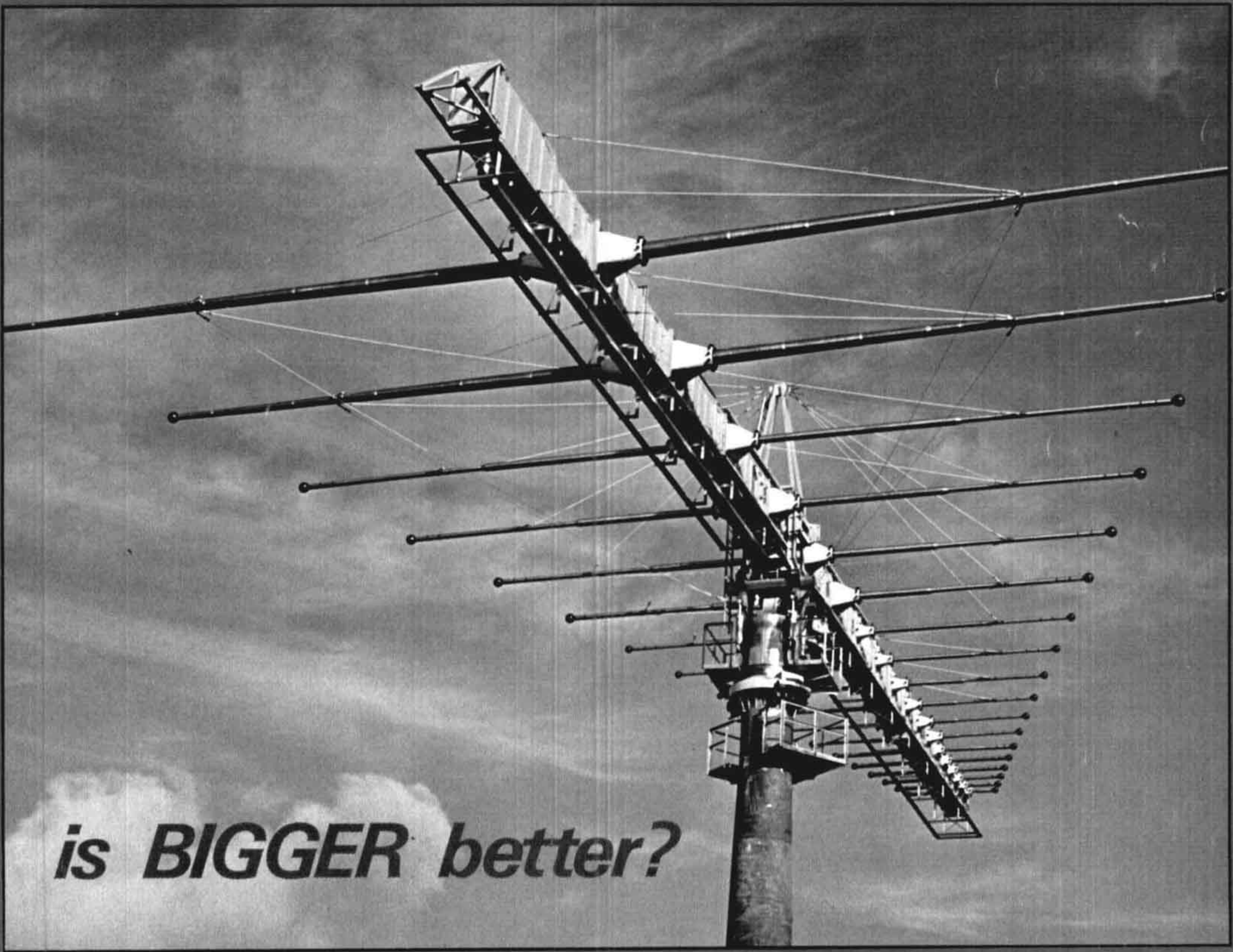
MAY 1985 / $2.50

ANNUAL ANTENNA ISSUE

ham radio magazine



is BIGGER better?

focus
on
communications
technology

in this issue: stacking Yagis properly • 0.5-30 MHz active antenna • vary your take-off angle • switchable vertical wire array • alternative method of feeding phased arrays • multiband sloping vee beam • 160-meter transmission line antenna • RF transmission cable for microwave applications • baluns • convert your fixed tower to a tilt-over • plus W1JR, W6SAI, K0RYW, and the Guerri report

stacking Yagis
is a science

Determining E/H plane patterns results in optimized performance

Several years ago I began a project designed to develop a means of determining gain of a particular 144 MHz Yagi. Knowing that number, I would be able to calculate the aperture. Once the aperture was known, I would know the correct stacking distance and would then be able to build the perfect 144-MHz array.

As one might expect, things didn't quite work out as planned. But eleven years and seven EME arrays later, I believe I have found an improved method of determining the optimum stacking distances for multiple Yagi VHF and UHF arrays.

what is optimum stacking?

"Best array performance" is a matter of opinion, and depends on how the antenna is used; an array can be optimally stacked, for example, to deliver maximum gain, or for a controlled azimuthal pattern that produces a deep null in the direction of interference. This article primarily addresses Yagi stacking for use in EME (Earth Moon Earth or moonbounce) communications. However, this technique is also appropriate for other space communications applications such as satellite communications and radio astronomy. It could also be used for land-based communication requiring high gain such as tropospheric scatter.

table 1. Typical temperatures of "objects" at 144 MHz and 432 MHz.

object	144 MHz degrees K	432 MHz degrees K
cold sky	175	10
hot sky	3,200	190
earth	290	290
arcing power line	100,000	6,000

For EME and other weak-signal VHF/UHF work, optimum stacking distance can be defined as that distance which yields the greatest array gain versus lowest array temperature. Used by professional space communications engineers, this definition refers to maximizing the G/T ratio. With Yagis, the best G/T usually never occurs at the distance which yields maximum stacking gain. It normally occurs at significantly closer spacing. In simpler terms, optimum stacking distance is that stacking distance which yields the greatest array gain increase while simultaneously keeping all sidelobes at an acceptable level.

the effect of antenna temperature

Several good sources of information are available for those unfamiliar with the concept of antenna temperature.[1,2] To review, antenna temperature is the temperature of the object at which the main lobe of the antenna is pointed — i.e. the Earth, Moon, Sun, hot sky, or cold sky. However, if the array has sidelobes of significant area and amplitude, unwanted noise can be picked up from noise sources in the direction in which the sidelobes are pointed. This unwanted noise reception will increase the net antenna temperature. (**Table 1** lists typical temperatures of several "objects" at 144 MHz and 432 MHz.) A 432-MHz array with large sidelobes pointed at the Earth will suffer a significant receive signal-to-noise loss because of the reception of Earth noise; likewise, a 144-MHz array with sidelobes directed toward a hot sky or a leaky power line will experience a similar degradation in receive performance.

