Design of a 2-3-Element Full-Performance Yagi for Portable and Field Use with No-Tool Configuration Changing
Part 1: Electrical Design

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Introduction

These notes describe the electrical and mechanical design of a Yagi beam for field and other portable uses. It employs a 12' boom for high performance from 3 elements on 15, 12, and 10 meters and full 2-element performance on 17 and 20 meters. The maximum element length is 26.33' to optimize gain and front-to-back ratio on each band. The beam requires no matching section, but connects directly to a 50-Ω coaxial cable with 1.6:1 SWR or better. By virtue of the mechanical design, the beam allows modification for any desired band within the 14- to 30-MHz range.

The assembly and disassembly of the beam for storage and transport requires only that the user snap into place spring clips. Careful attention to structural detail results in a package no longer than about 42". Each half-element consists (excluding a special center piece) of 4 40" sections of aluminum tubing that nest together when not in use. The boom uses 4 36" sections of aluminum or strong non-conductive tubing that, together, form a 12' boom. Special extensions that hang downward provide the final element pieces for 20 and 17 meters. 3 special element-to-boom assemblies and a boom-to-mast assembly complete the package. Although some assemblies require nuts and bolts (or equivalent fasteners), they are fixed and require no attention in the field.

Background

A field or portable Yagi antenna for directional communications in the upper HF spectrum (14 through 30 MHz) has special needs.

1. The beam must easily assemble and disassemble so that the transport and storage package is reasonably small. A package length of less than 4' with a 6" by 6" cross-section is desirable.

2. Assembly should require no tools and no post-assembly adjustments.

3. Although the requirements for durable electrical contact are not as stringent as for a beam placed in a permanent location, good contact between all antenna components must be reliable for several days without attention.

4. The antenna should require no matching section, but connect directly to a coaxial cable feedline (normally 50 Ω) with a very low SWR across each proposed operating band.

5. Within the physical limits of the package, the antenna should provide maximum forward gain and maximum front-to-back ratio commensurate with other requirements for the antenna.

6. Even though the antenna is not designed for high wind loads, the antenna should be sufficiently strong and durable for many field or portable uses.

7. The antenna should be as light as materials will permit, perhaps 10-12 pounds maximum.

Several alternative beams are available that often function as portable or field antennas. Some antennas provide tri-band operation. However, the lightest use riveted construction and are not easy to assemble and disassemble repeatedly in the field. There are also re-configurable 2-element beams. However, they use very short booms and very high element loading, resulting in reduced performance on all bands below 12 meters. Indeed, one such beam achieves a free-space forward gain of only 3.1 dBi on 20 meters, scarcely more than a simple full-size dipole element. A 2-element driver-reflector beam for 20 meters should be able to reach at least 6 dBi forward gain with a 10-dB front-to-back ratio.

The challenge facing the designer is to settle on a workable boom length that will allow full performance using at least 2 elements on each band while sustaining a light total weight and no-tool band changes. Ideally, the design should not sacrifice either the element length or the boom length needed for full performance. Rather, the design should maximize each within the constraints of the transportation and storage requirements.

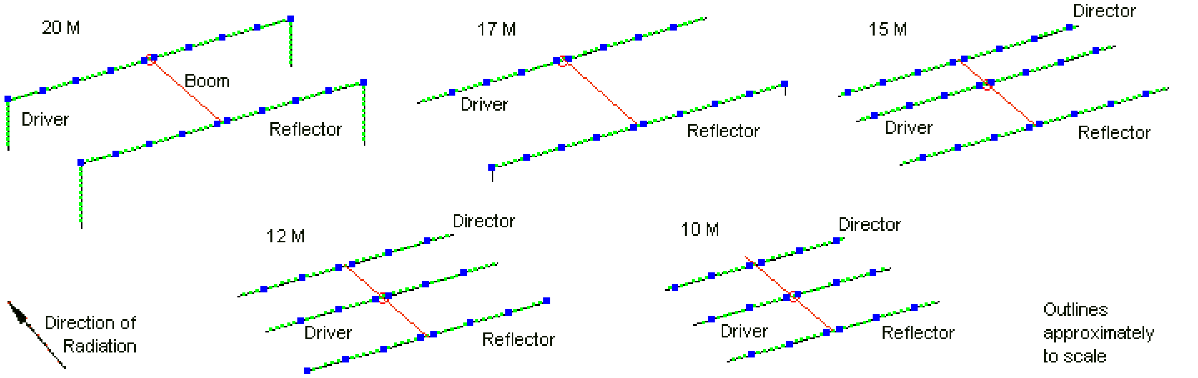
Electrical Design of the 2-3-Element Field Yagi

Although the electrical and mechanical design facets of the field beam are inseparable, we may artificially split the two for ease of following the design philosophy. For both mechanical and electrical reasons, the design uses a structural boom length of 12', with a usable electrical length of 11.8' (141.6"). The mechanical side of the boom selection rests on using commonly available materials that one may subdivide into storage sections well under 4' long. The electrical side of the question is a joint function of the 50-Ω feedpoint impedance goal along with the length needed on 20 meters for full-size 2-element performance and the length needed on 10 meters for full-size 3-element performance. Ultimately, the design uses 3 elements (a reflector, a driver, and a director) on 10, 12, and 15 meters and 2-elements (a reflector and a driver) on 17 and 20 meters.

The maximum element length horizontally is a function of several mechanical requirements, of which the disassembled element structure is critical. Besides a short center section, each half-element consists of 40" sections of aluminum tubing (6063-T832, with a wall thickness of 0.056") with diameters that range from 0.75" at the center down to 0.375" at the tips, in 0.125" increments. With a 6" half-center-section, the limit on the half-element length is 158". This length (or shorter lengths) provides full-size elements on 15 through 10 meters. On 17 meters, the driver is full size. However, the reflector requires short vertical extensions at each tip. On 20 meters, each element requires a significant vertical extension, but the low current in these extensions does not degrade performance.

