antenna design for omnidirectional repeater coverage

The problem of good coverage with vhf antennas on towers with large cross-sectional areas is resolved in this article

This is the story of how one club obtained uniform coverage in all directions with a repeater antenna mounted on the side of a very wide tower. Perhaps the solution will help others with the typical problems of side-mounted antennas.

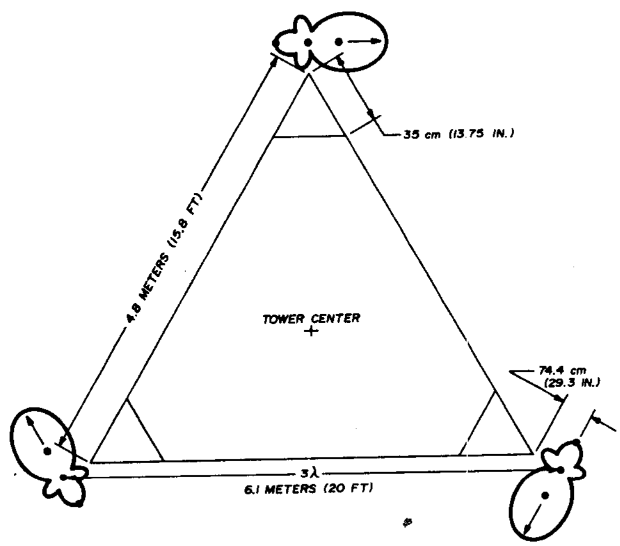
the problem

The difficulty that the Western Illinois Amateur Radio Club (WR9AEA) faced was not an unusual one on side-mounted repeater antennas. Coverage was not uniform in all directions; there were many peaks and many nulls. In some directions range was disappointingly short. Unless the repeater antenna is mounted on top of a structure this situation is typical, because a side-mounted antenna pattern usually has peaks and nulls resulting from the interference, reflections, and absorption of the structure. The local TV station, unfortunately, wouldn't let us put our array on the top of their tower above the TV antenna.

An interesting aspect of the WR9AEA problem was the large cross-sectional area of the TV broadcast tower we're using. The triangular shape is 4.8 meters (15 feet, 10 inches) on each side. Although this tower is very wide for a 244-meter (800-foot) structure, the problem and solution are relevant to both smaller and larger structures.

solution

The solution needed was some type of antenna array all the way around the supporting structure. Minimum coupling to the tower and uniform illumination of the horizon with good input vswr were required. A search of Amateur Radio reference materials yielded no answers. At this point the club



NOTES:
1. 63.5 mm (2-1/2 IN.) OD TUBING AT ALL TRIANGLE CORNERS.
2. ANTENNA HEIGHT: 223 METERS (731 FT) ABOVE GROUND.
3. OPERATING PARAMETERS:

FREQUENCY (MHz)		WAVELENGTH, CM (IN.)
TRANSMIT:	147.03	204 (80.3)
RECEIVE:	147.63	203 (79.9)

4. RMS GAIN:
2 LAYER ≈ 0.8 dB
3 LAYER ≈ 3.8 dB

fig. 1. Tangential-fire antenna array using Yagis attached to a tower of large cross section. Note that the main lobe of each radiator is perpendicular to the tower and that free space exists in front of, and to the rear of, each pattern. The resultant radiation pattern of each antenna is summed so that the overall pattern is essentially omnidirectional.

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president, Tom, W9NJV, approached a local professional antenna engineer, Ron, W9NOO. Ron is very well respected for his many years of designing vhf and uhf broadcast antennas.

As usual, Ron knew what to do. He suggested a "tangential fire arrangement" for mounting antennas on the very large triangular tower. Of course, we didn't know what he was talking about; but as if often the case with someone who really knows his subject, Ron was able to make it simple for us.

description

By "tangential" Ron meant that the radiators would have their maximum radiation on a tangent, or at right angles, to the tower. This seems a little unusual at first, because we normally think in terms of an antenna radiating straight out from a tower. But here, if you're standing at the center of the tower, the maximum energy is pointed off to one side rather than straight out. To obtain constant signal amplitude in all directions, one radiator is placed on each leg of the tower. Notice from **fig. 1** that the main lobe of each radiator is prependicular to the tower and there is free space in front of, and to the rear of, each radiation pattern. The tower structure is off to one side of the radiator, so there's a minimum of coupling and distortion.

pattern sum

To obtain omnidirectional coverage it's necessary for the pattern from one radiator to add to the next, so that the resulting sum is as close as possible to a circle. **Fig. 2** illustrates this concept of the addition of the patterns. (In this figure the patterns are drawn to a very large scale, and the tower triangle to a very small scale, to represent the addition that takes place in the far field.)