By Steve Powlishen, K1FO, 816 Summer Hill Road, Madison, Connecticut 06443

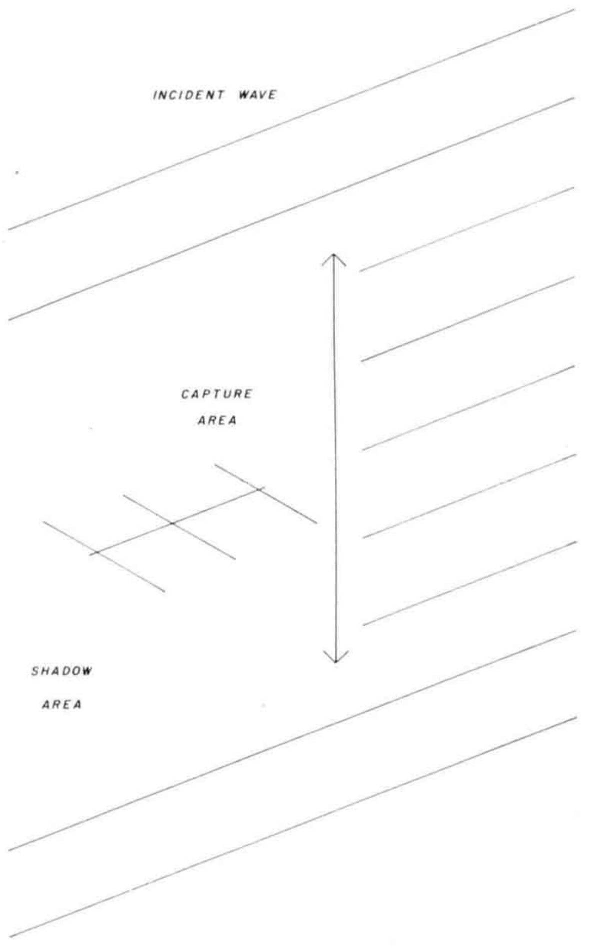


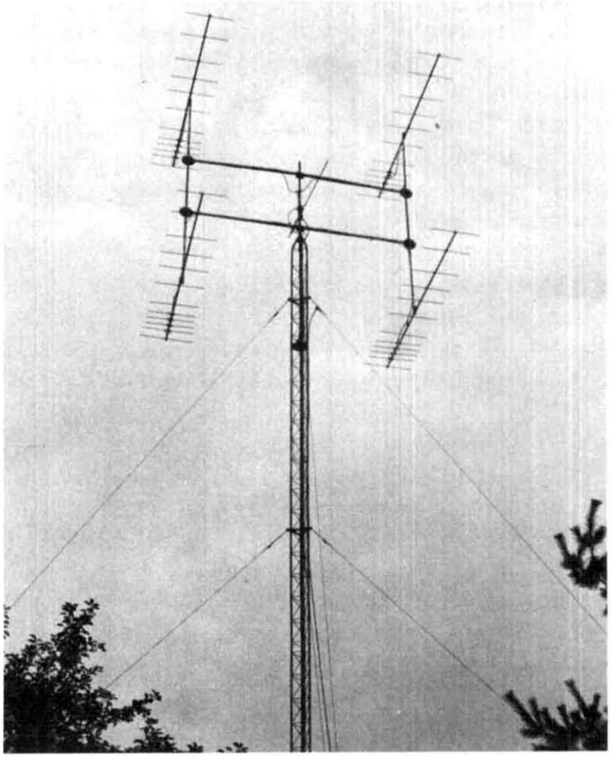
fig. 1. Antenna aperture and shadowing effect.

As a point of reference, commercial satellite Earth station antennas that use parabolic dish antennas with Cassegrain or Gregorian subreflector systems have antenna temperatures as low as 18 degrees K. In comparison, an Amateur dish using a simple dipole or horn feed at 432 or 1296 MHz has a typical antenna temperature of 65 degrees K, while a 16-Yagi 432-MHz array with the Yagis spaced for maximum gain may have an array temperature over 170 degrees K (or even worse if low-loss phasing lines are not used). Conversely, stacked 432-MHz EME Yagi arrays incorporating optimized stacking distances have been built to provide array temperatures lower than 85 degrees K — including phasing line losses. These antenna temperatures were measured by pointing the antenna at the Earth and then at the cold sky and comparing the noise ratios. The noise contribution due to the receiver can then be factored out if the receiver system noise temperature is accurately known. The significance of the lower array temperature cannot be overstated. If we assume a high performance receiver with a 0.45 dB system noise figure, lowering a 432 MHz array temperature from 170 degrees K to 85 degrees K results in a receive signal-to-noise improvement of about 2.3 dB or almost the equivalent of doubling the array size! These results have been obtained using standard Yagi designs such as the NBS Yagis and the K2RIW 19-element Yagi. I expect further improvements can be obtained when Yagis designed with best G/T in mind are available to Amateurs.

methods of determining optimum stacking distances

There are three methods of determining optimum stacking distances. The first method to be examined briefly, is based on classic antenna theory. The second, which will be emphasized, is experimental. Computer analysis, currently used by the professional community is the third, and will not be discussed here. With programs for Yagi analysis now readily available to the Amateur, it is hoped that the more mathematically inclined and computer-knowledgeable Amateurs will carry on where this article leaves off and extend computer modeling to include optimum stacking.

The concept of antenna directivity, (**fig. 1**), put forth by Kraus[3] and introduced to Amateurs by Orr and Johnson,[4] holds that all antennas have an effective capture area, or area around the antenna that "captures" or extracts the electromagnetic energy from space. The higher the gain of the antenna, the



Four 12-element LPYs stacked on a telescoping H-frame.

larger the area from which energy will be extracted. Behind the antenna there will be a shadow area, or space where the field strength of the incident wave is reduced in magnitude. (This concept is analogous to putting an object in front of a light source and creating a shadow behind it.) In mathematical terms the capture area is directly proportional to gain and is defined in **eq. 1**.

$$A_{em} = 0.13 \cdot 10^{dBd/10} \qquad \textbf{(1)}$$

Where A_{em} is the effective capture area in wavelengths squared and dBd is the gain of the antenna in decibels over a half wave dipole. For antennas such as Yagis, which have an elliptically shaped aperture, the size of the effective aperture will be slightly different between the E and H planes. The aperture dimensions in wavelengths squared can be calculated by using **eqs. 2** and **3**.

$$A_H = 2\sqrt{\frac{A_{em} \cdot \theta_E}{\pi \cdot \theta_H}} \qquad \textbf{(2)}$$

$$A_E = 2\sqrt{\frac{A_{em} \cdot \theta_H}{\pi \cdot \theta_E}} \qquad \textbf{(3)}$$

Where A_E is the E-plane aperture dimension, A_H is the H-plane aperture dimension, θ_E if the E-plane half power beamwidth, and θ_H is the H-plane half power beamwidth.

There are two problems with using these formulas to calculate stacking distances. First, an antenna's aperture is not an ellipse with a clearly defined boundary, with radio waves being extracted on one side of the boundary and nothing happening on the other side. Instead, an antenna progressively extracts less and less energy from space continuously. In addition, the half power beamwidths of an antenna are merely a point on the field strength gradient of the antenna. Therefore, proper stacking distance becomes a question of determining where two *unclearly* defined volumes separate. It is not a solid boundary like a brick wall.

The second problem, largely self-inflicted by Amateurs eager to believe they could defy the laws of physics and discover something that antenna engineers could not, is that of believing inflated gain figures produced by both Amateurs and some manufacturers of Amateur antennas. (In defense of Amateur equipment manufacturers, their claims are restrained in comparison to their CB and home TV counterparts). Using these optimistic gain claims, which in some cases are typically 3-dB high, leads to arrays which have grossly oversized stacking dimensions. The gain figures shown in the recommended stacking distance table (**table 2**) represent hundreds of hours of antenna measurements I have performed, the compilation of data from ten years of antenna gain contests, and finally, computer analysis of almost all the antennas listed in the table. The result is a listing of gain figures closer to reality, I believe, than anything previously available. (For further discussion of how much gain can be expected from a given boomlength Yagi, reading DL6WU's article is suggested.)[5]

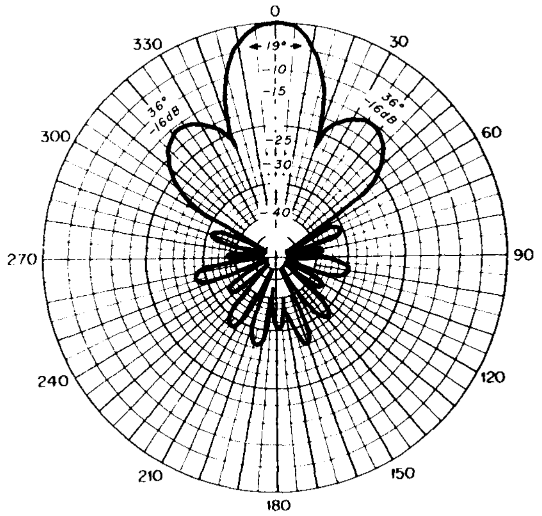


fig. 2. Four stacked 12-element Swan 2-wavelength LPY array E-plane pattern with 10-foot (1.5 wavelength) E and H-plane spacing.

