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Title: Optimum Design for 432-MHz Yagis, An--Part 1
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An Optimum Design for 432-MHz Yagis

Part 1: What's involved in designing a high-performance antenna array? This month: Some of the parameters that must be considered in an antenna design. Part 2 will present construction information so you can build your own antenna.

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The latest rage in 432-MHz Yagi design seems to be extremely long antennas—more than 10 wavelengths. I spent nearly two years perfecting two different 10.5-wavelength designs (24-foot boom length) and presented the results of those efforts in 1986 at the major VHF/UHF conferences.[1] Frank Potts, NC1I, successfully used one of the 10.5-wavelength designs in a 16-Yagi earth-moon-earth (EME) array. Frank's success encouraged me to plan a 26.0-dBd-gain array using eight of those Yagis. The antennas would be stacked two wide by four high and located 80 feet high for tropo and EME use. After thoroughly researching this planned array, however, I came up with a different solution. This article describes my efforts.

Will It Stay Up?

An often overlooked antenna design consideration is wind load. Wind load is the force put on a structure by wind blowing against it. I live in an area where ice loading combined with moderate winds can quickly destroy a poorly engineered antenna system. With this in mind, I analyzed possible antenna configurations for gain versus wind load.

Calculations showed that the eight-Yagi array would cause the collapse of my present tower the first time winds exceeded 40 mi/h! The eight long Yagis, stacking frame and cables exhibit a total wind load area of nearly 40 sq ft. Since the Yagis were to be elevated for EME, the array had to be centered more than 14 feet above the top guy wires. I calculated the bending moment for this configuration in an 80 mi/h wind. The resultant force of almost 17,000 foot-pounds is nearly the level that would collapse an 18-inch-face commercial steel tower and three times that which would destroy a 12-inch-face steel tower. These sobering figures encouraged me to find another way to construct a high-gain 432-MHz array.

Next, I examined a plan that used 16 moderately sized Yagis. Using low-wind load, lightweight antennas (similar in size and mechanical construction to the popular K2RIW 19-element design), a 16-Yagi array has a wind load area of 32 sq ft. The antenna booms are much shorter, so this array has to be mounted only nine feet above the top tower guys. The resultant bending moment on the tower for the array of 16 shorter Yagis is a manageable 8600 foot-pounds—half that of the array of eight long Yagis. I anticipated that the 16-Yagi array would have 27.0 dBd gain. In terms of gain versus wind load, the array of shorter antennas seemed to be a better approach. The only penalty would be a more complicated feed system.

As an interim step, I decided on a 25.7-dBd-gain array of 12 shorter Yagis. The 12-Yagi array has a wind load area of 24 sq ft and a bending moment of 6500 foot pounds. My over-guyed tower could handle this antenna.

Yagi Development

Once I decided on the array configuration, the next step was to choose an antenna design. The 19-element K2RIW Yagi (RIW 19) is enormously popular in North America because of its

- light weight
- low wind load
- clean pattern (except for rear lobe)
- self-supporting boom (no braces required)
- good wet and dry weather performance.

I had been using arrays of RIW 19s for several years with good success. I had learned enough from working with Yagis extensively over the past few years, however, to convince me that a much better design could be had within the same approximate wind load as the RIW Yagi. In March 1986, I started work on a new moderate sized Yagi, one that I hoped would become a replacement for the RIW design. The design criteria included

- low wind load (<1 sq ft)
- light weight (<4 lbs)
- no boom support
- gain about 1 dB better than the RIW 19
- improved pattern compared to the RIW 19[2]:
- E-plane sidelobes −17 dB or better
- H-plane sidelobes −16 dB or better
- H-plane minor lobes substantially better
- rear lobe −20 dB or better (5 dB improvement)
- lobes surrounding the rear lobe −25 dB

Much of the design and analysis work was done using MININEC, a microcomputer-based antenna analysis program. Modeling antennas on the computer makes it possible to try many designs without drilling a single boom. I do not have sufficient computer power, or a sophisticated enough Yagi analysis program, to optimize element spacing and element lengths simultaneously. I started with a spacing pattern based upon knowledge and experience and used the computer to optimize element lengths. Several possibilities came to mind.