Fig. 1 provides outline drawings of each beam configuration. The outline for each band shows the transition from each diameter of tubing to the next one with a blue dot. A red line marks the boom location. The beam uses the full boom on all bands except 10 meters, which only needs about 136" for full performance. On 15 and 12 meters, the reflector and director are at the boom ends, but the driver placement differs for each band, with a third placement for 10 meters. Changing from one band to another is simple with the use of snap-on elements placed at pre-marked locations.

The outline sketches are approximately to scale. The use of vertical extensions for 20 and 17 meters is evident. The green dots in each sketch represent segmentation markers for the NEC-4 models used to develop the electrical design of each configuration.



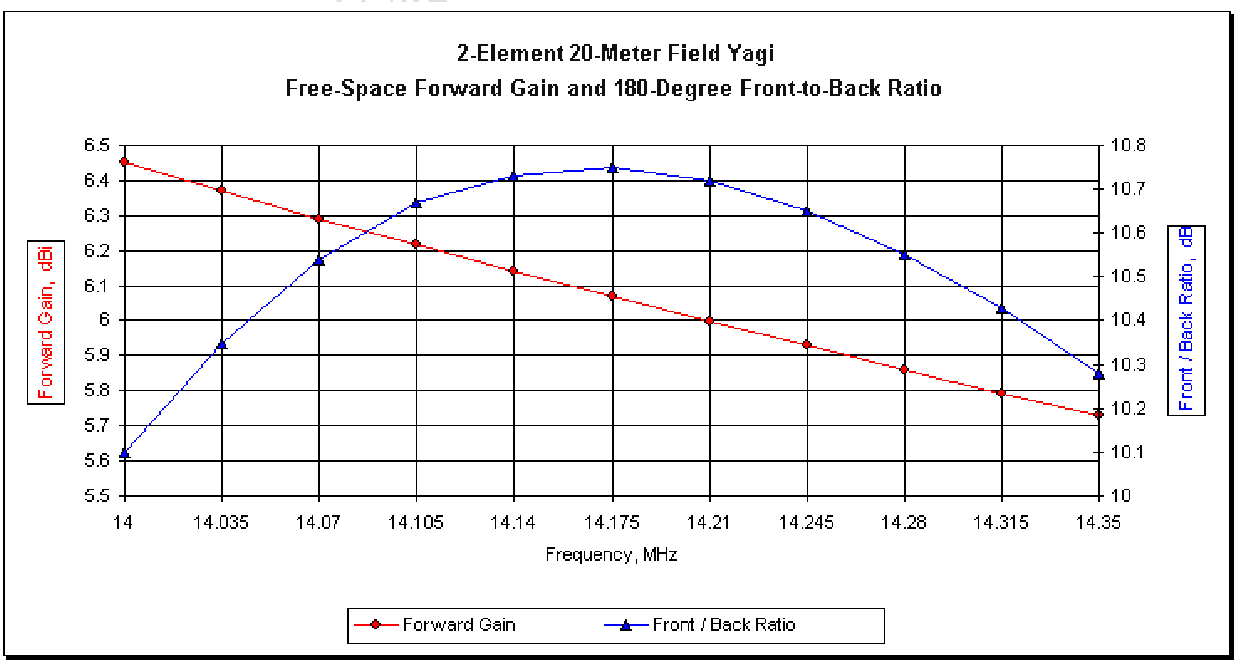
Outlines of Beam Configurations on Amateur Bands from 20 Meters to 10 Meters
Showing Element Segmentation (Blue/Green) and Boom (Red)

Fig. 1

The following notes provide a band-by-band listing of the outer dimensions of each beam configuration. (We shall discuss the element structure further in the mechanical section of this report. The listed outer dimensions apply only to the element taper shown in the discussion of mechanical considerations.) In addition, each of the following sections will show graphs of the gain, front-to-back ratio, and impedance performance of the antenna, with spot tabular entries for orientation. In addition, the performance data also include relevant free-space E-plane patterns for each configuration. These patterns correspond to the patterns anticipated over real ground. However, since each installation may vary, the free-space patterns are the most general plots that are useful for overall beam evaluation.

20 Meters

A minimum boom length for a 3-element Yagi on 20 meters is 16'. For a 50-Ω feedpoint impedance with no matching section, the boom length grows to nearly 24'. However, a 12' boom allows full 2-element driver-reflector Yagi performance with the desired impedance.



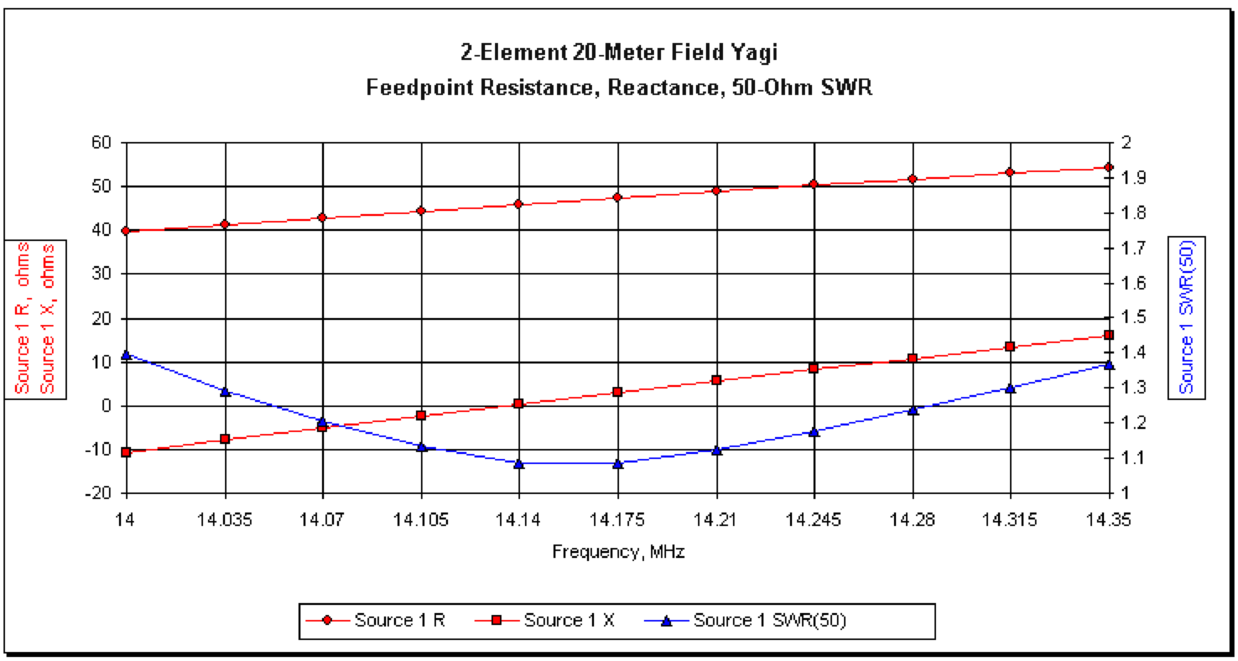
A full-size driver-reflector Yagi shows a descending gain curve as frequency increases. The table lists the dimensions, including the length of the vertical element ends, along with the performance of the beam in free space at the band edges and at mid-band.