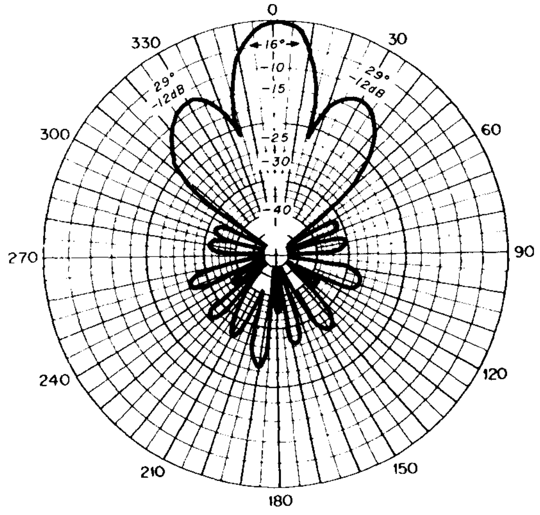


fig. 3. Four stacked 12-element Swan 2-wavelength LPY array E-plane pattern with 12 foot 0 inch (1.76 wavelength) E-plane and 11 foot, 4 inch (1.66 wavelength) H-plane spacing.

measuring antenna gain

As part of my experiments to measure antenna gain and determine proper stacking distances, a telescoping H frame was constructed on my 60-foot (18.3 meters) tower to measure the 144-MHz antenna. This arrangement allowed for rapid placement of Yagis along with a simple method of adjusting the spacing to any separation of up to 16 feet (4.9 meters). A smaller frame (6 feet/1.9 meters) was used to measure the 432-MHz Yagis.

The next step was to figure out a relatively accurate means of making pattern measurements. Over the years I tried a variety of measurement techniques, including use of strip chart recorders, spectrum analyzers, and RF voltmeters. Out of all this came a relatively simple and reasonably accurate method that is within the reach of most serious VHF/UHF experimenters.

The basic requirements for pattern measurement are:

- an accurate direction indicator;
- a receiver with a calibrated signal strength indicator; and
- a signal source located so as to minimize reflection problems.

Satisfying each requirement was surprisingly simple. The direction indicator I used was a selsyn readout* with close to 1 degree accuracy. Alternatively, the digital readout system using 10 turn pots and popularized by many EMErs[6] could be used. The availability of signal generators such as the Hewlett-Packard 608 series (or their military counterparts, the TS-510 series)* solves the receiver calibration problem. My method of measurement consisted of connecting a digital voltmeter (DVM) to the AGC (automatic gain control line) of the station receiver (an R-4C and TR-7). Care must be taken to keep signal strengths high enough above the noise (floor) to eliminate signal-to-noise plus noise ratio correction problems. The signal level must not be so high that it causes gain compression problems. The quick way to get a pattern was to run the antenna through 360 degrees while recording the AGC voltage readings on the DVM. The antenna was then replaced with the signal generator and the AGC readings were converted to a dB scale. (A 10 dB attenuator was placed between the converter and antenna or signal generator to eliminate impedance problems.) This "calibration" of the receiver was done after every measurement to eliminate receiver gain drift errors.

The signal source presented the trickiest problem, but again a simple solution was found. A number of signal sources were tried including locating signal sources in my back yard, in the woods about 1000 feet (305 meters) away, and at a local ham's QTH about 2 miles (1.3 km) away. All of these solutions gave marginally repeatable results. That is, an antenna would look different from day to day and from source to source. Because I believed the problem to be reflections from various objects, I decided to try a signal source located above the clutter. My location at that time was 105 feet (32 meters) above sea level. The antennas were located at 65 feet (20 meters), well above the nearby trees. My location was surrounded by hills up to 1200 feet (366 meters) high, 10 to 12 miles (16 to 19.2 km) away. The ground between my location and the hills dropped in elevation, which made the tops of the hills a completely clear shot at about a 0.5 degree elevation angle. A fellow ham located on one of the hills was called upon; by using high gain source antennas (stacked 3.2 wavelength NBS Yagis on 144 MHz and RIW19s on 432 MHz), repeatable pattern measurements became a reality. After performing many measurements I was able to "calibrate" my range such that I could see how different antennas gave the same false lobes or left to right unbalance. The patterns shown in this article have been cleaned up to eliminate known range errors. Various NBS antennas were constructed and their patterns measured. My measured patterns correlated very well with the NBS published patterns and offered proof of the method's validity.

It was also found that accurate relative gain measurements were possible. Gain measurement calibration was made by putting two identical antennas on the frame and measuring the relative signal level between them. The antennas were then switched in position and the measurement repeated. In this manner any differences in signal strength could be factored out before a test antenna was measured. Results were found to be repeatable to within 0.2 dB over the two-year period the gain tests were made. A similar method was used to measure the gain increases to be had from stacking antennas.

the effects of antenna spacing

To get an indication of what happens when the spacing of Yagi arrays is changed, an array of four 12-element LPY (log periodic Yagis, as introduced by Oliver Swan and later produced by KLM) was set up on the telescoping H-frame. Pattern measurements were made at one foot (0.3 meter) spacing increments from 10 feet (3.0 meters) up to 16 feet (4.9 meters) (1.4 to 2.3 wavelengths). The resultant patterns are

---

*Available from Fair Radio Sales, P.O. Box 1105, Lima, Ohio 45802 typical of all two-wide Yagi arrays. As the spacing between Yagis is increased, the main lobe beamwidth narrows, the sidelobes increase in amplitude and the nulls get much deeper. The E-plane pattern at 10 feet (3.0 meters), 12 feet (3.7 meters) and 14 feet 4 inches (4.4 meters) spacings is illustrated in **figs. 2**, **3**, and **4**. Looking at the sample patterns, it can be seen that the beamwidth of the first sidelobes is close to that of the main lobe for each spacing and that its amplitude increases rapidly at larger separations. Other minor lobes start to have significant amplitudes at the greater separations.

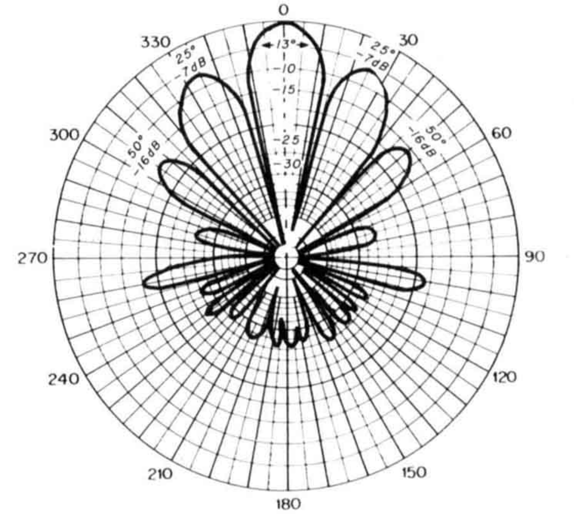


fig. 4. Four stacked 12-element Swan 2 wavelength, 144-MHz LPY array E-plane pattern with 14 foot 4 inch (2.1 wavelength) E and H-plane spacing.

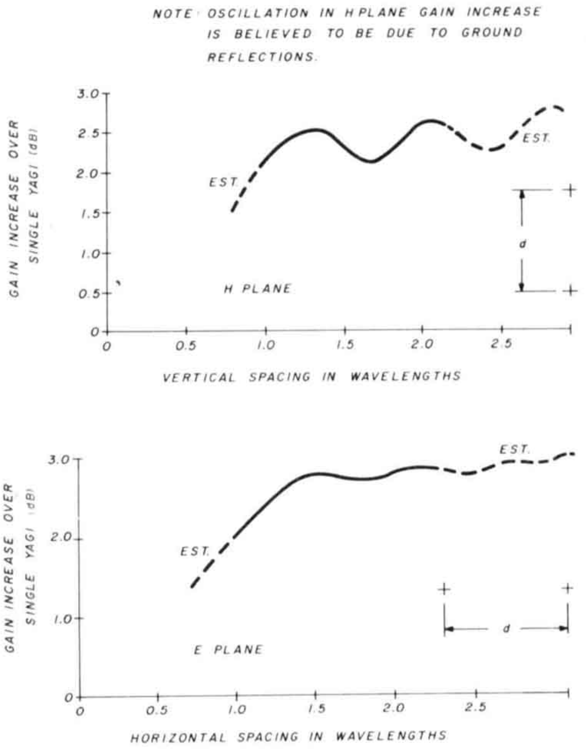
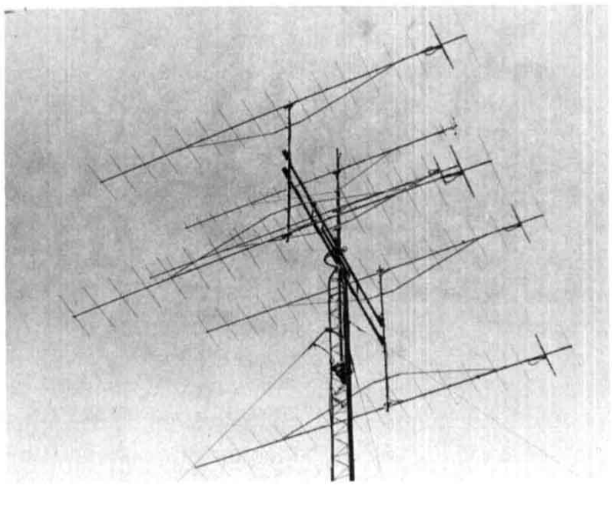


fig. 5. Array gain versus spacing using Swan 12-element, 2 wavelength 144-MHz LPYs.