Modifying the RIW 19. Much computer time was spent on this approach because I had a significant investment in RIW 19 Yagis (12 of them to be exact). Although I found I could get more gain out of an RIW 19 by making a longer center boom section and using a single reflector, the RIW design was compromised by change. The target gain could not be reached with a reasonable boom length while keeping a

[1]Notes appear on page 24.

clean pattern.

Using the DL6WU design. The antenna design by Gunter Hoch, DL6WU, is an excellent performer. Its flexible design (it can be made 2 to 14 wavelengths long) requires a trade-off, though: The Yagi will not be optimized for any given boom length. Using the DL6WU element spacing yielded a 20-element Yagi on a 13-ft, 8-in boom. Computer analysis indicated that this antenna would not meet my gain target. If an additional director was added, the boom would be 14 ft, 7 in long. I don't feel comfortable using a self-supporting small-diameter boom of this length. I had previously optimized the DL6WU director lengths for a 31-element, 24-ft Yagi. Reducing this antenna to a 20-element, 13-ft, 8-in Yagi did not give good results; that optimization had negated the variable-length design feature.

Starting from scratch. In this day and age, starting from scratch is almost like reinventing the wheel, and it soon became apparent that it would take a major effort to design from scratch an antenna that would outperform the modified DL6WU design. My objective was to create a better EME array; it was not merely a theoretical exercise.

The W1EJ Designs

Fortunately, I found someone who had *already* reinvented the wheel! Tom Kirby, W1EJ, had spent several years working on computer-optimized Yagi designs. Tom found that each Yagi size needs its own set of spacings to achieve the best combination of gain and pattern. He had worked out two geometries that might be suitable for my use. One was a 33-element, 10.6-wavelength (24-ft) model, and the other was a 17-element, 4.5-wavelength (10-ft) version.

I modeled two different approaches on the computer. The first cut the 33-element Yagi to a 22-element version; the second extended the 17-element model to 21 elements. Both the 21- and 22-element models (which use different element spacings) would be about 14 ft long. This is the maximum boom length I felt safe with, considering that my antenna criteria called for a lightweight, low-windload and no-boom-support design.

I built examples of Tom's 33- and 17-element Yagis, but found they performed considerably worse than expected. Careful pattern measurements and further computer analysis indicated that the antennas were tuned too low in frequency. Revised versions of the 33-element Yagi (with shorter elements) gave measured performance near what the computer predicted. This indicated that the W1EJ designs were worth pursuing. It also showed how a computer-created design must go through post-computation measurement and adjustment to verify its performance.

Examination of adjusted computer models of the 21- and 22-element Yagis showed that, as with any engineering design problem, there were trade-offs between both designs—and no clear-cut winner. The 21-element model could be computer tweaked for more gain (15.9 dBd theoretical versus 15.8 dBd for the 22-element Yagi). The pattern on the 22-element design was easier to control, and it had a significantly smaller rear lobe. When test antennas were constructed, the 22-element version won because of its better pattern (important for EME work). Note that the 21- and 22-element designs are not the ultimate in gain, as their spacings were not specifically optimized for a 14-ft boom length. Optimization of spacings for such a Yagi of this specific length could take several months and produce no more than an additional tenth of a decibel in forward gain!

Tom's computer design work provided antenna dimensions given in tenths of millimeters. I spent several weeks adjusting the Yagi's geometry on the computer to create an easy-to-build version with dimensions given in US customary units that would retain the theoretical performance of the computer model in real life. In addition, I worked on tuning the Yagi's center frequency to the desired range. It took only two tries to build a real Yagi with acceptable performance from the computer model.

The finished 22-element antenna was presented at the New England and Central States VHF conferences in 1986. On my home antenna range, I measured an antenna gain of 15.7 dBd—0.8 dB better than an RIW 19. The front-to-back ratio (F/B) measured 20 dB (5 dB better than the RIW). At the New England conference, the measured gain was 0.6 dB better than the RIW; at the Central States conference, it measured 1.0 dB better. Overall pattern measurements showed the 22-element antenna to have a better pattern than the RIW 19.

