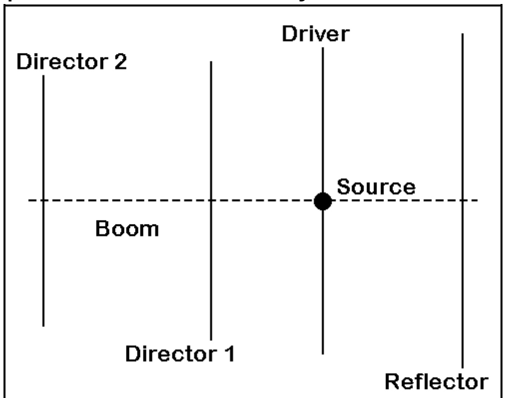
18.
Yagis

Objectives: The Yagi antenna is among the most common and varied horizontally polarized antenna design used from HF through UHF. In these exercises, you will become acquainted with some of the characteristics of parasitic antenna element modeling and operation. You will also work with multi-band Yagis and with stacks.

The Yagi, named for the Yagi-Uda discoveries and developments of the 1920s, has become a *de facto* standard for multi-element antenna arrays in the HF through UHF range. Used as horizontally polarized beams at HF, Yagis also perform as vertically polarized antennas at VHF and UHF. Versions of the antenna range from 2-element copper wire antennas for lower HF operation to long-boom giants, including up to 40+ elements for UHF use.

In these exercises, we shall confine ourselves to HF Yagis, since a future chapter will pay special attention to VHF and UHF antenna designs. Even within these limits, there are too many design variations to sample adequately. Therefore, we shall focus instead on some of the primary characteristics of Yagis as revealed by some common members of this family of antennas.

The Yagi is based on principles of parasitic elements, that is, elements not directly fed by an energy source. These elements achieve their ability to alter and focus the radiation pattern by the currents induced in them by radiation from the driven element. According to their length and spacing from the driven element, the parasitic elements become either directors or reflectors. Directors are shorter than the driven element (by 1 to 5%, depending upon spacing) and result in the radiation pattern being sharply distorted in the direction of the director. Reflectors are longer than the driven element (again, by 1 to 5%, depending upon spacing) and result in a radiation pattern directed away from them.



18.0 A typical 4-element Yagi

It is possible to create Yagi arrays with just two elements--either a director-driver combination or a reflector-drive combination. However, Yagis acquire significantly more gain and a better controlled front-to-back ratio when they employ at least three elements. Normally, for Yagis of 3 or more elements, there is one reflector and one driver, with additional elements being directors. **Figure 18-0** illustrates a 4-element Yagi to give a general impression of the taper of the elements. Traditional Yagi design tends toward reducing the length of each director forward of the driver. However, some designs optimized for various purposes may have equal length directors or even one that is shorter than its adjacent directors.

Recommended reading on Yagi design includes Dr. James L. Lawson's *Yagi Antenna Design* (Newington: ARRL, 1986), which developed a large body of systematic data about many aspects of Yagi design via computer models. Although a number of ingredients in Lawson's analysis have undergone refinement, basic principles remain intact. The dependency of Yagis for gain upon boom length rather than the number of elements and the recognition of the role of tapered-diameter elements are but two of many Lawson precepts.

Despite intensive work by many over the decades since the 1920s, Yagi design is far from exhausted. Moreover, design debate continues to this day. For example, some designers prefer high gain and accept a narrower operating bandwidth and lower source impedance as the cost of that gain. Others opt for a higher source impedance and wider operating bandwidth at a cost of either less gain or an additional element for a given boom length.

In this set of exercises, we shall first look at models exhibiting basic Yagi properties and limitations. We shall then move to models that exemplify some of the design trade-offs inherent in Yagis. Finally, we shall explore a few multi-band Yagi models to discover additional trade-offs involved in multi-frequency design.

Yagi antennas generally refer to a subclass of parasitic antenna arrays, normally those involving a 1/2λ driven element and parasitic elements close to 1/2λ long. However, parasitic arrays can also include other antenna types, including vertical monopoles and non-resonant driver arrays. For example, we have known since the mid-1930s how to create a parasitic array from two extended double Zepp (1.25λ) elements.