The question of which distance is the proper one still remained to be answered. Gain and individual pattern measurements on the 12-element LPY indicated an actual gain of about 11.2 dB over a half-wave dipole (dBd). By using **eq. 1**, **2**, and **3** (single antenna pattern of 36 degrees E-plane by 40 degrees H-plane), stacking distances of 10 feet 8 inches E-plane (3.3 meters) 9 feet 7 inches (2.9 meters) H-plane were calculated. The 10 foot 8 inch (3.3 meter) E-plane spacing gave a pattern similar to **fig. 2**, but with first sidelobes down 14 dB. Next relative gain measurements were attempted between one and two antennas. Resultant gain curves showing stacking gain versus spacing are shown in **fig. 5**. The general shape of the curves are similar to those given in the now-famous NBS Technical Note 688,[7] (**fig. 6**) except I did not see any gain decrease as the spacing was increased to large distances, only a flattening of the gain curve. I also saw an apparent larger gain increase in the E rather than the H-plane. This is again indicated in NBS Note 688. As illustrated in **fig. 5**, the knee in the gain increase occurs at about 2.7 to 2.8 dB in the E-plane and at 2.5 to 2.6 dB in the H-plane. (When phasing line losses are factored out.)

Next, I attempted to relate first sidelobe levels to position on the gain increase curve and found that the gain increase started to flatten out when the first sidelobes were −12 to −13 dB down. It should be pointed out that at the time these measurements were made,



Four 17-element, 3.2 wavelength NBS Yagis stacked on an H-frame.

very wide spacing was very popular and many Amateurs, including myself, thought the NBS report with its relatively close spacings was in error. The correlation between my measurements to the NBS curves was truly amazing, especially considering that I was intent on proving NBS *wrong*.

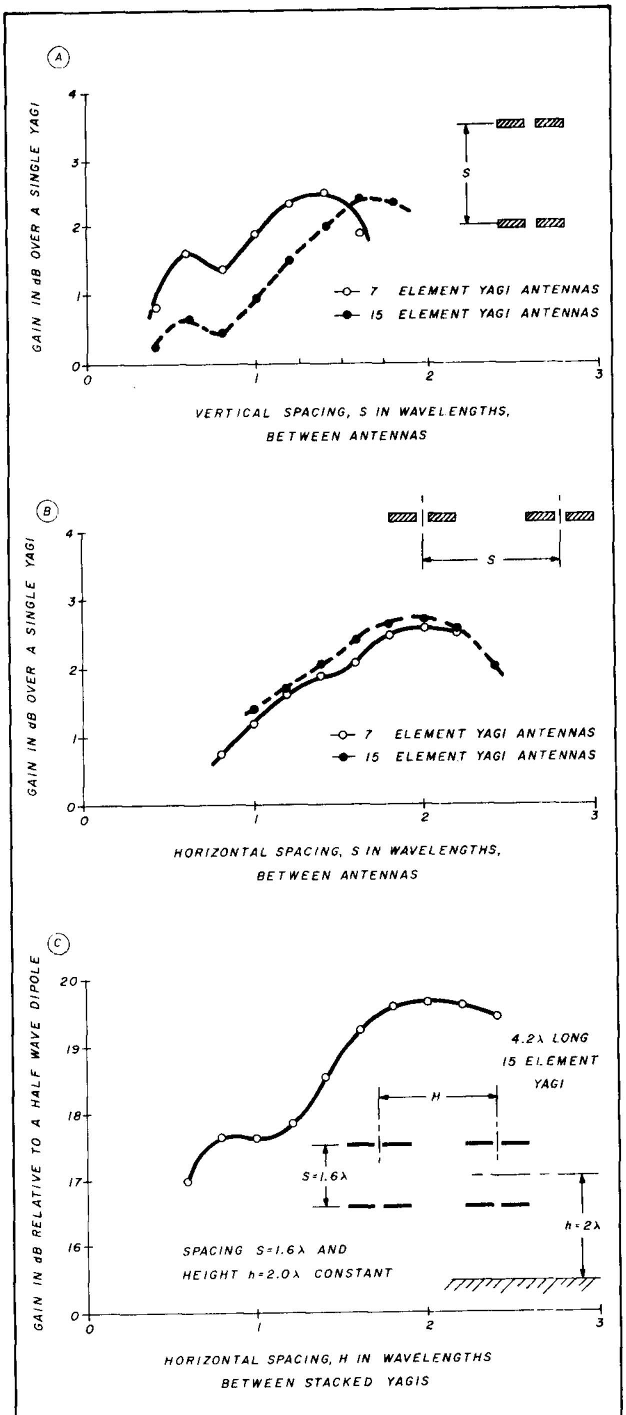


fig. 6. Array gain versus spacing per NBS Technical Note No. 688. (A) Vertical stacking improvement for either a 7 or 15-element Yagi, (B) horizontal stacking improvement for either a 7 or 15-element Yagi, and (C) horizontal stacking improvement for two sets of stacked Yagis spaced vertically 1.6 wavelength apart.

The additional rule of thumb used by Amateurs was to stack Yagis so that the first sidelobes were 13 dB down. This seemed to correspond to where the gain increase curves flattened out; however, when the sidelobes were − 13 dB, the main lobe was less than one half that of a single antenna. When I attempted to find out where the − 13 dB rule of thumb came from, the only explanation I could find was that two sidelobes at − 13 dB were, in total, − 10 dB from the main lobe and anything 10 dB down (or 1/10 amplitude) was insignificant. This seemed plausible except that the H-plane should have a pattern similar to the E-plane — and if it also had two sidelobes 13 dB down (with similar beamwidth to the main lobe), the sum of just those four lobes would be − 7 dB relative to the main lobe or 20 percent of the amplitude of the main lobe. Thus if all four sidelobes were looking at noise sources 10 times stronger (in reality, it is not very likely all the sidelobes would be facing similar noise sources) than the background noise the main lobe was looking at, the array would suffer a 6 dB signal-to-noise loss on receive.

improving a 144-MHz EME array

With this information in mind, I began to look at the 144-MHz EME array I was using at that time. It consisted of 4 Cushcraft A32-19, 19-element 3.2-wavelength 22 foot (6.7 meter) long Yagis patterned after the NBS 17-element Yagi, with a tri-reflector added. The gain of a single A32-19 is about 13.2 dBd with − 3 dB beamwidths in the E and H-plane of approximately 28 by 33 degrees. By using the previously defined aperture calculation method, spacings of 2.1 by 1.75 wavelength or 14 feet (4.3 meters) E-plane by 12 feet (3.7 meters) H-plane were calculated. The manufacturer of the antenna was recommending the same spacings, so it seemed reasonable to use them when constructing the array.

The performance of the array seemed acceptable. I usually received good signal reports, but on receive, signals always were poorer than expected. I easily dismissed the lack of hearing on a noisy urban environment. Looking at the NBS stacking curves, NBS was recommending 2.0 by 1.6 wavelength spacing for the 15-element 4.2 wavelength Yagi, an antenna with about 0.8 dB more gain than the A32-19. I then made some sidelobe measurements and found that the first E-plane sidelobes were down about 12 dB and the H-plane sidelobes were down only 10 dB. A quick decision was made to move the antenna spacing in to 1.9 by 1.6 wavelenghts or 13 by 11 feet (4.0 by 3.4 meters) E by H-plane, respectively. The results were startling. During the first two months of operation at the closer spacing, about 20 new stations were worked on EME,

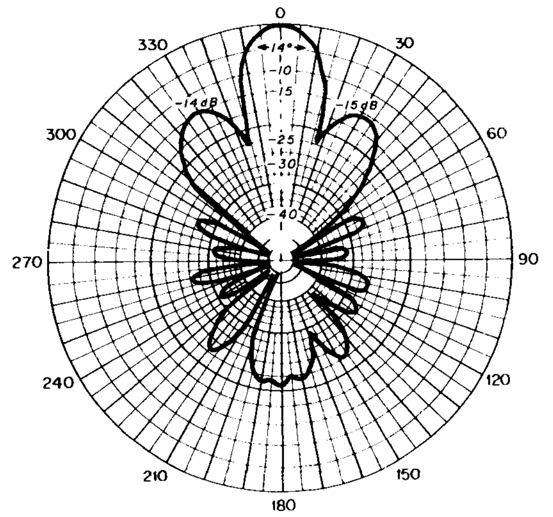


fig. 7. Four stacked NBS 17-element, 3.2 wavelength Yagi E-plane pattern with 13 foot 0 inch (1.9 wavelength) E-plane and 11 foot 0 inch (1.61 wavelength) H-plane spacing.

many of them stations I had tried to work in the past without success.