Computer modeling calculates the 22-element antenna gain to be 0.9 dB more than the RIW 19 with the pattern improvements confirmed on the test range. When you use a computer program to optimize a design, you can never be sure that the design will work as expected. This is because all models have some errors caused by calculation assumptions, algorithm errors or just plain "multiple-calculation build-up" errors. If a design is optimized with an even slightly erroneous calculation, the resultant dimensions will incorporate those errors.

Further Optimization

I still wanted to try for a better pattern and more gain before building the new EME array. Another two months were spent further optimizing the design and reworking the dimensions for metric units. I felt that metric units were appropriate *if* this was to be an antenna design of the 1980s and beyond. The final design has the same gain at 432 MHz (15.7 dBd) and an improved pattern. The peak gain of this Yagi is 1 MHz higher than the previous version (437 MHz). This was done to improve the pattern, assure excellent operation in large arrays and retain that performance in wet weather.

In its final form, no element length or spacing dimensions are the same. This seems to be characteristic of Yagis with maximum all-around performance. By maximum all-around performance, I mean a combination of a very clean pattern, excellent gain bandwidth and high gain for the boom length.

Resistive Losses

You may wonder where the missing 0.1 dB is between the calculated and measured Yagi gain. Such a small difference (3%) could easily be attributed to calculation error. After several years of building and measuring Yagis and comparing them to computer models, however, I have added correction factors to account for most of the difference.

Resistive losses account for most of the gain difference. Aluminum has an electrical resistance. Because current flows in all elements of a properly designed Yagi, losses will accumulate in the elements. DL6WU has shown that resistive losses are distributed fairly evenly throughout all elements. For maximum performance, the Yagi must be built from material with good conductive characteristics that will perform well in the weather.

Rainer Bertelsmeier, DJ9BV, has analyzed the K1FO 22-element Yagi with the sophisticated NEC3 program and calculated its resistive losses to be about 0.06 dB. Changing to copper elements would reduce these losses to 0.04 dB. My antenna is among the better designs in terms of resistive loss. Although lower losses are possible (0.04 dB is the lowest calculated by DJ9BV for a Yagi with similar gain using aluminum elements), lower-loss designs require greater boom length to achieve the same gain. There is no perfect solution. Part of the design problem is determining a tolerable resistive loss versus gain per boom length. The resistive-loss problem demonstrates another trap in computer analysis: It's possible to come up with a great theoretical design that may be a poor real-world performer because of resistive losses—this has occurred!

The other 0.04 dB difference between calculated and measured gain is caused by losses in the UT-141 balun. The use of an air-dielectric quarter-wave sleeve balun could reduce these losses to about 0.02 dB.

As a practical matter, of course, element and balun losses are not detectable in an antenna system used for terrestrial work. Even in an EME array, it will require the

