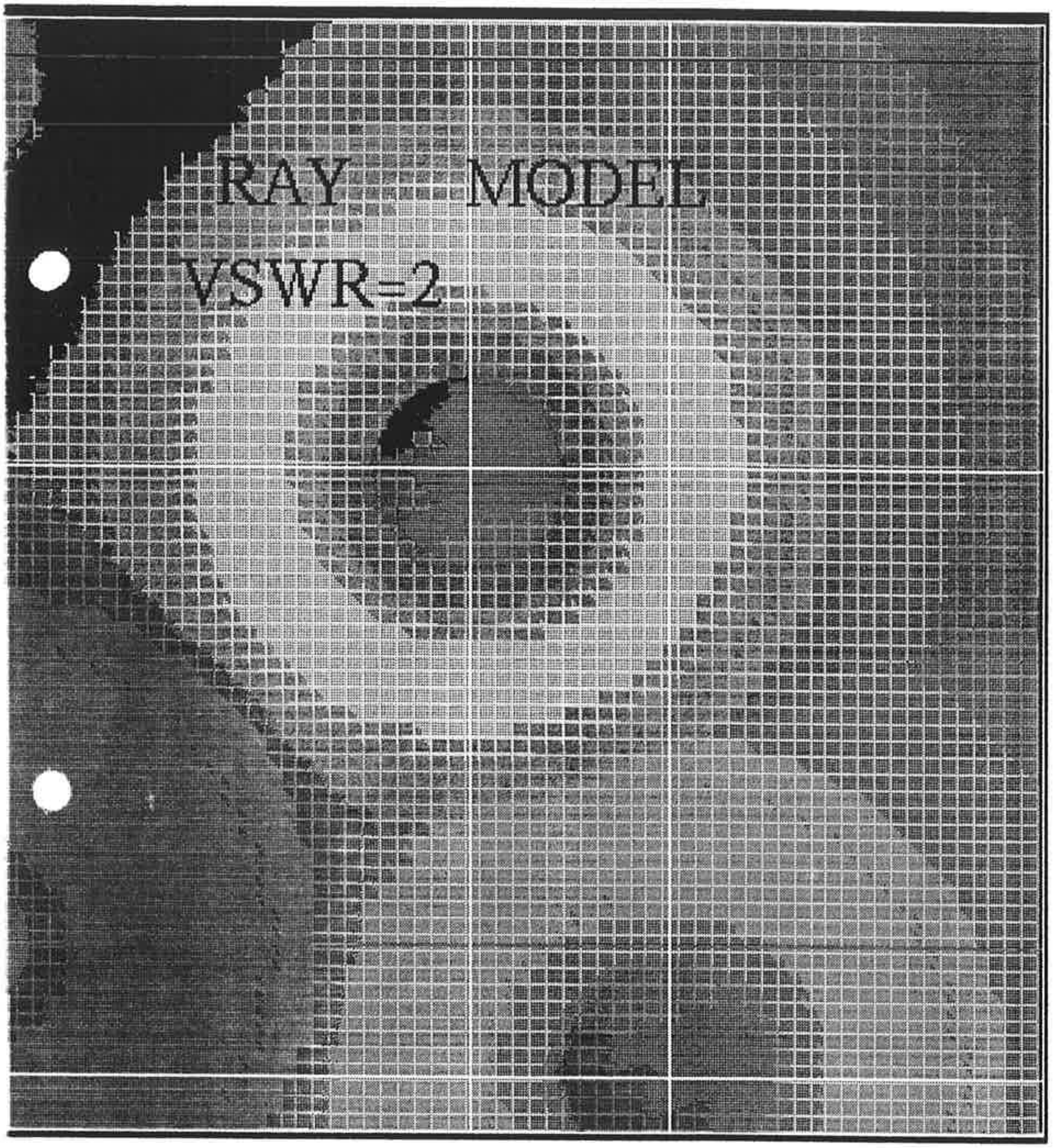
Further work:

This program assumes omni directional antenna for both receive and transmit. Spatial coherence will be much greater if receive antenna are directional, though a similar fractal is likely due to not quite parallel paths, this becomes interesting at 18 GHz.