After that I obtained four more A32-19 Yagis. I modified them to standard NBS dimensions and removed the tri-reflectors. I then set them up on the telescoping H-frame and set out to find what was going on. The E-plane pattern of the 17-element 3.2λ NBS array spaced at 13 feet (4.0 meters) E-plane is shown in **fig. 7**. The pattern looks very good, with first sidelobes down 14 to 15 dB and all other lobes down 25 to 30 dB. H-plane patterns are usually more difficult to measure. Reflections from objects such as trees and utility poles, which are essentially vertically polarized, complicate the problem. Tilting the array back causes changes in ground reflections, which can induce errors if that method is used. Because of that I did not make a complete H-plane pattern measurement, but I did check the first H-plane sidelobes and found them to be only 12 dB down at the 11 foot (3.4 meter) spacing. The aperture calculations indicated that the spacing was already too close — however, NBS had indicated that 1.6-wavelength or 11-foot (3.4 meter) spacing was correct for the higher gain 15-element Yagi. To explain this wide discrepancy between calculated spacings and measured patterns, the patterns of the individual Yagis were examined. **Figure 8** is a computer-generated plot of the E and H-plane patterns of the 3.2 wavelength NBS Yagi. The H-plane pattern is noticeably less directive than the E-plane with larger sidelobes over the entire pattern. The array pattern of a number of Yagis is the resulting interference pattern of the individual Yagi patterns interacting with each

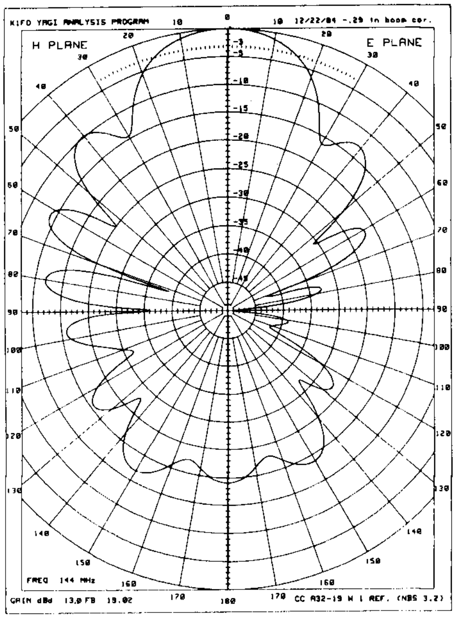


fig. 8. NBS 17-element, 3.2 wavelength Yagi computer generated E and H-plane patterns.

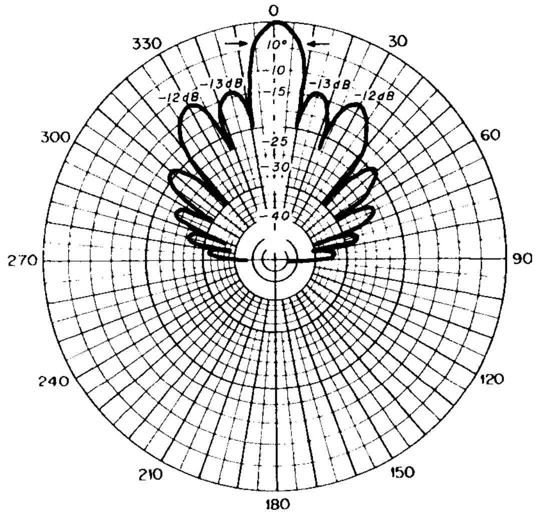


fig. 9. Six stacked NBS 17-element, 3.2 wavelength Yagi half H-plane pattern with 13 foot 0 inch (1.90 wavelength) (2 wide) E-plane and 11 foot 0 inch (1.61 wavelength), (3 wide) H-plane spacing.

other. It follows that the resulting array pattern of multiple Yagis will have larger sidelobes in the H-plane.

While measuring the four 3.2-wavelength NBS Yagi array, it was decided to attempt to relate array main lobe beamwidth to sidelobe level and array gain increase. The 3.2 wavelength NBS Yagis reacted similarly to the 12-element LPY antennas previously meas-

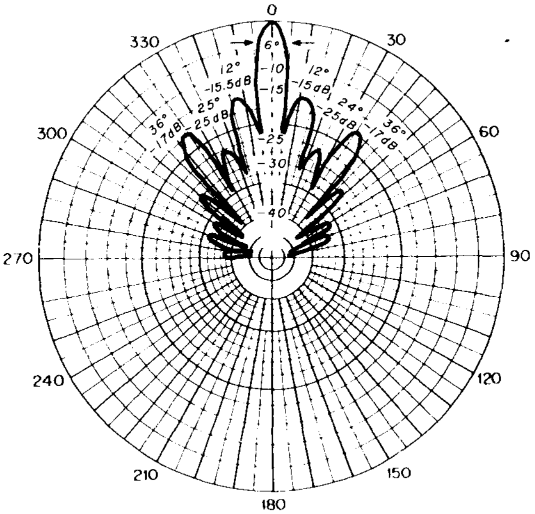


fig. 10. Sixteen stacked Cushcraft 424B Yagi E-plane pattern with 60 inch (2.2 wavelength) E-plane and 58 inch (2.1 wavelength) H-plane spacing.

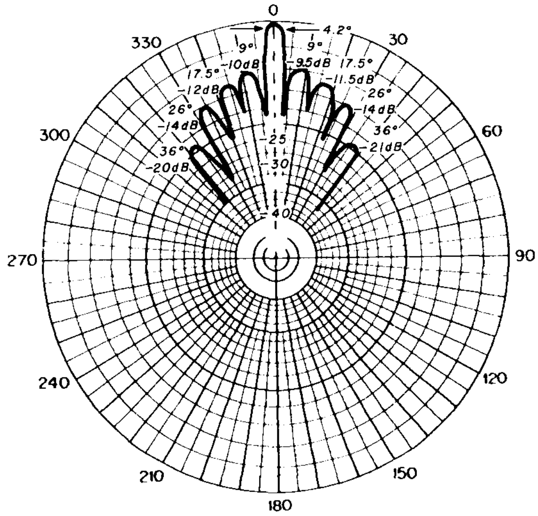


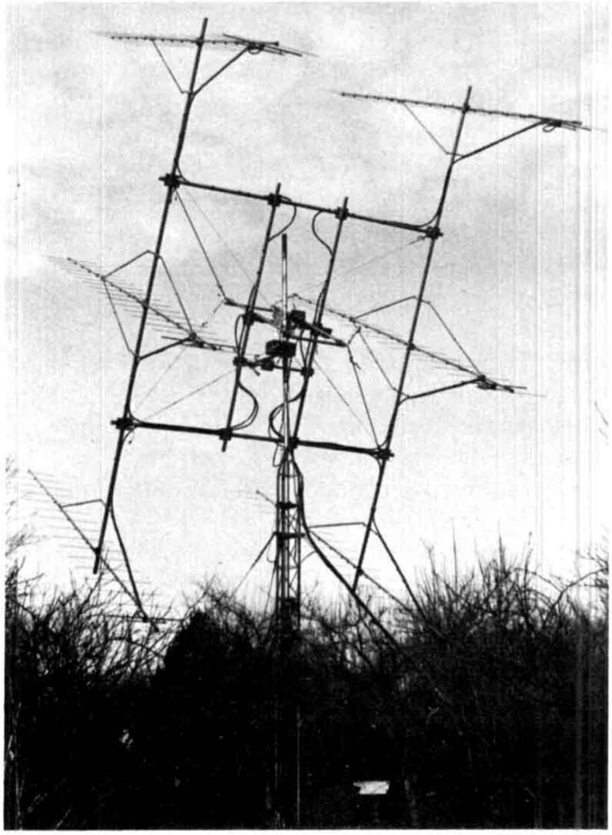
fig. 11. Sixteen stacked Cushcraft 424B Yagi H-plane pattern with 60 inch (2.2 wavelength) E-plane and 58 inch (2.1 wavelength) H-plane spacing.