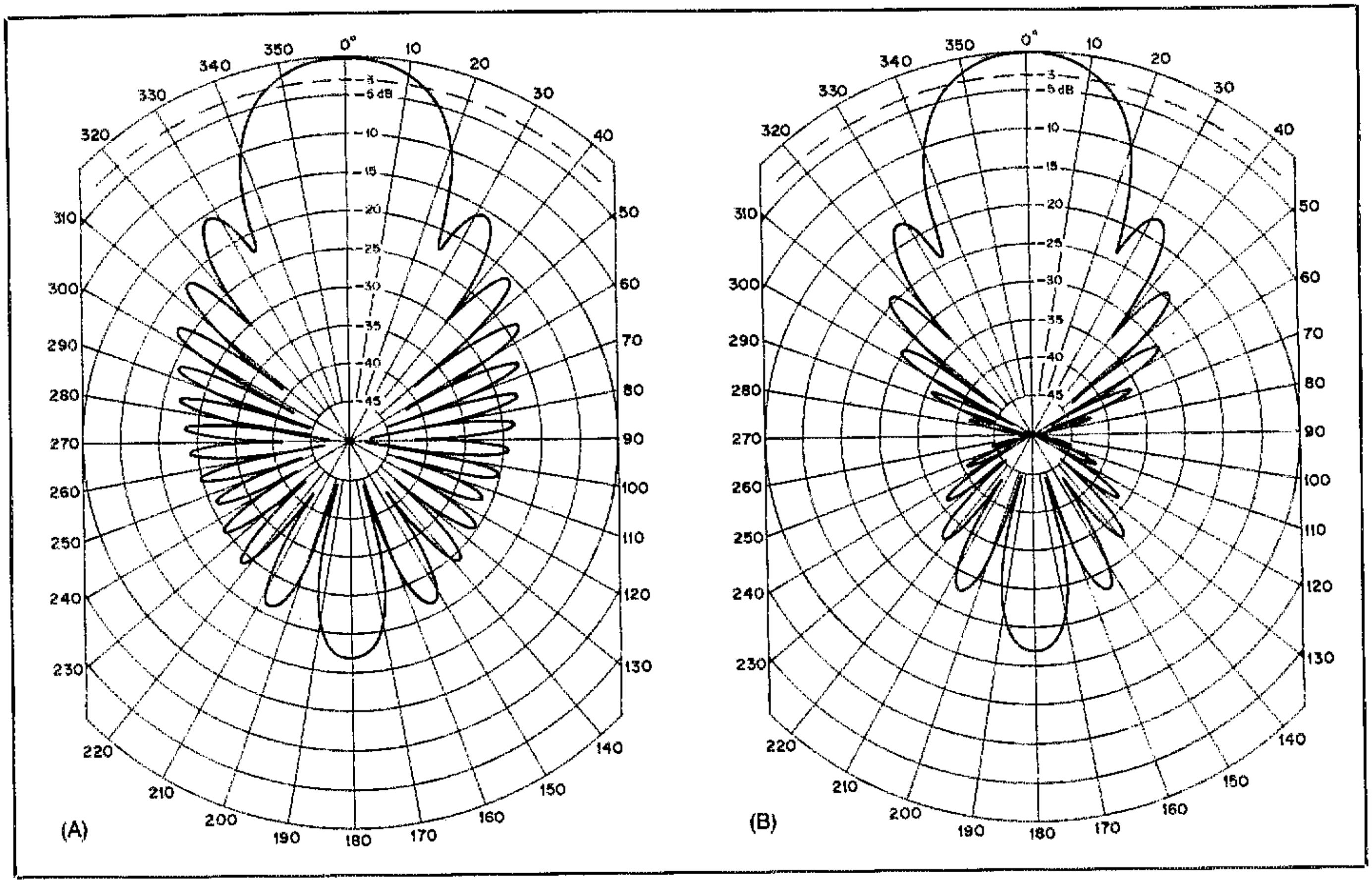
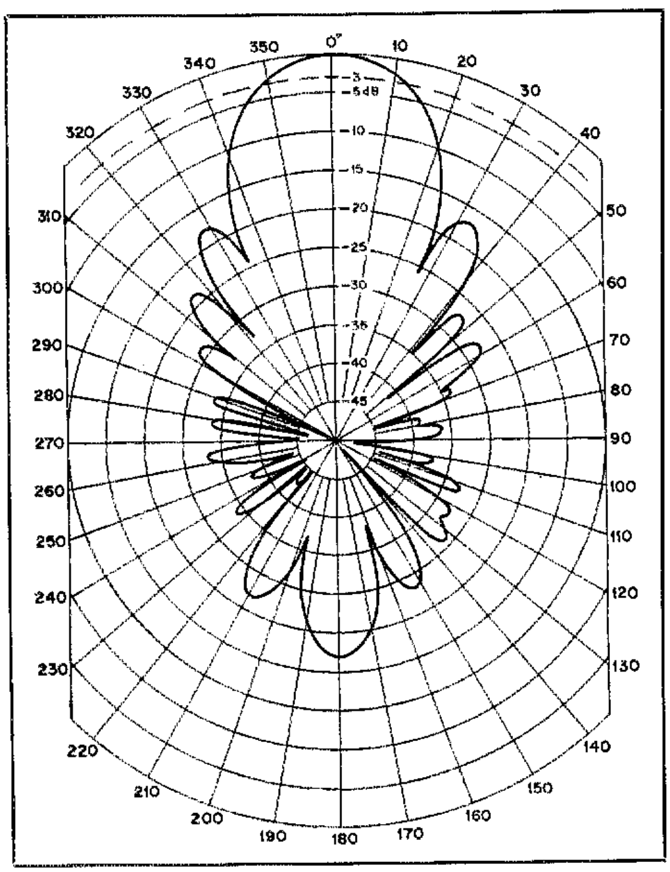