The ideal individual radiation patterns would have a 6 dB beamwidth of 120 degrees. The half voltage (−6 dB) intensity of one radiator would then coincide with the half voltage radiation of the next. If the components from adjacent radiators are in phase, they will then sum to equal the full intensity. **Figs. 3 and 4** illustrate the development of this concept. Since the cosine function has a value of one-half ±60 degrees, the desired pattern shape is referred to as a cosine pattern.* The repeater antenna is vertically polarized, so our concern is the pattern

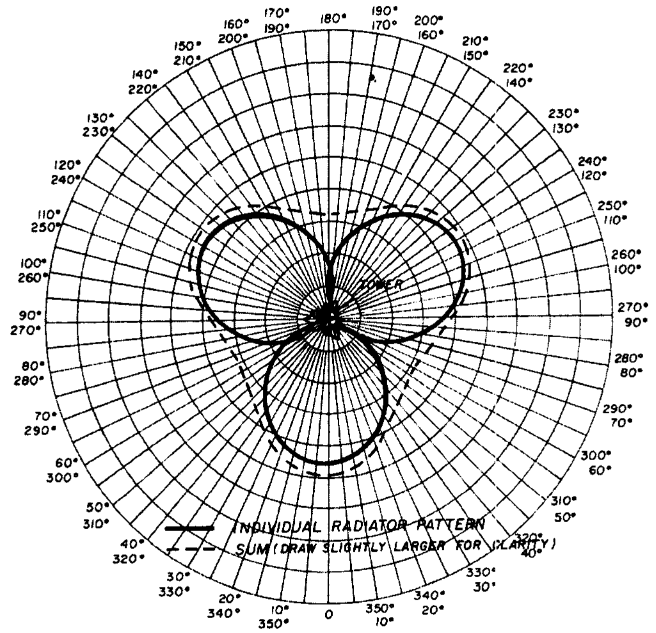


fig. 2. Development of the cosine radiation pattern resulting from three antennas fed with the proper phasing system. The sum of the patterns approaches a circle.

in the plane perpendicular to the radiating elements (**H** plane). Other patterns lend themselves to four or more radiators around a tower.[1, 2]

radiators

Ron told us that the desired cosine-shaped pattern is approximated by the typical short Yagi antenna. We decided to use on each leg of the tower a five-element Yagi manufactured locally. This beam

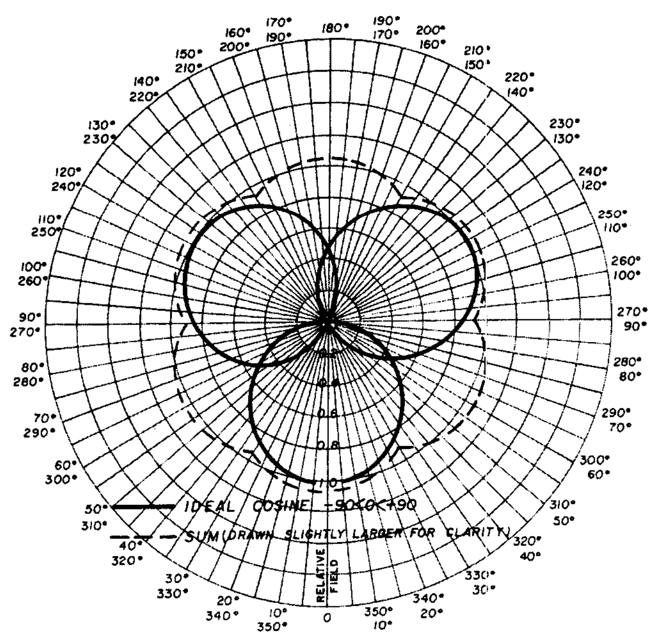


fig. 3. Ideal cosine pattern of three antennas fed in phase. The cosine of the angle, θ, lies between −90 and +90 degrees.