ured. When the first sidelobes were − 13 dB, the main lobe was narrower than one half that of a single Yagi. Likewise, the main lobe was approximately one half the beamwidth of a single Yagi when the first sidelobes were − 14 to − 15 dB. *This relationship of first sidelobes at − 14 to − 15 dB when the main lobe beamwidth is half that of a single Yagi has held up in all subsequent arrays I have measured.* This also includes arrays that are three and four Yagis wide where the array − 3 dB beamwidth is approximately equal to the beamwidth of a single Yagi divided by the number of Yagis in that plane. As an example, my 144-MHz array was expanded to six 3.2 wavelength Yagis. The vertical spacing was kept at 11 feet (3.4 meters). The array's H-plane pattern is shown in **fig. 9**. The number of major sidelobes in an array is equal to the number of elements in a plane minus 1. Thus the six-Yagi array will have two major H-plane sidelobes. In this case, the first sidelobe is − 13 dB down and the second is − 12 dB down. As expected, the main lobe is narrower than one third that of a single Yagi at 10 degrees. Note that as the number of elements in an array are increased (and consequently the number of major sidelobes increase) it becomes much more important to keep the sidelobe amplitudes under control. A look at a 16 Yagi 432-MHz EME array will expand on this point.

more dramatic results at 432 MHz

Frank Potts, WA1RWU, had erected a 432 MHz EME array consisting of 16 Cushcraft 424B 24-element 7.6 wavelength Yagis. The instruction sheet for the 424B recommended 66-inch E-plane by 60-inch H-plane spacing. This was considerably closer than the spacings determined from calculating the aperture. Based on actual antenna gain of 15.8 dBd and a pattern of 20 degrees by 22 degrees (E by H), the spacings were calculated to be 72 inches (1.8 meters) by 65 inches (1.7 meters) E-plane by H-plane. When Dave Olean, K1WHS, of Cushcraft was contacted, he recommended the use of even closer spacings for an EME array — as close as 60 inches (1.5 meters) by 54 inches (1.4 meters). Because of mechanical considerations, the array was assembled using 60-inch (1.7 meter) horizontal (E-plane) by 58-inch (1.5 meter) vertical (H-plane) spacing. Phasing lines consisted of 1/2-inch and 7/8-inch hardline and were cut on a return loss bridge known to be accurate. The performance of the array had a familiar ring to it; Frank would receive excellent signal reports, but on receive, signals were far poorer than expected. Checking into the 432-MHz EME activity, Frank found that there had been a considerable number of other hams who had erected 16-Yagi EME arrays for 432 MHz that never worked well, and as a result, their stations had disappeared from the EME ranks.

At this point I began helping Frank to improve the array. The first priority, I decided, was to obtain a pattern measurement. The height of the array, 20 feet (6.1 meters) above ground, made the likelihood of taking accurate measurements remote. However, with the amount of array gain available (close to 26 dBd) I decided it should be possible to make adequate measurements by using Sun noise.[8,9] The E-plane pattern looked excellent, with the three major sidelobes down over 15, 25, and 17 dB, respectively



Six stacked NBS 17-element, 3.2 wavelength Yagi 144-MHz EME array.

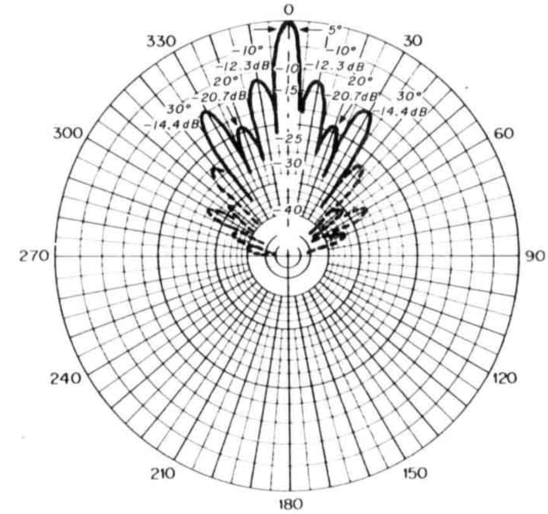


fig. 12. Sixteen stacked Cushcraft 424B Yagi H-plane pattern with 60 inch (2.2 wavelength) E-plane and 52 inch (1.9 wavelength) H-plane spacing.

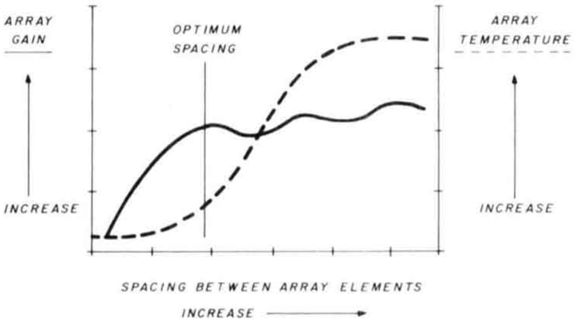


fig. 13. Array gain and array temperature versus spacing.

(**fig. 10**). The main lobe beamwidth was close to 6 degrees or greater than one quarter that of a single antenna. The H-plane was a shock with the −3 dB beamwidth of 4 degrees or much narrower than the expected 5.5 degrees. The major sidelobes were very large, at only 9.5, 11.5, and 14 dB below the main lobe (**fig. 11**). No EME signals had ever been copied when the array elevation was below 18 degrees. The fact that this angle was the same as the second sidelobe direction was no coincidence.

Some tests with a pair of K2RIW 19-element Yagis were run to measure changes in H-plane sidelobe levels. It was found that the first sidelobes changed at about 1 dB for every 2 inches of spacing change. Since the gain of the RIW19 (15.1 dBd) is close to the 424B it was felt that the results would be similar with the 424B. The vertical spacing was moved in by 6 inches (15 cm) to 52 inches (1.3 meters). The first sidelobes were expected to drop down to −12.5 dB. The results of that spacing change were amazing. The major sidelobes were now −12.3, −20.7, and −14.4 dB (**fig. 12**). Sun noise was up over 2 dB.* The on-the-air performance improvement was even more spectacular, with 41 QSOs made with 34 different stations during the first ten days of operation at the new spacing. Fewer than 20 QSOs were made in over two months of operation at the wider spacing. Most of the contacts were on random operation (as opposed to pre-arranged schedules) and included several 8 Yagi and one 4 Yagi stations. EME signals, including echoes, were now consistently copied down to 2 degrees elevation (the elevation angle where the main lobe would be clearing the earth). The main lobe beamwidth was still narrower than one quarter that of a single 424B at 5 degrees. This again supports previous measurements which indicated that a 1/4 beamwidth (5.5 degrees) would not occur until the first sidelobes are down 14 to 15 dB. The pattern indicates that the array has not yet been optimized. It is estimated that the best performance would occur at 62

---

*Sun noise is measured by pointing the array at cold sky, noting the noise level, and then pointing the array at the sun and measuring the noise increase. Sun noise is a combination measurement of overall receiver temperature and array gain.

inches (1.6 meters) E-plane by 50 inches (1.27 meters) H-plane spacing.

The reason for this dramatic improvement can be explained by looking at the approximate Earth noise pickup from the major sidelobes when the array was operated at low elevation angles. The main lobe at 432 MHz may typically see a sky temperature less than 20 degrees K. The sum of the first three sidelobes at −9.5, −11.5, and −14 dB would be equivalent to a single lobe 6.5 dB below the main lobe. Pointed at Earth (290 degrees K), those lobes would contribute about 65 degrees K of noise or cause a 5.1 dB degradation in signal-to-noise ratio. With the reduced sidelobes at the closer spacing, the sum of the three major sidelobes is about −9.8 dB and would cause about a 1.8 dB signal-to-noise degradation. This represents a *3.3 dB receive improvement*, which is quite significant on EME. The actual array noise is much more complicated; to calculate it would require summing all the sidelobes and accounting for the strength of the noise sources toward which they pointed. The over-2 dB Sun noise improvement nonetheless confirms the performance improvement.