Fig 1—Computer-predicted H-plane (A) and E-plane (B) patterns for the K1FO 22-element, 432-MHz Yagi. Note: These antenna patterns are drawn on a linear dB grid, rather than the standard ARRL log-periodic grid. The linear dB grid shows sidelobes in greater detail and allows close comparison of sidelobes among different patterns. Sidelobe performance is important when stacking antennas in arrays for EME work.



← Fig 2—Measured E-plane pattern for the K1FO 22-element Yagi. Note: This antenna pattern is drawn on a linear dB grid, identical to the grids in Fig 1, rather than the standard ARRL log-periodic grid.

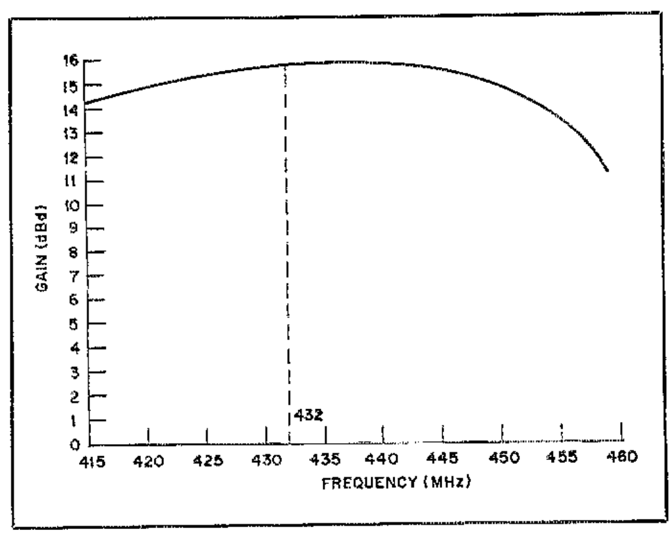


Fig 3—Gain versus frequency for the K1FO 22-element Yagi. Note that the 1-dB-gain bandwidth is 31 MHz and that the gain peak occurs at 437 MHz.

best of receiving systems to detect any improvement made from the reduction of these losses.

Pattern Measurements

Both the calculated and measured results demonstrate the value of the time spent in cleaning up the pattern. Fig 1 shows the calculated E- and H-plane patterns, and Fig 2 shows the measured E-plane pattern. The front-to-back ratio is 22 dB, and the first E-plane sidelobe is down about 17.5 dB.

Gain Bandwidth

Fig 3, a plot of calculated gain versus frequency, demonstrates the extremely wide gain bandwidth of the K1FO 22-element Yagi. Swept gain measurements of the Yagi using a network analyzer have confirmed the calculated gain bandwidth and center-frequency tuning. With an absolute gain peak at 437 MHz, the gain is less than 1.0 dB down between 420 and 450 MHz. The persistent myth that Yagis have very narrow bandwidths should be discredited forever.

Gain bandwidth (a measure of forward gain versus frequency) should not be confused with SWR bandwidth (SWR versus frequency). SWR bandwidth is a measure of the feed-point impedance and is not necessarily indicative of gain or pattern performance.

A wide gain bandwidth is important, even if operation will be on only a narrow band of frequencies. This is true for the following reasons:

1) *Construction tolerances.* The wider the bandwidth, the less critical the tolerances when building the Yagi. This makes it easier to retain excellent performance when duplicating antennas.