The program's algorithm stores all distance and phase information for all rays traced, therefore delay spread and complex impulse response can also be computed across the receive plane.

[2]Ramo, Whinnery, and Van Duzer. "Fields and Waves in Communication Electronics." John Wiley and Sons, Inc. 1965. p 648.


25 - RAY MODEL
VSWR=2 FRAME=24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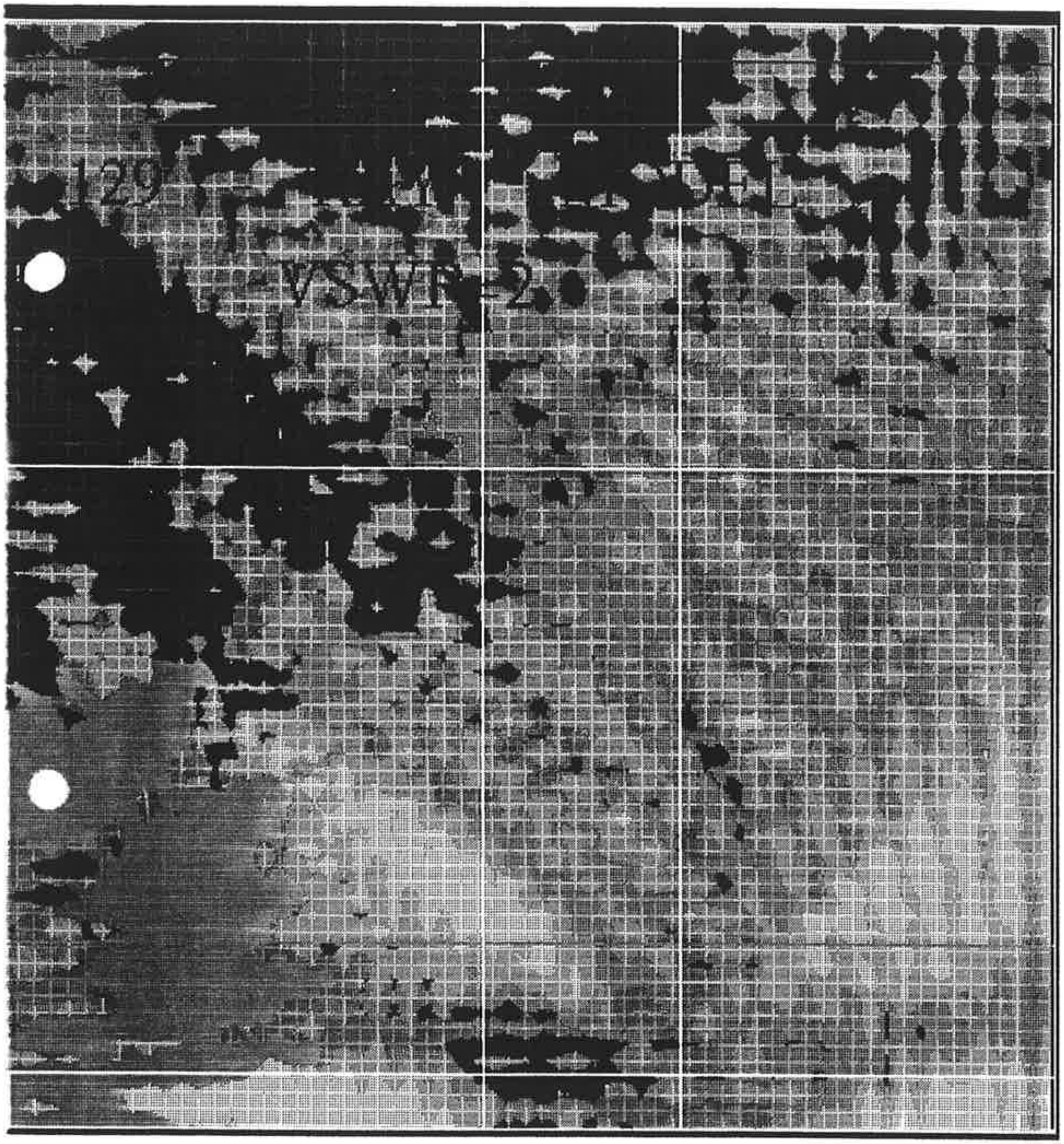
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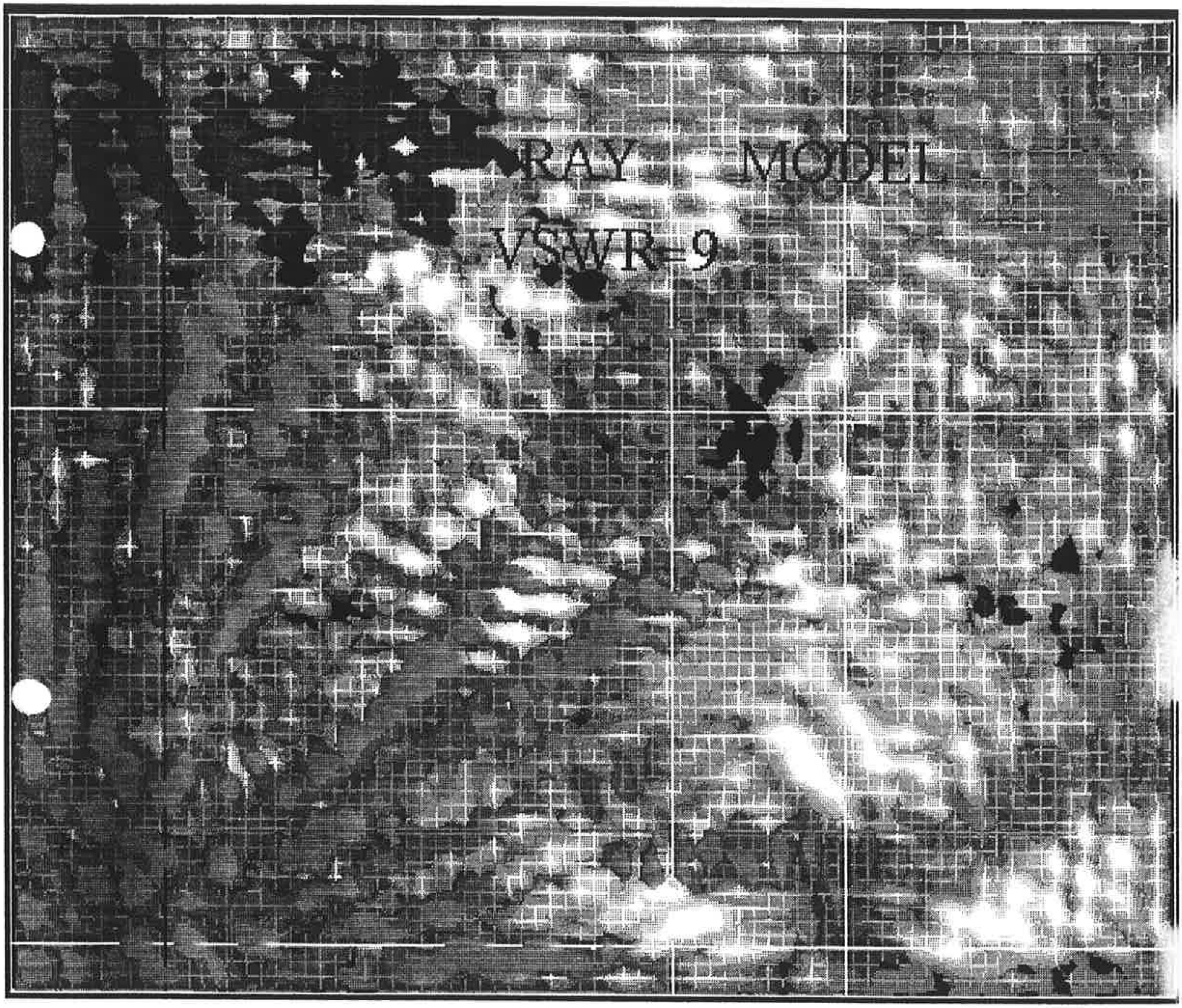
RAY MODEL
VSWR=9