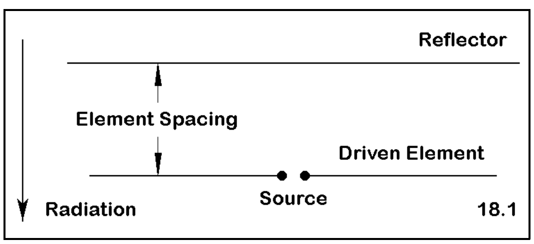
ExercisePreparation

The characteristics of most Yagi beams or arrays are best gathered by running a frequency sweep across a band of frequencies of interest. The antennas in this set of exercises are designed for the amateur radio high frequency spectrum, where bandwidths may range from 13% of the band center frequency down to 0.4%. These bandwidths present Yagi designers with very different challenges, which may call for different types of configurations of reflectors and/or directors.

All of the Yagi designs in this exercise set have placed the point of maximum front-to-back ratio at the design center frequency, midway between the frequency sweep limits built into the initial models. Since the frequency of maximum gain ordinarily does not coincide with the frequency of maximum front-to-back ratio in Yagi design, the peak gain obtainable from a design may be near the frequency sweep limit at one or the other end of a band--or it may lie outside the band. In actual designs, the front-to-back ratio peak may be moved closer to one or the other end of a range of frequencies to achieve the best pattern balance across a band. In addition, the driven elements have been resonated at the design center frequency. In reality, the driver may change it length by a considerable amount without affecting either the gain or the front-to-back ratio. This feature permits the designer to make the driver either capacitively or inductively reactive to suit a particular matching system of choice, if the source impedance does not match the system feedline characteristic impedance.

Some exercises may call for supplemental frequency sweeps in addition to the one programmed into the model. Be sure to save these additional sweeps as separate models, using whatever filename scheme you have developed to this point. More importantly, please do make the recommended additional sweeps.

18-1.NEC: A 2-element driver-reflector Yagi for 28.5 MHz



One of the most fundamental Yagi designs is the 2-element configuration, consisting of a driven element (or driver) and a reflector, as sketched in **Figure 18.1**. The reflector is longer than the driver, but the exact amount depends upon element spacing. We shall sample two different spacings to catalog their effect on performance and source impedance.

Model 18-1.NEC uses element spacing close to 1/8λ, a typical value in 2-element design. This and the next model use 0.75" diameter 6061-T6 aluminum elements, with dimensions in feet. For convenience, these models are in free space. However, upon completing the work of this exercise, you should systematically examine the performance and source impedance characteristics of both models at heights ranging from 1/2λ to 2λ above various qualities of ground in order to develop a fuller understanding of their operation.

```
CM 2-element Yagi:  DE/Ref-.123wl sp
CE
GW 1 13 -7.96 0 0 7.96 0 0 .03125
GW 2 13 -8.67 -4.25 0 8.67 -4.25 0 .03125
GS 0 0 .3048
GE 0
EX 0 1 7 0 1 0
LD 5 1 1 13 2.4938E7
LD 5 2 1 13 2.4938E7
FR 0 6 0 0 28 .2
RP 0 1 360 1000 90 0 1 1
EN                                    18-1
```

```
CM 2-el Yagi: de-ref--.174 wl spacing
CE
GW 1 13 -7.92 0 0 7.92 0 0 .03125
GW 2 13 -8.67 -6 0 8.67 -6 0 .03125
GS 0 0 .3048
GE 0
EX 0 1 7 0 1 0
LD 5 1 1 13 2.4938E7
LD 5 2 1 13 2.4938E7
FR 0 6 0 0 28 .2
RP 0 1 360 1000 90 0 1 1
EN                                 18-1-1
```

Model 18-1-1.NEC, shown on the next page, increases the spacing closer to 3/16λ, a small fractional increase, but a real distance of 1.75' at 28.5 MHz, the design center frequency of both models. Note that the reflectors of both models have the same length. However, the driven elements differ in resonant length, with the one in the wider-spaced model being marginally (1") shorter.