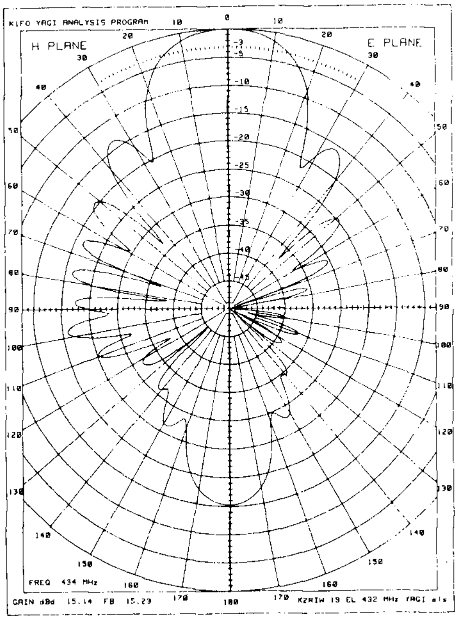


fig. 14. RIW 19-element Yagi computer generated E and H-plane patterns.

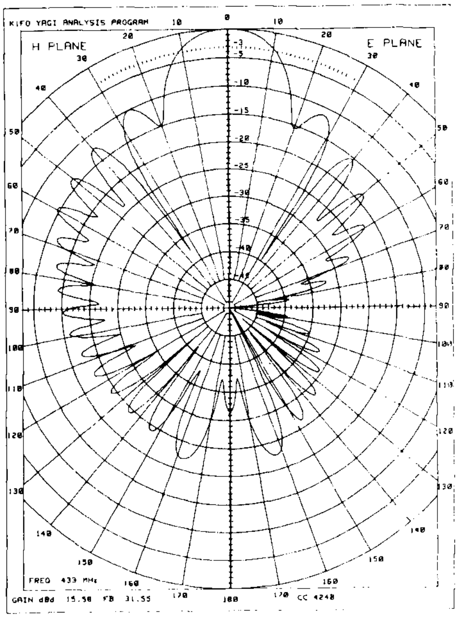


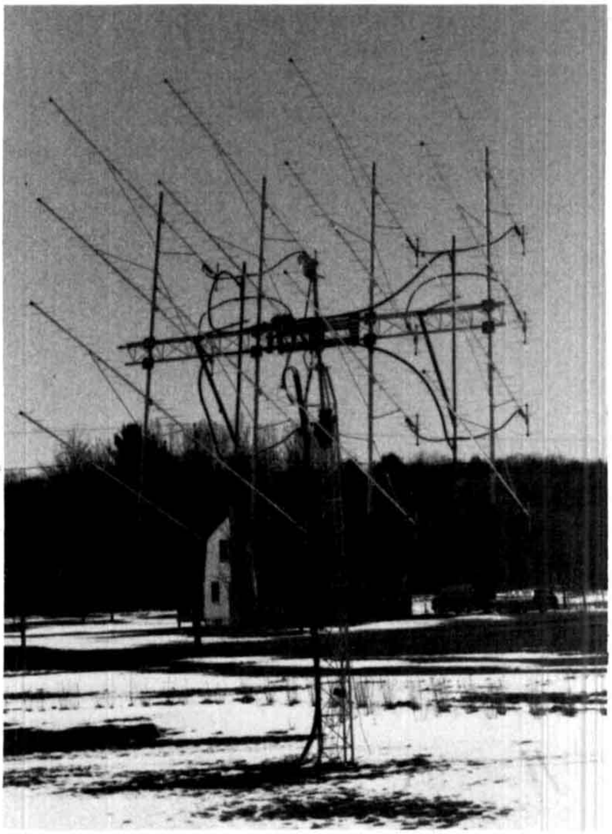
fig. 15. Cushcraft 424B Yagi computer generated E and H-plane patterns.

An alternative method for checking system temperature without taking array gain into account is to measure Earth noise. This is done by pointing the array at cold sky and then at the Earth and then comparing the noise levels. A well-performing 432-MHz EME system should see over a 4 dB ratio. Since this measurement does not take array gain into account it should not be used for array optimization because doing so could result in significant gain loss. **Figure 13** is a graph of typical array temperature versus stacking gain increase. The temperatures are not "real world" because they are quite different for the various Amateur frequencies.

easier method for measuring array beamwidths

Measuring the −3 dB beamwidths on high gain arrays with very sharp beamwidths can be a difficult task. WA1RWU's 16-Yagi 432-MHz array uses a prop-pitch motor for an azimuth rotator and has a 360-degree rotation time of over 3 minutes. The elevation leadscrew drive takes over 2 minutes to run 90 degrees. Even with such a rotating system, attempting to measure a 5 degree beamwidth can be a taxing experience. With a conventional commercial rotator it appears to be impossible to get an accurate measurement. It was discovered very early on that the half-power beamwidth was always equal to slightly less than 1/2 the spacing of the first nulls on either side of the main lobe. Interestingly, DL6WU has said that the beamwidth of a single Yagi is equal to 0.485 times the first null spacing. The measurement of the first nulls provides a much easier and most likely more accurate means of determining antenna half-power beamwidths.

The H-plane pattern measurements on the RIW19 Yagi provided yet another surprise. A pair of RIW19s had first H-plane sidelobes down 13 dB at a spacing of 54 inches (1.37 meters). The 424Bs had first H-plane



Sixteen stacked Cushcraft 424B Yagis in a 432-MHz EME array.

sidelobes down 12.3 dB at a spacing of 52 inches (1.32 meters). Considering that the 424B has an appreciably narrower H-plane beamwidth (22 inches versus 26 inches) and that it has more gain (15.8 dBd versus 15.1 dBd), just the opposite might be expected. The explanation again lies in the patterns of the individual antennas. **Figures 14** and **15** are computer-generated patterns for the RIW19 and the 424B. The RIW19 has, in general, sidelobes significantly lower than the 424B which would explain the different spacings for best array sidelobe levels. This effect has been noted in other Yagis also, and unfortunately makes most of the methods of calculating stacking distances (such as the aperture equations, or any of the various beamwidth formulas) of little use when array temperature is of concern. I spent a considerable amount of time trying to come up with a clever little formula for calculating stacking distances, but every one I tried had more Yagis disobey its numbers than ones that would.

This causes the optimum stacking distances to be different for different Yagis *even if they have the same gain*. Likewise a Yagi with a very clean pattern may have an optimum stacking distance greater than another with more gain but a poorer pattern. Keep in mind that "optimum" has, in this case, been defined as the highest G/T ratio.

mounting different frequency antennas on the same tower

The effect of having antennas for different bands located in close proximity has not received much attention. The interaction between antennas can be understood by looking again at **fig. 1**. If another antenna is located in the shadow of the first, it will not be able to extract as much energy as the first simply because the field strength is reduced behind the first antenna. To quantify the effect of having different antennas located nearby can be complicated. To evaluate the effect of a 144-MHz antenna on a nearby 432-MHz antenna, the aperture of the 144-MHz antenna at 432 MHz would have to be calculated in order to see how much of the capture areas overlapped. Next it would have to be determined who had "first dibs" on the signal or which antenna was in the other's shadow.

The only conclusive measurement I have been able to make has been to measure the Sun noise of a given array by itself and then add the other antennas and again measure Sun noise. I have found a consistent degradation in Sun noise by having arrays interlaced. Surprisingly, in most cases it is the lower frequency array that suffers. A side effect also appears to be the occurrence of stray sidelobes. The explanation of that phenomenon is that the unused antenna is re-radiating signals it had captured. Although not conclusive, terminating the unused antennas in a 50-ohm load appears to minimize the effect.

To be on the safe side, antennas should be located such that their apertures do not overlap. This can sometimes lead to very large spacings. As a practical matter the casual VHF/UHF operator may never see the performance degradation. The EME operator or enthusiastic weak signal worker who is looking for the last bit of performance is advised to either not mix arrays or to maintain sufficient spacing between them.

alternate stacking arrangements

This article has addressed only arrays with the Yagis arranged in uniform rows and columns. It may be possible to obtain additional stacking gain while controlling sidelobes by using other arrangements such as circle or diamond configurations. This would be due to the lower amount of aperture overlap required for sidelobe level control. I have not examined these alternative arrangements because of the difficulty in adapting them to an array with elevation control.

conclusions

Since most readers are likely to be more interested in a guide to how far apart to stack various antennas than in duplicating my work, **table 2** is provided. It covers a number of popular 144 MHz and 432 MHz antennas and their recommended stacking distances.

table 2. Measured performance of 144 and 432 MHz antennas.