*Another variation of this concept is the cos² pattern, which was developed for vhf antennas on ballistic missiles. The same problem existed: the requirement for omnidirectional coverage with minimum attenuation from antennas mounted on the side of a huge mass of metal (the missile). Much time and effort went into the development of the cos² antenna, which is now standard for range safety and telemetry electronics on large rocket launch vehicles. Some of the early work on these antennas was done by the engineering department of the Convair division of General Dynamics for the Atlas missile in the late 1950s. Editor.

has standard dimensions with about 9 dB gain. It is very well constructed to take the rigors of being mounted 163 meters (535 feet) in the air. This was an important consideration, because nobody was interested in climbing up there — or paying a professional to go up there — in windy, cold weather to tighten a bunch of flapping aluminum.

spacing between radiators

For the amplitudes of the patterns of the radiators to add, it's necessary for the phasing and spacing to be correct. In our case, each Yagi was fed in phase

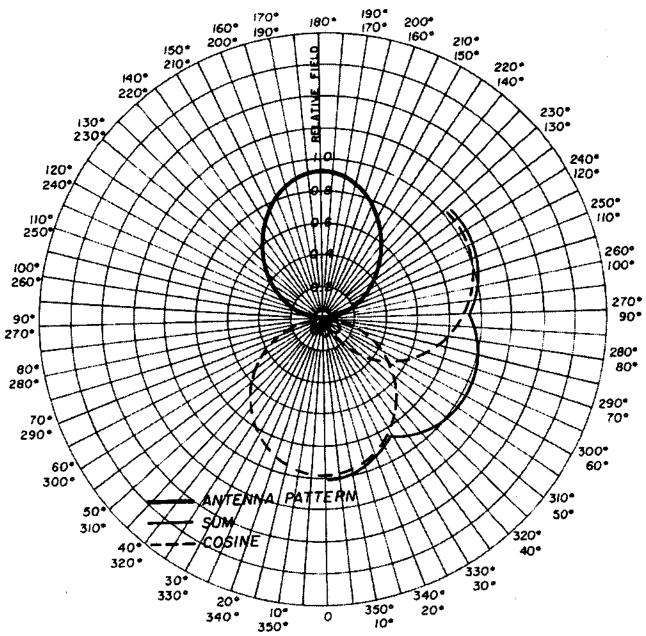
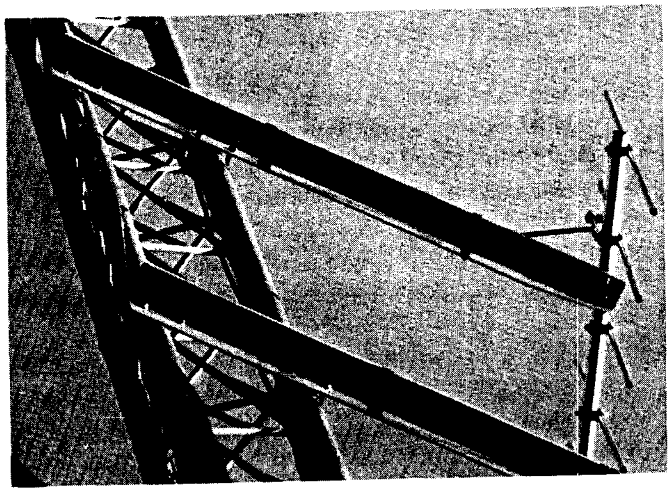


fig. 4. The development of the cosine pattern of n antennas fed in phase. This data is from a pattern recorder used during tests of the WR9AEA two-meter system.

through an equal length of feedline. The center of radiation (driven element) of each beam must be an integral number of free-space wavelengths apart. This requirement assures that the energy of each element will add correctly with energy from the next element. This is represented by the dimension $n \cdot \lambda$ (n times lambda), **fig. 5**. To suspend the Yagis at least one-half wavelength from the tower legs, the spacing worked out in our case to three wavelengths (see **fig. 1**). Ron pointed out that there are techniques for spacing the radiators at any multiple of one-third wavelength.[3]

gain of the array

At this point some of us got enthusiastic about the gain of this concept. After all, with three 9 dB Yagis the gain should be high, right? Wrong. When the patterns add up to a circle, the average gain drops to that of a half-wavelength dipole. It was hard for