For this exercise, run both models across the span from 28 to 29 MHz in 0.2 MHz steps. Record the forward gain (90°), the rearward gain (270°), the resulting 180° front-to-back ratio, the source impedance, and the 50-Ω VSWR for each step.

18-1			**Test Data**		
Frequency MHz	**Forward Gain dBi**	**Rear Gain dBi**	**F-B dB**	**Source Z R ± jX Ω**	**50-Ω VSWR**
28.0 18-1 18-1-1					
28.2 18-1 18-1-1					
28.4 18-1 18-1-1					
28.6 18-1 18-1-1					
28.8 18-1 18-1-1					
29.0 18-1 18-1-1					

Comments: There are two different aspects to the data you have collected. One facet is the comparison of 2-element Yagis of different spacings. The other is the general pattern of reflector-driver design performance.

Although the differences are small in practical operational terms, the closer-spaced Yagi shows consistently higher gain and front-to-back ratio than the wide-spaced model. However, the wider-spaced version has a source impedance that is closely matched to the typical 50-Ω coaxial cable system feedline. The wider spacing between reflector and driven element yields a higher source impedance, but a longer boom. Operationally, then, the final decision between these designs would involve mechanical as well as electrical factors.

The two designs nevertheless have a number of significant features in common, features that are earmarks of the basic arrangement of elements. First, the gain increases as the frequency decreases. The gain diminishes slowly with frequency increases. However, as the frequency goes down, there will be a point at which the gain no longer increases. In a small span, the antenna will reverse direction, with maximum gain on the reflector side of the array. You should revise the frequency sweep to run from 26 to 30 MHz in 0.5 MHz steps in order to track the gain curve more closely.

At a frequency below the bandwidth scanned in this exercise but above the reversal frequency region, the antenna will exhibit a free space gain above 7 dBi. However, at that point, the front-to-back ratio will be negligible (4 to 7 dB), and the source impedance will be very low (10 to 15 Ω).

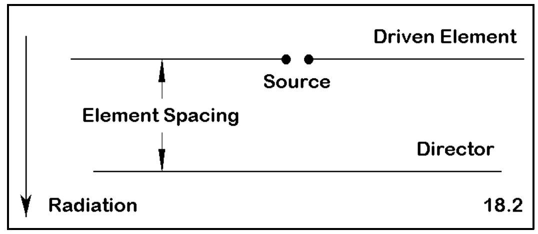
Second, the source impedance increases as the frequency increases. Despite the design differences and the average value of the resistive component of the source impedance, the resistance increases by about the same amount for both designs across the 1 MHz scanned range.

18-1		**Reference Data**			
Frequency MHz	**Forward Gain dBi**	**Rear Gain dBi**	**F-B dB**	**Source Z R ± jX Ω**	**50-Ω VSWR**
28.0 18-1	6.72	-3.26	9.98	24.1 - j20.0	2.49
18-1-1	6.45	-3.46	9.91	41.9 - j16.8	1.50
28.2 18-1	6.55	-4.23	10.78	27.4 - j11.7	1.96
18-1-1	6.30	-4.12	10.42	45.7 - j 9.8	1.25
28.4 18-1	6.38	-4.77	11.15	30.7 - j 3.9	1.64
18-1-1	6.15	-4.52	10.67	49.3 - j 3.1	1.07
28.6 18-1	6.21	-4.97	11.18	34.0 + j 3.7	1.48
18-1-1	6.01	-4.69	10.70	52.8 + j 3.3	1.09
28.8 18-1	6.05	-4.91	10.96	37.2 + j10.9	1.47
18-1-1	5.87	-4.70	10.57	56.1 + j 9.5	1.24
29.0 18-1	5.91	-4.71	10.62	40.4 + j17.9	1.57
18-1-1	5.75	-4.60	10.35	59.3 + j15.6	1.39

Despite the limitations of this design, it is able to operate across an entire MHz in the vicinity of 30 MHz. Of course, these figures would be proportionately lower as one decreases the frequency, amounting to about 0.5 MHz in the 15 MHz region. In terms of Yagi design, the reflector-drive configuration is considered a broad-band antenna.