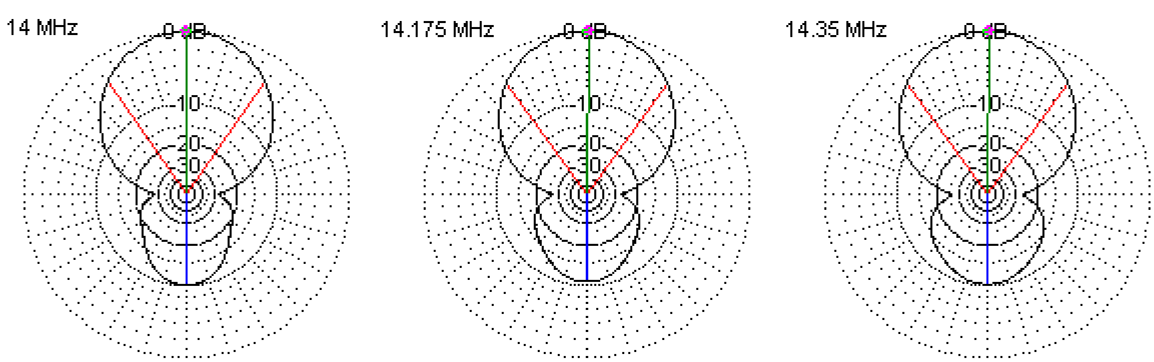
20-meter outer dimensions in inches

Element	Length	Space from Reflector	Vertical end length
Reflector	316	---	71
Driver	316	141.6	55

Performance

Category	14.0	14.175	14.35
Gain dBi	6.45	6.07	5.73
180° front-to-back ratio dB	10.09	10.75	10.28
Impedance (R +/- jX Ω)	39.7 – j10.9	47.5 + j3.0	54.4 + j15.8
50-Ω SWR	1.40	1.08	1.37

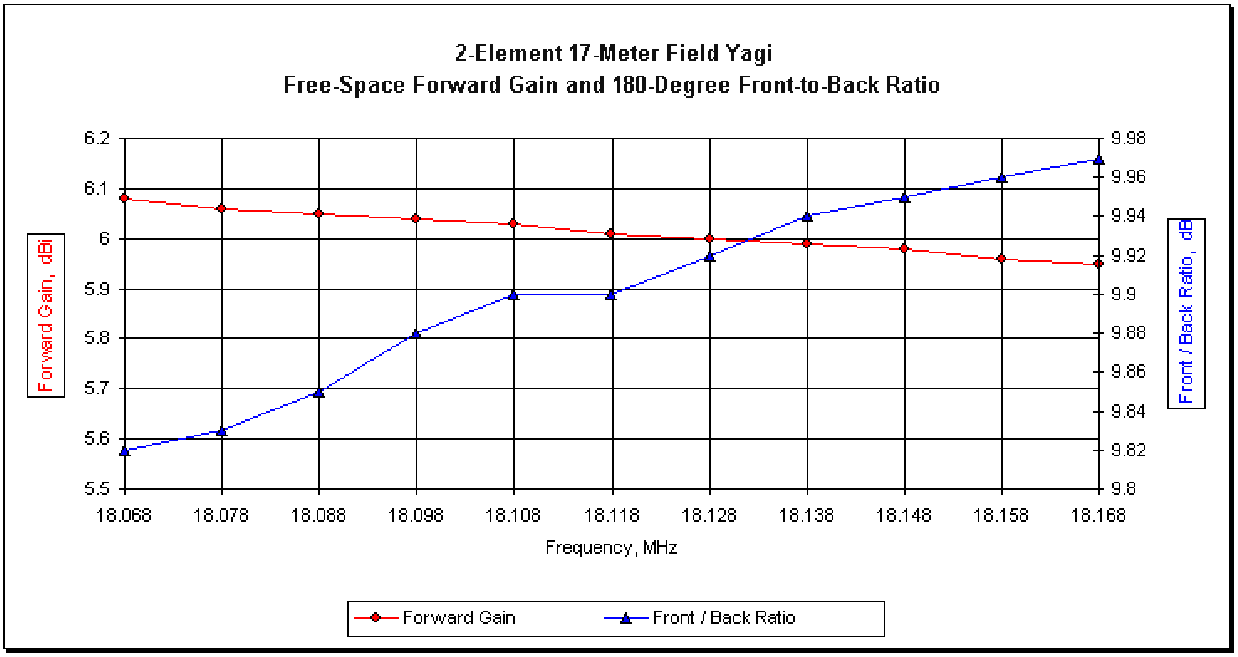




Free-Space 20-Meter E-Plane Patterns

17 Meters

Because the 17-meter band is only 100 kHz wide, a single plot serves for all parts of the band. However, both graphical and tabular data follow the pattern established for 20 meters. The 17-meter beam is also a driver-reflector Yagi. The outline of the 17-meter configuration shows vertical end pieces that are 14" long on the reflector only. One may replace these pieces with 12" horizontal end extensions of the reflector for exactly equivalent performance.