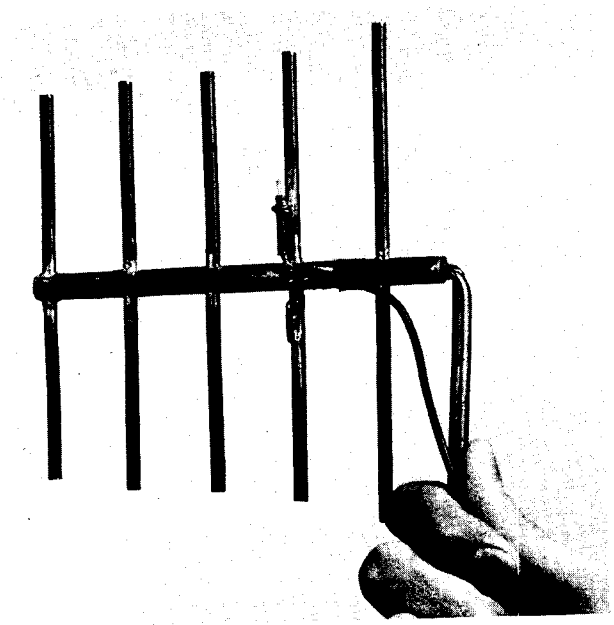
Antenna-mounting hardware consists of stainless steel and heavy-gauge aluminum.

some of us to get this through our thick heads, but the single stack or "bay" of three radiators around the tower yields to gain equal to that of a reference dipole.

Ron pointed out that the addition of a second level, or bay, of three more Yagis, stacked one wavelength above, would double the gain and give 3 dB over a reference dipole. So we decided to build a two-bay system with three Yagis per bay.

scale-model tests

To make sure the thing would work, Ron and his collaborator, Joe Donovan, tested a scale model of



Scale model of one of the antennas used for tests.

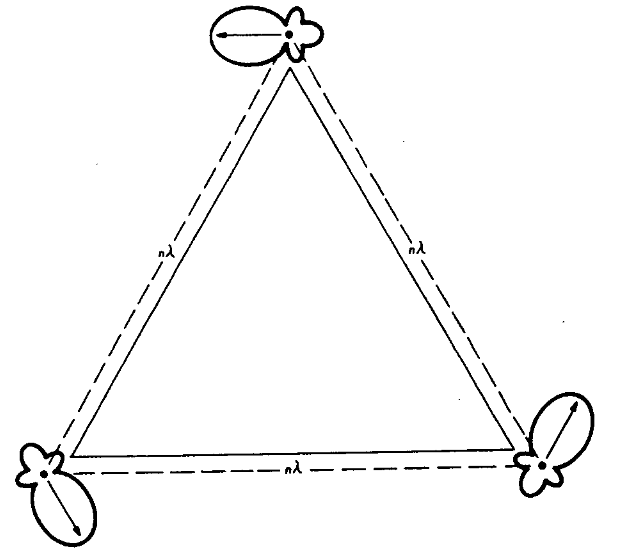


fig. 5. The center of radiation from each beam must be an integral number of free-space wavelengths apart so that the energy of each element (antenna) will add with energy from the next. This is represented by the dimension $n\lambda$, where λ is the spacing in wavelengths.

the tower cross section and Yagi elements. A convenient test frequency for their scale-model antenna was 955 MHz. At this frequency the models are small enough to be easily rotated by a powered turntable. A continuous plotter automatically recorded the pattern shape. **Fig. 6** shows the pattern with three Yagis pointed straight out, or a radial-fire arrangement. Note the nulls down to 20 dB below maximum and broad areas of poor gain. This type of poor circularity is typical of many side-mounted vhf antennas. **Fig. 7** shows the pattern of the tangential-fire configuration used for our new array. The circularity is ± 3 dB or better. In other words, the gain in any direction is no more than 3 dB from the average.