2) *Minimum shift of phase center.* A Yagi with smooth gain roll-off characteristics usually has less of a phase difference at the driven element as frequency changes. This is important in large arrays where the center Yagis will be operating at different points on their frequency response (this is caused by unequal mutual-impedance effects). Large phase shifts are characteristic of Yagis with many element spacings and lengths that are the same. It is also one of the major reasons why early amateur long Yagi designs were poor performers when used in large arrays.

3) *Array center frequency.* The value of wide gain bandwidth is related also to mutual-impedance effects. At 432 MHz, most of us are using arrays of Yagis (two or more antennas). Mutual-impedance effects tend to lower the center frequency of an array of Yagis relative to the center frequency of an individual Yagi. I have measured the drop in center frequency for an array of four RIW 19s to be about 400 kHz. Based on this experience, an array of 16 RIW Yagis might exhibit a center frequency drop of more than 1 MHz. An array made from wide-gain-bandwidth Yagis is a better choice than an array made from Yagis that exhibit a sharp gain drop on the high side of the peak gain frequency.

If the gain of a Yagi drops off rapidly just above the desired frequency of operation, lowering the array center frequency causes the stacking gain to be substantially lower than the theoretical 3.0 dB for doubling the array size. In addition, the pattern deteriorates rapidly above the maximum gain frequency for most Yagis (and especially for narrow bandwidth designs). For EME operation at 432 MHz, such poor Yagi pattern characteristics also create poor array patterns. This results in inferior receive performance because of unwanted earth-noise pickup.

SWR Bandwidth

A lot of time was spent designing a driven element that would have excellent dry weather and good wet weather SWR. I decided on a T match and optimized it at 432 MHz using a Hewlett-Packard 8753A network analyzer. A sweep of SWR versus frequency is shown in Fig 4. In dry weather, the SWR measured less than 1.10:1 from 431.2 MHz to 433.1 MHz.

The good SWR bandwidth results from the wide gain bandwidth of the Yagi and from tuning the director string above the center operating frequency. For this Yagi design (as well as for other designs that were built and tested), the driven element impedance changes less with frequency on the low-frequency side of the gain peak than at or above the gain peak.

I used a garden hose to wet the Yagi for simulated heavy rain conditions. A plot of SWR versus frequency under these wet conditions (Fig 5) demonstrates how the match center frequency shifts when the Yagi is wet. The network analyzer showed that when wet, the driven element impedance becomes more inductively reactive. The SWR at 432 MHz is still an excellent 1.18:1 when the Yagi is wet. My present array of 12 22-element Yagis measures (in the shack) well under 1.2:1 when dry, and about 1.3:1 in heavy rain. Icing is a different story. As with all other 432-MHz Yagis I have tested, performance is seriously degraded under icing conditions.

I have been asked if a quad-loop driven element could be used with this Yagi. I do not favor the use of a quad-loop driven element on a long Yagi. The only advantage of a quad loop is a slightly greater

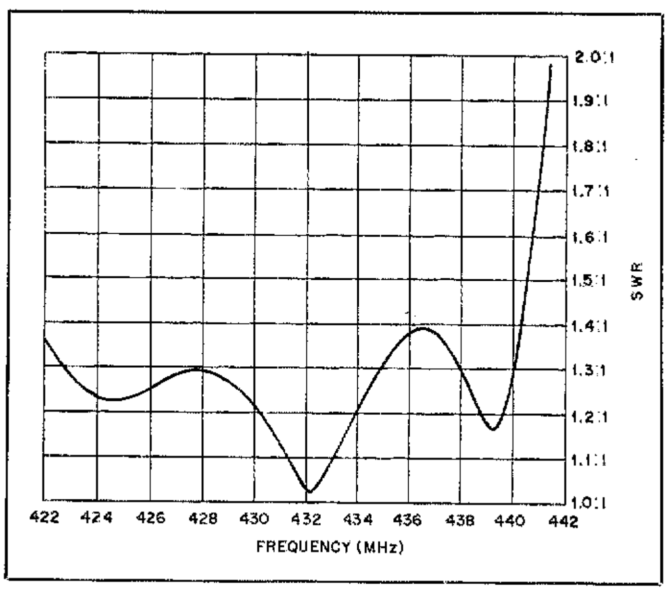


Fig 4—SWR performance of the K1FO 22-element Yagi in dry weather.