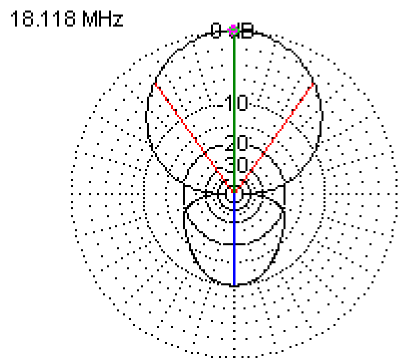
17-meter outer dimensions in inches

Element	Length	Space from Reflector	Vertical end length
Reflector	316	---	14
Driver	312	141.6	---

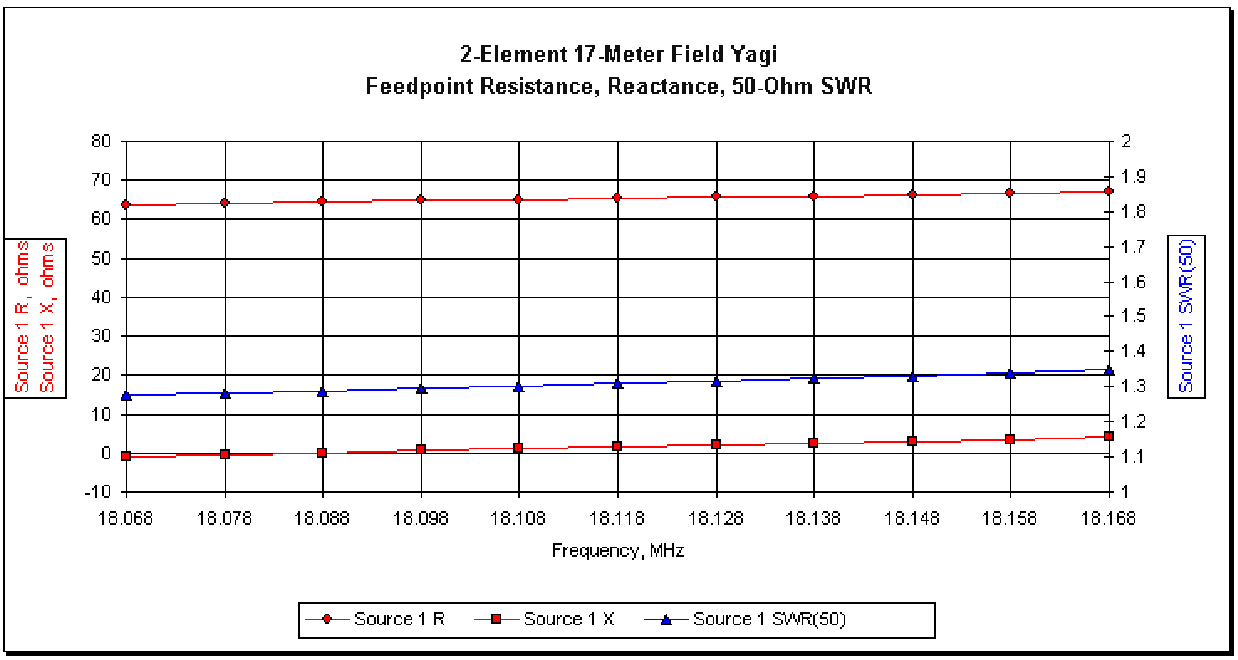
Performance

Category	18.068	18.118	18.168
Gain dBi	6.08	6.01	5.95
180° front-to-back ratio dB	9.82	9.90	9.97
Impedance (R +/- jX Ω)	63.8 – j0.9	65.4 + j1.6	66.9 + j4.0
50-Ω SWR	1.28	1.31	1.35

The gain graph shows the typical driver-reflect decrease in gain with rising frequency. Because the spacing between the element is slightly greater than optimal for user convenience in setting up the antenna, the front-to-back ratio shows a rising curve, but over a very small range of values. The stair-step nature of the front-to-back curve results from the limitation of the front-to-back increments to 2 decimal places. The feedpoint impedance is slightly higher than optimal, but the SWR values are all below 1.4:1 across the band, as shown in the graph of impedance and SWR values. A single free-space pattern suffices for all frequencies on the band, since the pattern changes so slowly relative to the narrow width of the band.