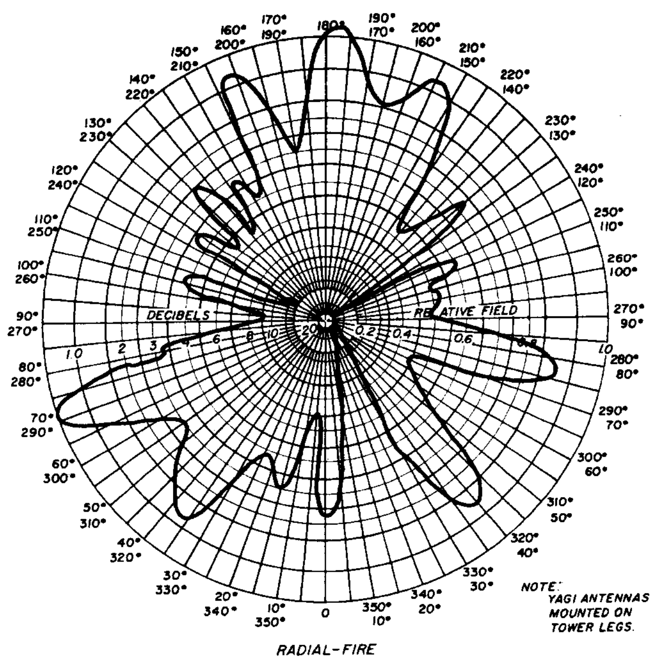


fig. 6. Radial-fire pattern in which three Yagis are pointed straight out from the tower. Note nulls and broad areas of low gain. The poor circularity is typical of many side-mounted vhf antennas.

power divider

A power divider to feed the six Yagis in phase from a single feedline was the next design task. A quarter-wavelength transmission-line transformer is perhaps the most simple technique. If all six Yagis are matched to 50 ohms and fed through convenient, equal lengths of feedline, the feedlines can be paralleled at a single point. Six 50-ohm loads in parallel result in an impedance of 8.3 ohms. In other words, we need an impedance transformation of six to one.

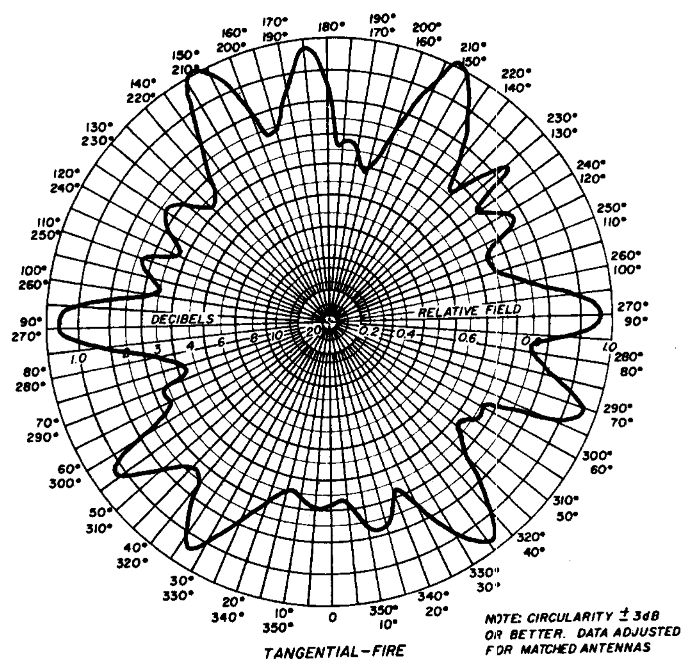


fig. 7. Radiation pattern of the tangential-fire arrangement used at WR9AEA. Circularity is ±3 dB or better, which means that the gain in any direction is no more than 3 dB from the average.

The design curves in Chapter 22 of reference 4 shows about a ± 5 per cent bandwidth at a vswr of 1.2 for a six-to-one transformation with a single 1/4-wavelength transformer. The usual equation, $Z = \sqrt{(Z1)\,(Z2)}$ or $Z = \sqrt{50\,(8.3)}$, tells us that 1/4 wavelength of transmission line, with a characteristic impedance of 20.4 ohms, would match 8.3 to 50 ohms. However, the design curves also show that, by making the transformation in two steps, the bandwidth at a vswr of 1.2 can be increased to ± 20 per