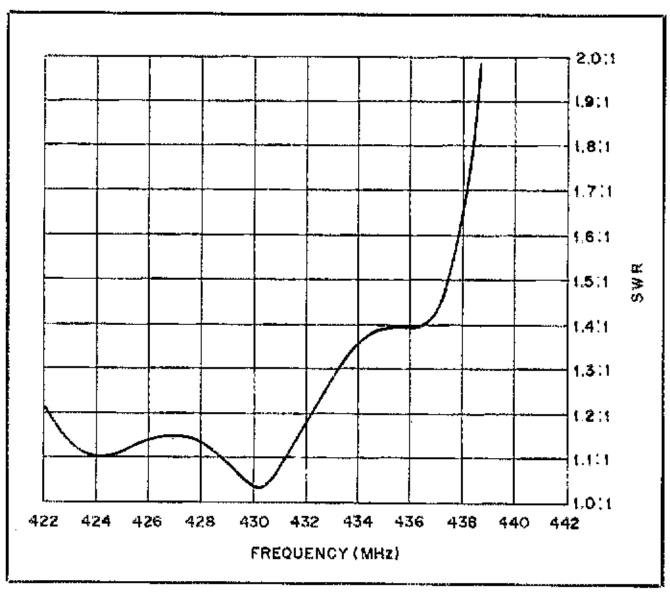


Fig 5—SWR performance of the K1FO 22-element Yagi in wet weather.

driven-element match bandwidth. All the old myths about lower noise pickup, higher gain and better pattern are exactly that: old myths. The quad-loop driven element also adds weight and windload area to the antenna without improving its gain. (I modeled this design on the computer with a quad-loop driven element and found that to make it work at all would require extensive changes to the first three or four director lengths and positions. If you want to try a quad-loop driven element or a driven-element feed system other than a T match, you have quite a job ahead of you, and you're on your own.)

Conclusions

The excellent pattern and gain of the 22-element Yagi are confirmed by the stacking spacings that give best array gain versus noise temperature. Optimum stacking distances are 65 inches in the E-plane and 62 inches in the H-plane. At those distances, stacking gain is almost 2.9 dB in both planes. (Phasing-line losses and gain loss caused by mechanical errors such as frame sag and misalignment are not included). The beamwidth of the Yagi at 432 MHz is 23 degrees in the E plane and 24 degrees in the H plane.

In examining the stacking characteristics of several popular 432-MHz commercial Yagis, I found it to be impossible to obtain more than 2.5 dB stacking gain (excluding phasing-line losses).[3] This phenomenon was not a function of the physics of stacking Yagis. It was caused by the design limitations of the Yagis under test. By comparison, calculated and measured stacking gains of approximately 2.9 dB (in both the E and H planes) were obtained with the K1FO 22-element design. This figure excludes phasing-line losses.

At 15.7 dBd gain for a 6.1-wavelength boom, the gain of the K1FO 22-element Yagi approaches the theoretical maximum for its boom length. It may seem that I have done a lot of work perfecting the design—and that a gain variation of a few tenths of a dB one way or the other isn't worth worrying about for a single 14-foot long Yagi. For an EME array of 8, 12 or 16 Yagis, however, the array gain versus wind load problem makes the effort required to tweak the antenna *very* worthwhile!

Coming in Part 2: Dimensions and details for duplicating the K1FO 22-element Yagi—and how to scale the K1FO design for other boom lengths.

Notes

[1]Powlishen, S., "High-Performance Yagis for 432 MHz," *Ham Radio*, Jul 87, pp 8-31.

[2]The first E- and H-plane sidelobes are actually a single cone-shaped lobe which surrounds the main lobe when the pattern is viewed in three dimensions.