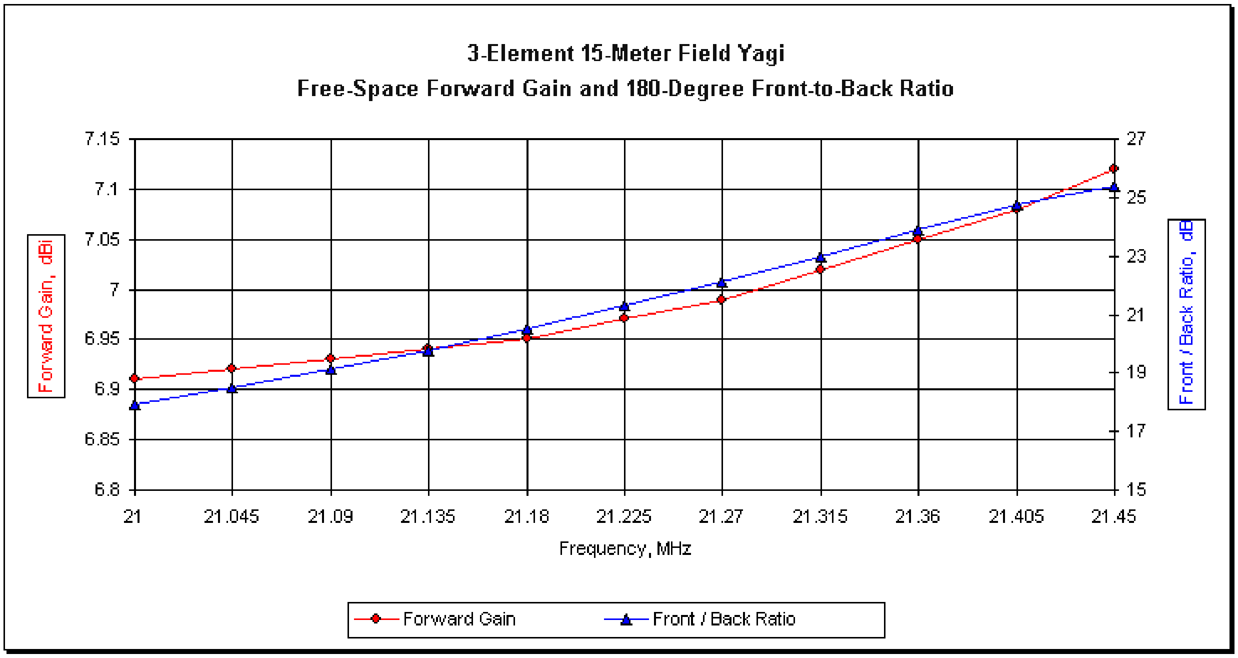
Free-Space 17-Meter E-Plane Patterns



15 Meters

15 meters is the first band on which it is practical to use 3 elements within the limits of the boom length. The presence of a director in the beam reverses the gain curve so that it shows a rising value as frequency increases. Because driver-to-director spacing is less than optimal within the limitations of the boom length, the front-to-back ratio curve shows a rising value rather than being centered within the passband. This concession is required to provide an acceptably low SWR curve, with a maximum value below 1.6:1. Although the front-to-back ratio is not maximum at the center of the band, the lowest value is about 18 dB, which is considerably higher than a value that a driver-reflector 2-element Yagi can achieve.

The elements for the 15-meter configuration are shorter than the maximum possible length. As the element length decreases, the outer (0.375" diameter) section decreases in length and may disappear altogether with some elements on this or higher bands. For 15 meters and higher, the elements do not require vertical extensions of any sort.

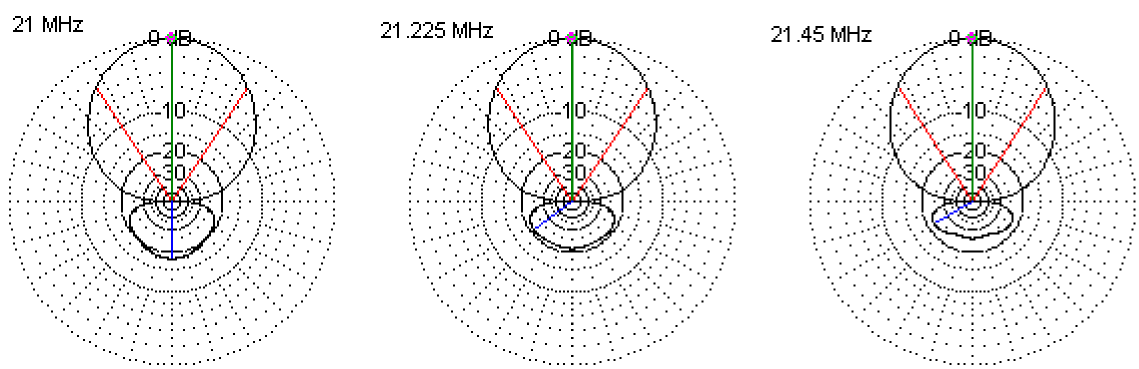


15-meter outer dimensions in inches

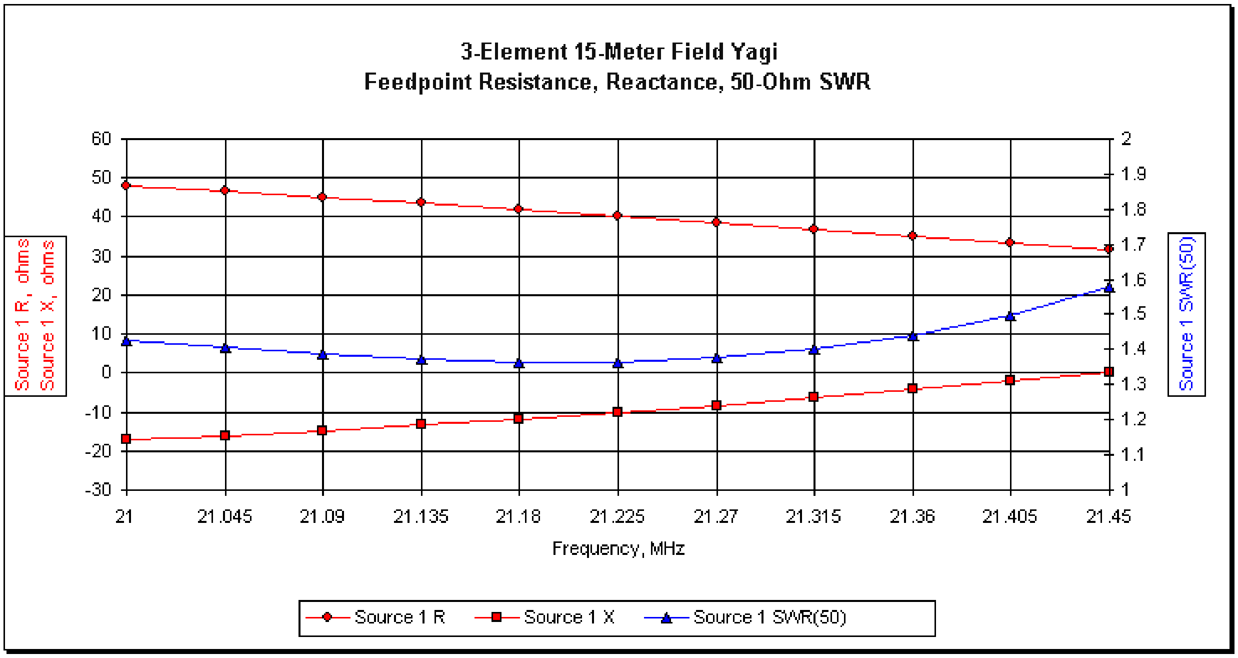
Element	Length	Space from Reflector
Reflector	292	---
Driver	280	91.2
Director	260	141.6