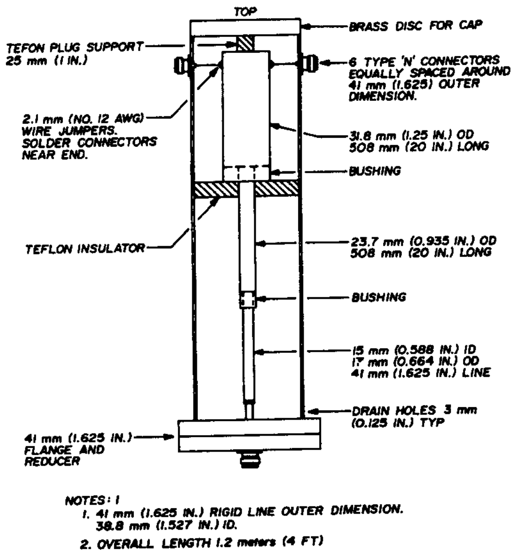


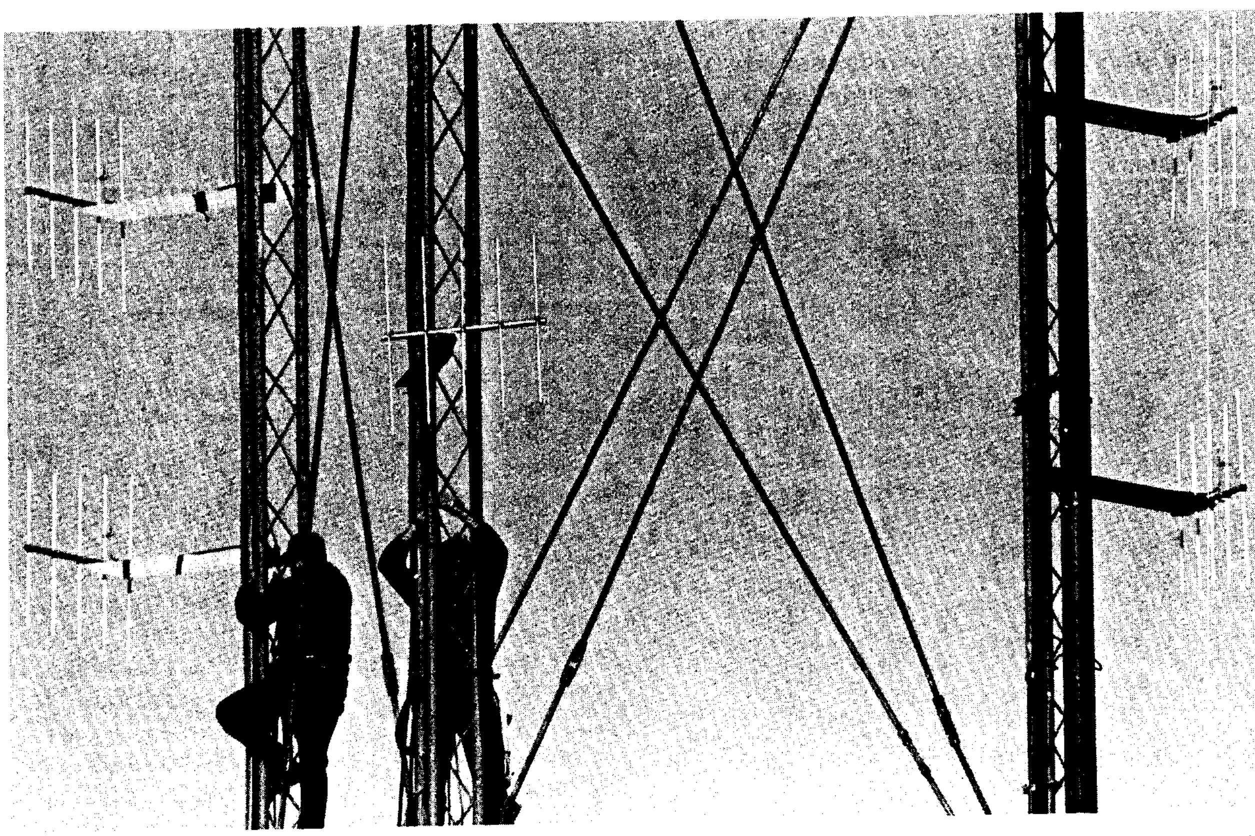
fig. 8. Construction details of the power divider used with the WR9AEA antenna.

cent. This configuration is less sensitive to inaccuracies and changes in the load impedance. Two 1/4-wavelength sections in series match the 8.3-ohm load to an intermediate value to 20.4 ohms, which is in turn matched to 50 ohms. One 1/4-wavelength section has an impedance of $\sqrt{(50)(20.4)} = 32$ *ohms* and the other $\sqrt{(20.4)(8.3)} = 13$ *ohms.*

divider construction

Fig. 8 shows the construction of the power divider. The 1/4-wavelength sections are coaxial. Therefore the usual formula $Z = 138 \log (db)$ was used to calculate the ratio of the diameter of the outer to inner conductors. It was convenient to construct the outer shell from a piece of 41-mm (1.625-inch) rigid coax line. The 50-ohm type N input was constructed from a 41-mm (1.625-inch) flange, a 41-mm (1.625-inch) reducer and a short section of 41-mm (1.625-inch) inner conductor. The six outputs are type N connectors spaced equally around the circumference at the opposite end. The center conductors of the six type N outputs are connected in parallel with short lengths of 2.1-mm (no. 12 AWG) solid copper wire to the end of the last 1/4-wavelength inner conductor. Some routine lathe work was necessary to construct the inner conductors, brushings, Teflon supports, and end cap.