144 MHz ANTENNAS

ANTENNA	GAIN		PATTERN	BOOMLENGTH		SIDELOBES		STACKING
TYPE	dBd		E x H		feet	E x H -dB		feet E x H
6 el NBS	10.2	a	40 x 42	1.2	8.2	17	9	9.6 x 7.5
9 el F9FT	10.6		38 x 46	1.6	10.8	18	14	9.9 x 7.0
11 el Swan/KLM	10.8		40 x 44	1.8	12.3	13	10	9.6 x 7.5
11 el Cushcraft	10.8	b	40 x 46	1.7	11.8	19	13	10.0 x 7.5
12 el Swan/KLM	11.2		36 x 40	2.0	14.1	14	10	10.6 x 8.6
14 el Swan/KLM	11.8		34 x 37	2.5	17.4	15	10	11.0 x 9.5
20 el CC Colin	11.9		45 x 26	-.-	--.-	--	--	9.8 x 13.2
14 el Hy-Gain	11.9		35 x 35	2.3	15.5	--	--	11.0 x 9.9
12 el NBS	12.0	a	34 x 36	2.2	15.0	15	11	11.2 x 9.6
14 el Cushcraft	12.1		34 x 36	2.2	15.0	15	12	11.2 x 9.6
16 el KLM	12.2		29 x 31	3.0	20.7	12	9	11.4 x 9.6
11 el KLM 11X	12.2	u	34 x 38	2.3	15.3	19	14	11.5 x 9.9
16 el F9FT	12.5		32 x 34	3.0	20.8	17	13	12.2 x 10.2
11 el LUNAR	12.6	c,g	32 x 35	2.6	17.4	16	12	12.4 x 10.2
13 el KLM LBA	13.0		31 x 32	3.1	21.5	14	10	12.7 x 10.6
15 el Cue Dee	13.1		30 x 32	3.1	21.3	--	--	12.8 x 10.7
17 el NBS	13.1		28 x 33	3.2	22.0	13	10	13.0 x 10.4
19 el Cushcraft	13.2		28 x 33	3.2	22.0	14	11	13.0 x 10.5
13 el W2NLY	13.4	d	27 x 29	3.5	23.5	12	9	13.3 x 11.2
15 el Telrex	13.5		26 x 28	4.1	27.8	12	9	13.3 x 11.3
14 el K1FO	13.7	g	29 x 31	3.6	24.3	15	13	13.7 x 11.2
15 el NBS	13.9	a	26 x 29	4.2	28.7	14	11	13.7 x 11.4
16 el KLM LBX	14.3	u	28 x 30	4.1	28.1	17	14	13.8 x 11.6
18 el Cushcraft	14.5		27 X 28	4.2	28.7	15	12	14.0 x 11.8

432 MHz ANTENNAS

TYPE	dBd		E x H		feet	E x H -dB		inches
11 el Tilton	11.8	f,g	34 x 36	2.6	6.0	17	13	46 x 40
13 el W6QKI	13.3		27 x 29	3.4	7.8	12	9	53 x 44
13 el K2RIW	13.5		27 x 29	3.4	7.8	13	10	54 x 45
15 el NBS	13.9	a	26 x 29	4.2	9.6	14	11	55 x 46
16 el KLM LB	14.4		24 x 25	5.3	12.0	11	9	56 x 48
19 el K2RIW	15.1		24 x 26	5.6	12.8	16	14	60 x 54
21 el F9FT	15.2	h	24 x 26	6.6	15.0	14	12	58 x 52
26 el DL9KR	15.5	u,i	24 x 25	6.1	13.8	17	15	62 x 58
24 el Cushcraft	15.8		20 x 21	7.5	17.1	12	10	62 x 50
22 el DL6WU	15.8	u,l	23 x 24	6.9	15.6	15	14	64 x 58
24 el K1FO	16.6	k	22 x 23	7.5	17.2	16	15	66 x 60
28 el W1JR/DL6WU	17.0	u	20 x 21	9.3	21.1	14	13	70 x 64
30 el KLM LBX	17.3	u	19 x 20	9.6	21.9	15	13	72 x 66
31 el W1JR/DL6WU	17.5	u	19 x 20	10.4	23.7	14	13	74 x 68

a	These NBS yagis have gain peaks 2 percent high in frequency.
b	Gain peak is 11.1 dBd at 146 MHz, 38 x 44 degree pattern.
c	Has incorrect balun length. With stock balun gain is 12.4 dBd.
d	Figures are for 0.125 inch taper version with 20 in. reflector spacing
f	Is tuned to 440 MHz. Retuned to 432 MHz gain would be 12.6 dBd.
g	Design based on Greenblum / Tilton information.
h	Is designed for 435 MHz. Gain peak is 15.5 dBd at 436 MHz.
i	Uses 8 element screen reflector.
k	Is a modified 424B using a single reflector and 22 directors.
l	Is designed for 435 MHz. Gain peak is 16.0 dBd at 436 MHz.
u	Design based on DL6WU information.

Although a few tenths of a dB additional gain may be obtainable at larger spacings, the added size, weight, and windload would most likely not justify the wider spacing even if EME or satellite communications are not anticipated.

It should be emphasized that gain alone does not tell the whole story. A Yagi with a cleaner pattern may be a better choice for an EME array than one with higher gain and a "messy" pattern. The highest gain Yagi in the world is of little use if it splits into 5 pieces the first time a storm passes by.

Finally, the following summary should serve as a guideline in building multiple Yagi arrays:

- Optimum stacking distance is a compromise between gain increase and sidelobe level (G/T).
- Array −3 dB beamwidth will be equal to single element beamwidth divided by the number of elements in a plane when the first sidelobes are −14 to −15 dB. This usually represents optimum stacking or best G/T.
- The H-plane's inherently less directive pattern requires substantially closer spacing than the E-plane to achieve optimum sidelobe levels.
- Negating phasing line losses, doubling the number of elements in an array at optimum spacing will give approximately 2.7 to 2.8 dB gain increase in the E-plane and 2.5 to 2.6 dB in the H-plane.
- The greater the number of elements in an array, the more critical it is to have that array optimally spaced.
- The higher the frequency of operation, the more critical it is to have an array with small sidelobes (i.e. optimally stacked).
- The cleaner the pattern of an individual Yagi, the greater the optimum stacking distance will be — hence the greater the array gain.
- Although spacings closer than the maximum gain distance can cause the loss of a few tenths of a dB in array gain, the closer spacing can result in several dB of signal-to-noise ratio improvement on receive.
- If you are going to make a mistake, put your antennas "too close together" rather than "too far apart."
- Placing different band antennas in close proximity can degrade performance.

references

1. Jim Kennedy, K6MIO, "The Real Meaning of Noise Figure," *ham radio*, March, 1969, page 26.

2. "Reference Data for Radio Engineers," Howard W. Sams & Co., Inc., New York, Sixth Edition, 1975, pages 29-1 to 29-6.

3. John D. Kraus, "Antennas," McGraw-Hill Book Company, New York, NY, 1950, pages 41-56.

4. William I. Orr, W6SAI, and H.G. Johnson, W6QKI, *VHF Handbook*, Radio Publications, Inc., Wilton, Connecticut, 1956, pages 91 to 96.

5. Gunter Hoch, DL6WU, "More Gain With Yagi Antennas," *VHF Communications*, April, 1977, pages 204 to 206.

6. Jerry Haigwood, KY4Z, "A Digital Readout Antenna Position Indicator," *The Lunar Letter*, March, 1983, pages 11 and 12.

7. Peter Viezbicke, W0NXB, "Yagi Antenna Design," *NBS Technical Note 688*, U.S. Department of Commerce, Washington, D.C., December, 1976, pages 6 and 11.

8. William L. Smith, W3GKP, "On Decibels and Noise," *QST*, January, 1968, pages 34 to 36.

9. D.W. Bray, K2LMG, and P.H. Kirchner, W2YBP, "Antenna Patterns from the Sun," *QST*, July, 1960, page 11.

ham radio