Performance

Category	21.0	21.225	21.45
Gain dBi	6.91	6.97	7.12
180° front-to-back ratio dB	17.90	21.29	25.39
Impedance (R +/- jX Ω)	48.0 – j17.3	40.2 – j10.1	31.7 + j0.3
50-Ω SWR	1.42	1.37	1.58

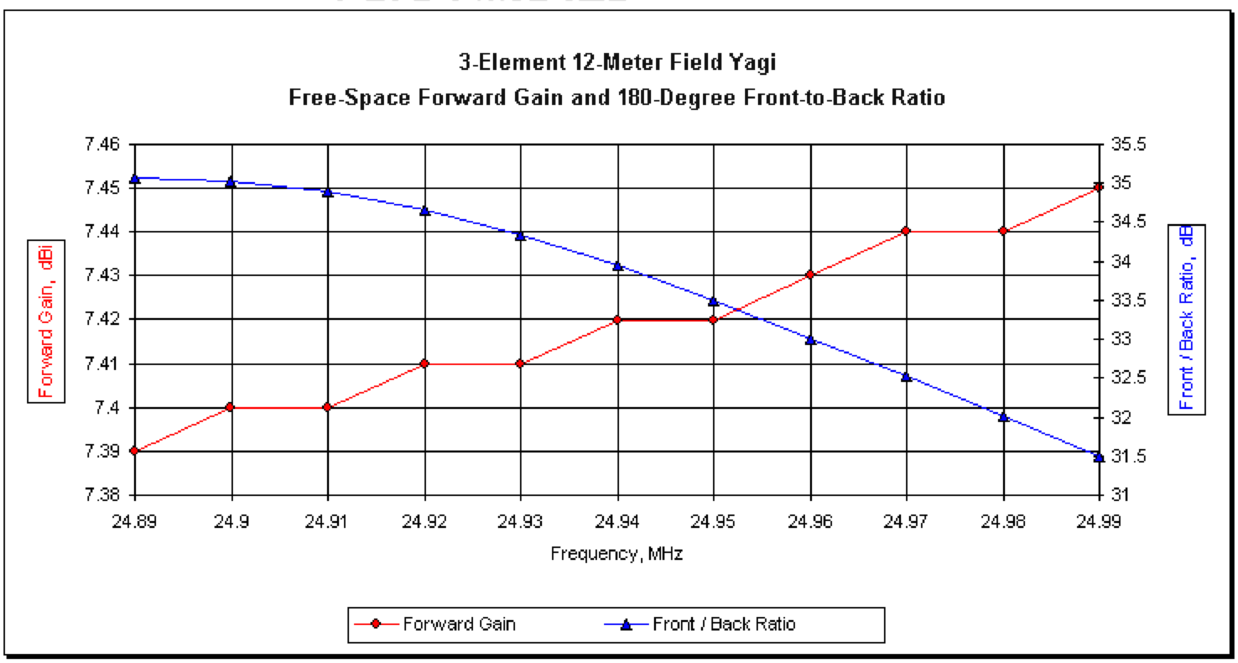


Free-Space 15-Meter E-Plane Patterns



12 Meters

The 12-meter band is also very narrow. Therefore, the E-plane free-space pattern shown applies across the entire small passband. As well, the gain graph shows the stair-step quality that results due to the limitation in the gain increment used. Because the boom length is slightly short of optimal, the front-to-back curve shows descending values, but all are above 30 dB. The maximum 50-Ohm SWR is less than 1.4:1, although the resistive component of the impedance is slightly less than 40 Ω.