[3]Powlishen, S., "Stacking Yagis is a Science," *Ham Radio*, May 85, pp 18-33.

New Books

SINGLE-SIDEBAND SYSTEMS AND CIRCUITS

Edited by William E. Sabin and Edgar O. Schoenike. Published by McGraw-Hill Book Co, New York, NY. ISBN 0-07-054407-7. Hard cover, 6 × 9 inches, 594 pages, $49.95.

In 1964, Pappenfus, Bruene and Schoenike, all members of the technical staff at Collins Radio, published *Single Sideband Principles and Circuits*. The text quickly became a standard reference for RF engineers and technically minded radio amateurs. We were quite excited to learn that this classic was to be replaced with an updated version. *Single-Sideband Systems and Circuits* was written by 22 members of the technical staff of Collins Defense Communications, a part of Rockwell International. Two of the original trio of authors are included in the present listing.

This book is a technical reference aimed at the circuit design professional. Mathematics is used liberally throughout. The resulting analytical sophistication extends to the text discussions. The reader without a formal technical background will probably be disappointed in the book.

As implied in the title, the text primarily treats SSB methods. Much of the discussion, however, is general and applies equally well to CW and data communications interests. An early chapter, System Design Considerations, presents the fundamentals of modulation theory for voice communications. These basics form background for the rest of the text. The chapter also examines many basic phenomena that limit SSB communications.

The chapters that follow examine specific aspects of SSB. The Receiver Design chapter and a later one on receiver measurements were of special interest to this reviewer. Many interesting amplifier and mixer circuits are presented. A similar chapter on exciter and transceiver design was of equal interest. An entire chapter is devoted to speech processing, squelch and noise blanking. Other chapters are devoted to preselector and receiver IF filters, power supplies, digital controls, frequency standards and even antenna matching.

The weak element in most present-day HF ham equipment is the frequency synthesizer. The chapter covering this subject is excellent, although it left this reader looking for more detail.

Three chapters are devoted to the design of RF power amplifiers. These range from the familiar solid-state PAs in the 100-watt class to very high power vacuum tube circuits. The discussions of RF transformer design and of advanced feed-forward methods are excellent.

Perhaps the most exciting chapter in the book is that devoted to Digital Signal Processing, or DSP. An analog signal may be digitized with a circuit termed an analog-to-digital converter, or ADC. The opposite conversion is performed with a DAC. Analog functions that used to require amplifiers, mixers or filters are now realized with computer-like manipulations applied to the equivalent digital signal.

DSP is a rapidly growing segment of communications technology with many new books devoted to the subject. Unfortunately, many of these texts are written by and aimed at the digital designers. The DSP chapter in *Single-Sideband Systems and Circuits* is a refreshing departure, with fundamental concepts presented in terms familiar to the more traditional communications engineer. There is excellent correlation between the DSP chapter and the earlier System Design chapter.

Sabin and Schoenike, the editors, have managed to maintain a uniformity of presentation style, a difficult chore with multiple authors. The resulting text is quite readable. I would recommend the book to anyone with a moderate technical background.—*Wes Hayward, W7ZOI*

Strays

I would like to get in touch with...

☐ any faculty, alumni and students of Louisiana State University for support in reviving W5YW. Doug Hensley, WJ5J, 5054 Holloway Ave, Baton Rouge, LA 70808.

☐ anyone who has 7-Band WAS. Jack Keller, WB9ETQ, R-7, Crawfordsville, IN 47933.

☐ anyone who was a Navy radio operator from WW II PC Splinter fleet. James Guarino, NQ2A, 20 Nadine Dr, Cheektowaga, NY 14225.

☐ anyone who speaks Greek to join a net that meets on 14,385 kHz every afternoon 1700-2200 Greece time. Dr Agis Sarakinos, SV1ACS/W5WB, 4 Chiou, Chalandri, Athens, Greece.

☐ anyone interested in meteor-scatter schedules as described in Nov 1986 *QST*. David Sarkozi, WB5N, 4278 Childress, Houston, TX 77005.