Rex, K9ZJV, put his workshop facilities to the task of constructing the divider. Initial testing showed a very flat vswr of about 1.22 over the whole 2-meter band. To bring the device up to professional stan-



The WR9AEA array on an fm broadcast antenna tower. Array is at the 20-meter (65-foot) level for testing. The heroes doing their thing for the cause are N9SN, left, and W9NWN.

dards, a stub was added to the input transmission line to reduce the vswr to less than 1.1 from about 142 to 151 MHz. See **fig. 9**.

full-scale tests

The Yagis, mounting hardware, feedlines, and power divider were then mounted on the TV tower at the 20-meter (65-foot) level. Jim, N9SN, and Dave, W9NWN, performed these tasks of installing and adjusting the antennas. This work provided a very important check of all parts of the system before the critical full-height installation. A check of the pattern was made by comparing the signal received from the array with that from a reference Yagi, hand-held out from the tower in the direction of the field-strength meter. Although this method of checking a pattern isn't accurate, seventeen measurements in all directions showed no major peaks or holes. Once all the minor mechanical bugs were corrected, a professional climber was hired to install the array several wavelengths below an fm broadcast transmitting antenna, approximately 163 meters (535 feet) high.

predicted coverage

Ed, W4HTP, calculated the predicted coverage using broadcast techniques. FCC 50/50 curves calculate coverage exceeding 50 per cent of the time in 50 per cent of the potential receiving locations. The calculations consist of two steps: prediction of field strength from the repeater transmitter and determination of field strength required by various configurations of fixed and mobile stations. The results are shown in **table 1**. (Reference 5 and 6.)

table 1. Predicted coverage of the WR9AEA two-meter repeater antenna array for various receiving antennas. Predictions are based on 50 per cent of the potential receiving locations for 50 per cent of the time. Distances are for receiving the repeater.

Example	receiving equipment	required field strength at 9 meters (30 ft)	Distance km	(miles)
1	1/4-wavelength rooftop mobile	+21 dBμV/m	77	(48)
2	5/8-wavelength rooftop mobile	+18 dBμV/m	85	(53)
3	Ringo at 9 meters (30 ft)	+1 dBμV/m	144	(90)
4	11-element beam at 12 meters (40 ft)	−12 dBμV/m	216	(135)
5	2 stacked 11-element beams at 24 meters (80 ft)	−21 dBμV/m	280	(175)

results

Results have been excellent. Coverage in all directions seems to bear out the predictions. Mobile coverage is 72-88 km (45-55 miles); fixed stations at 160 km (100 miles) check in regularly. There appear to be no holes in the pattern. All bad spots seem to be explained by local terrain. We hope our experience and the references will help other groups to obtain omnidirectional repeater service.

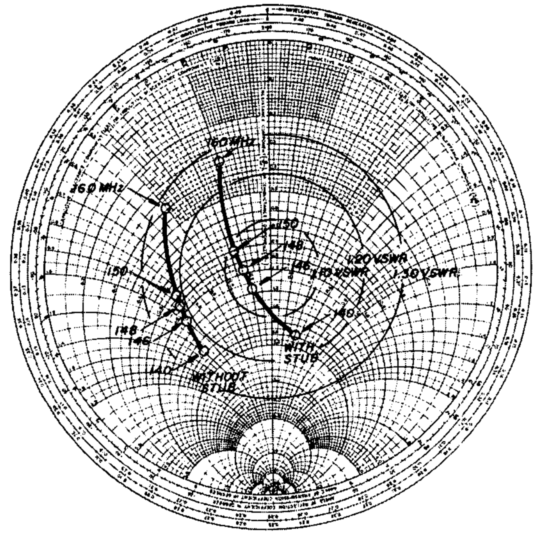


fig. 9. Response of the power divider with and without a stub on the transmission line.

acknowledgments

The Western Illinois Amateur Radio Club wishes to thank Ron Fisk, W9NOO, for his professional guidance. We also thank the club president, Tom, W9NJV, for his help during this project. Tom deserves public recognition for his constant, active leadership in getting everybody to work together. Photo credits to to Roger Humke, WA9KRG.

references

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