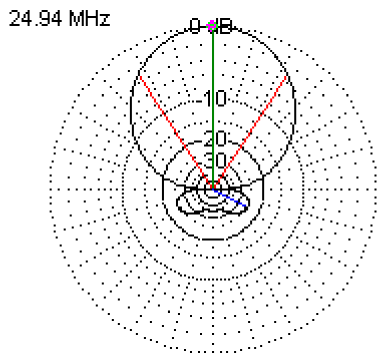


12-meter outer dimensions in inches

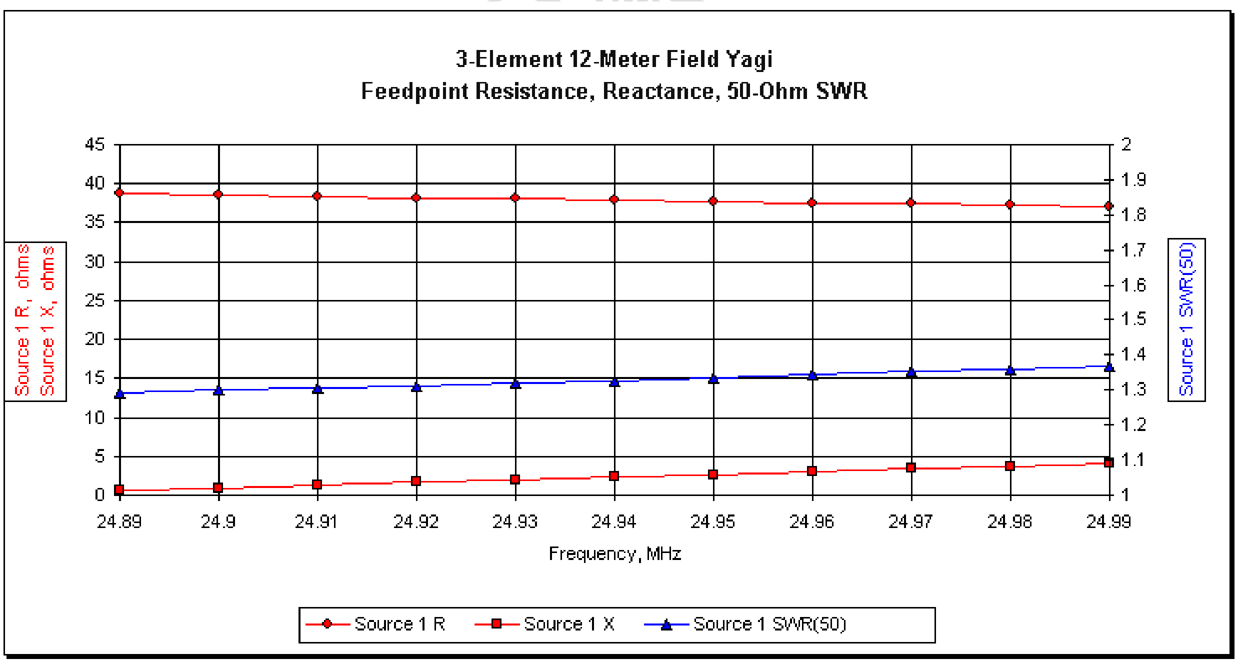
Element	Length	Space from Reflector
Reflector	248	---
Driver	234	78
Director	216	141.6

Performance

Category	24.89	24.94	24.99
Gain dBi	7.39	7.42	7.45
180° front-to-back ratio dB	35.07	33.94	31.49
Impedance (R +/- jX Ω)	38.7 + j0.6	37.9 + j2.3	37.0 + j4.1
50-Ω SWR	1.29	1.33	1.37

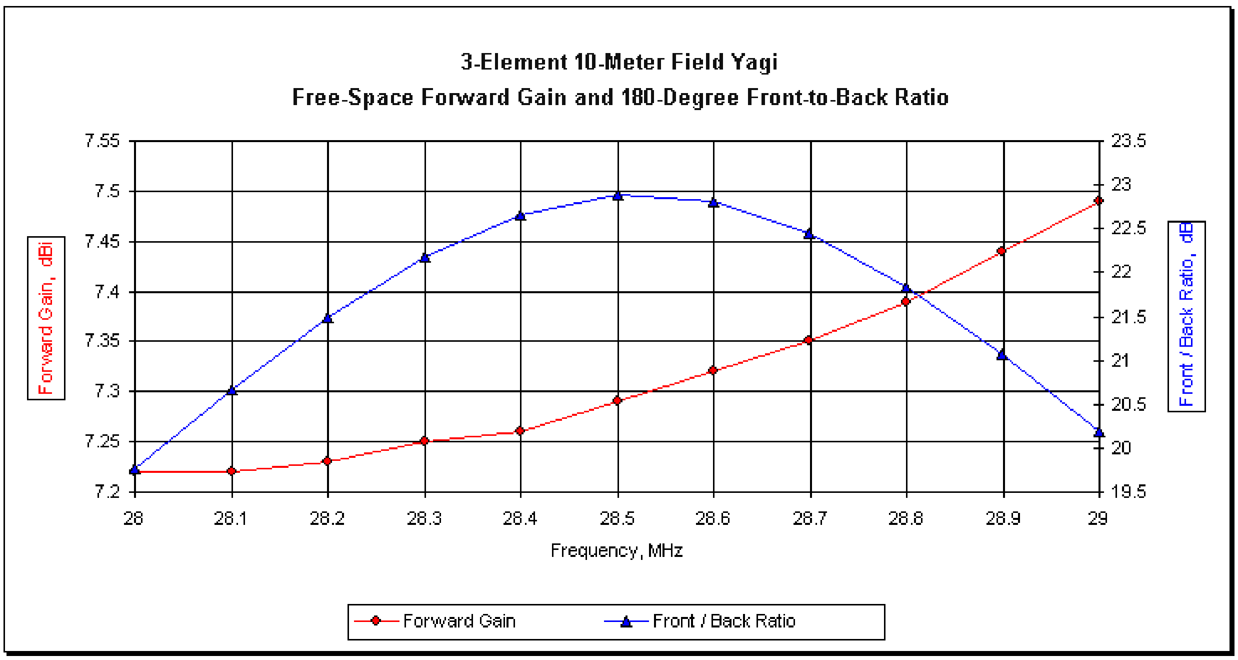


Free-Space 12-Meter E-Plane Patterns



10 Meters

The 10-meter band is the widest in the upper HF amateur collection. However, the available boom length is greater than needed for an optimized wide-band 3-element Yagi. Therefore, the antenna is capable of providing full performance for the entire span with a maximum 50-Ω SWR value that is only about 1.43:1. The graphical and tabular modeled data as well as the sample free-space E-plane patterns show smooth performance relative to the beam type. The front-to-back ratio curve is well centered within the passband, as is the 50-Ω SWR curve. The resistive component of the feedpoint impedance changes only by about 4 Ω, while the reactance change across the band is about j27 Ω. The front-to-back ratio only dips barely below 20 dB at the lowest end of the passband. Across the 1-MHz passband, the gain differential is only about ¼-dB.

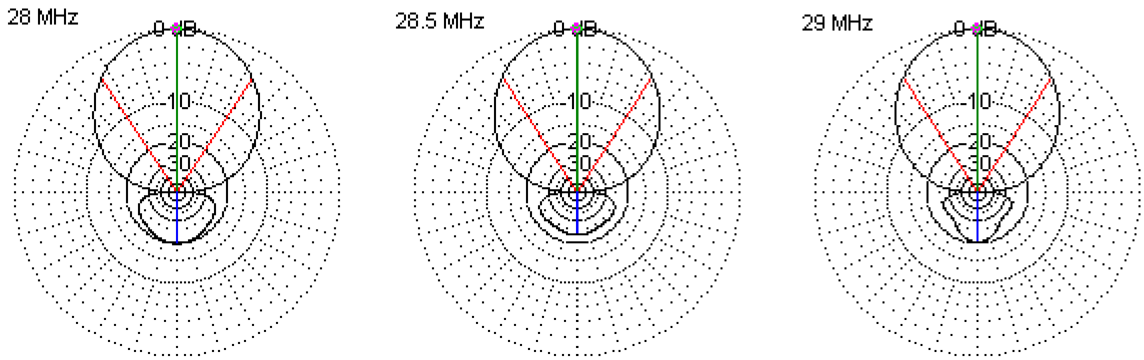


10-meter outer dimensions in inches

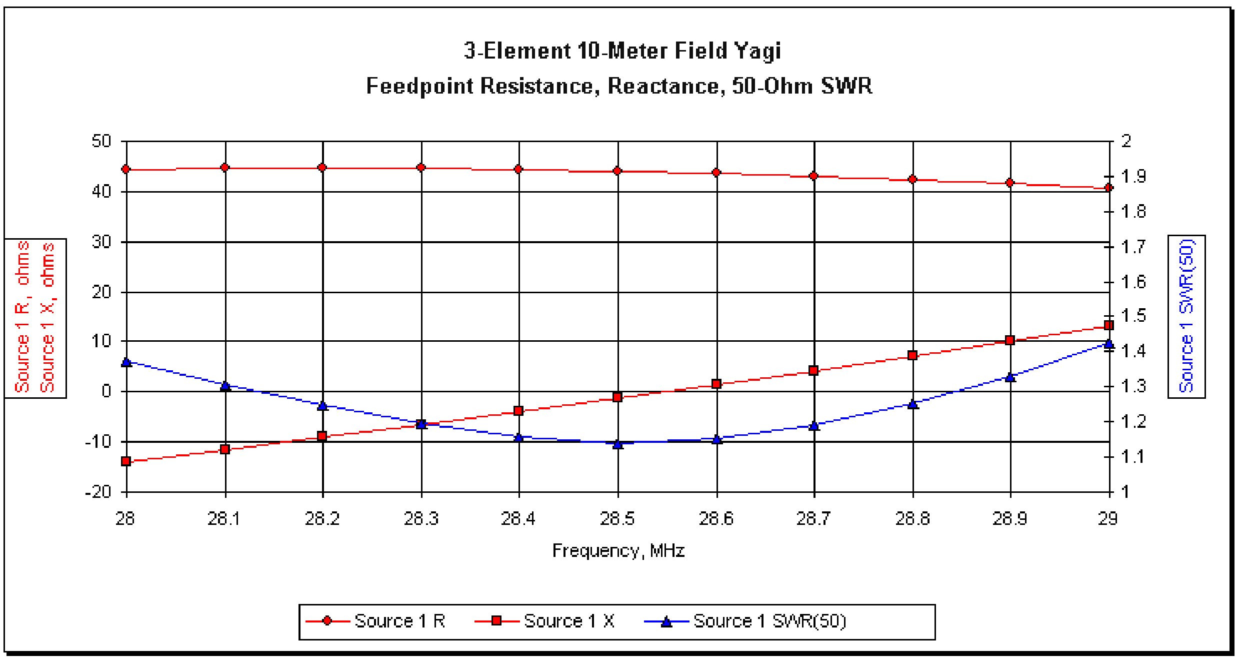
Element	Length	Space from Reflector
Reflector	216	---
Driver	201	71
Director	182	136

Performance

Category	28.0	28.5	29.0
Gain dBi	7.22	7.29	7.49
180° front-to-back ratio dB	19.76	22.88	20.18
Impedance (R +/- jX Ω)	44.4 – j13.9	44.0 – j1.3	40.7 + j13.4
50-Ω SWR	1.37	1.14	1.43



Free-Space 10-Meter E-Plane Patterns



Summary of Electrical Characteristics of the Beam Design

The electrical configurations shown are each unique to the element diameter taper schedule discussed more extensively in the following section on mechanical aspects of the design. Each configuration meets the criterion for maximum performance relative to the boom length and the number of elements, consistent with the additional criterion of showing a feedpoint impedance that allows a direct match to a 50-Ω coaxial cable transmission line.

The relatively broad curves for almost all performance properties reveals two other properties essential to reliable field operation. First, the operating points are not especially finicky in the sense that fractional displacement of the element positions would alter either the basic performance or the 50-Ω SWR curve. (Element lengths will be pre-set and therefore will be correct without possibility of field error.) Second, the configurations show generally broadband properties so that one may operate the beam outside the edges of the amateur band while retaining good performance and a 50-Ω SWR of less than 2:1. This property also contributes to reliable field operation, since it minimizes the effects of surrounding objects that may slightly detune the array.

Because one may set each element at a desired location on the boom and shrink the element lengths to a minimum of 88", one may also find special-purpose settings for operating the beam at frequencies above 100 MHz with the general performance level shown in the 10-meter graphs and tables. Therefore, one may use the beam (with modifications relative to the proposed mechanical set-up) on the worldwide 6-meter amateur band and the European 5-meter (72-MHz) amateur band. However, within the goals of this design, only the upper HF region settings appear.

The electrical design of the field Yagi achieves the goals set for the project within the boom length and element length constraints required both for physical stability and weight when assembled and by the requirements of a compact disassembled storage and transport package.

In Part 2, we shall examine the mechanical facets of the beam design.