18-2.NEC: A 2-element driver-director Yagi for 28.5 MHz

A 2-element Yagi composed of a driven element and a director can achieve higher gain and front-to-back ratios than a 2-element driver-reflector design. However, as we shall see, the antenna exhibits a fairly narrow operating bandwidth, especially when compared to the reflector-drive configuration.




```
CM 2-el Yagi: de/dir-.072 spacing
CE
GW 1 13 -8.02 0 0 8.02 0 0 .03125
GW 2 13 -8.59 -2.5 0 8.59 -2.5 0 .03125
GS 0 0 .3048
GE 0
EX 0 2 7 0 1 0
LD 5 1 1 13 2.4938E7
LD 5 2 1 13 2.4938E7
FR 0 6 0 0 28 .2
RP 0 1 360 1000 90 0 1 1
EN                                18-2
```

Model 18-2.NEC is a typical driver-director design set at a design center frequency of 28.5 MHz. Like the reflector designs, the material is 0.75" diameter 6061-T6 aluminum, and the antenna is modeled in free space. The spacing of this model is about 0.07λ, typical of the close spacing needed for maximum performance while maintaining a source impedance high enough to avoid the loss of a serious percentage of power to the resistance of connections and other mechanical junctions.

The companion model, 18-2-1.NEC, spaces the elements further apart by a bit under 0.9λ. Even though this increase amounts to only 0.5', the effects on the element lengths are very noticeable. The wider-spaced version has a slightly shorter driven element and a more significantly shorter director.

```
CM 2-el Yagi: de/dir-0.87 wl spacing
CE
GW 1 13 -7.95 0 0 7.95 0 0 .03125
GW 2 13 -8.54 -3 0 8.54 -3 0 .03125
GS 0 0 .3048
GE 0
EX 0 2 7 0 1 0
LD 5 1 1 13 2.4938E7
LD 5 2 1 13 2.4938E7
FR 0 6 0 0 28 .2
RP 0 1 360 1000 90 0 1 1
EN                                18-2-1
```

For both of these antennas, we shall perform the same frequency sweep as before: from 28 to 29 MHz in 0.2 MHz steps. As well, we shall record the same data: forward gain, reverse gain, front-to-back ratio, source impedance, and 50-Ω VSWR. Use the table on the next page to record the results of the sweep.

Comments: As with the first design that we explored, the data for the driver-director design has two aspects: a comparison between the two models and a set of characteristics common to all Yagis of this configuration. Comparatively, both models have similar gain curves, but the closer-spaced model achieves much better front-to-back ratios. Both antennas are designed to show a peak in the 180° front-to-back ratio near the design center frequency. However, the cost for the better rearward rejection is a lower source impedance. The rate of change of both the resistive and reactive components of the source impedance are similar for the two antennas.

18-2			**Test Data**		
Frequency MHz	**Forward Gain dBi**	**Rear Gain dBi**	**F-B dB**	**Source Z R ± jX Ω**	**50-Ω VSWR**
28.0 18-2 18-2-1					
28.2 18-2 18-2-1					
28.4 18-2 18-2-1					
28.6 18-2 18-2-1					
28.8 18-2 18-2-1					
29.0 18-2 18-2-1					

Consistent with each other, both driver-director designs show a high rate of change of both resistance and reactance at the source. This factor alone tends to limit the operating bandwidth to under 0.5 MHz in the 30 MHz region, with correspondingly smaller operating bandwidths at lower frequencies. Consequently, the design is rarely used on the wider amateur radio allocations at 20, 15, and 10 meters. However, the design can prove entirely adequate for the 30, 17, and 12 meter bands, each of which is at most 0.1 MHz wide.

Unlike the reflector designs, director designs increase in gain with increases in frequency, and they show a decreasing source impedance with frequency increases. The gain continues to increase beyond the range scanned in this exercise, although the front-to-back ratio almost disappears and the source impedance soon descends to about 10Ω. At some higher frequency, the pattern will reverse, with the most gain in the opposite direction from the director. You should expand the frequency sweep to go from 28 to 30 MHz on 0.25 MHz steps to find the reversal region in the vicinity of 29.75 MHz for model

18-2.NEC.

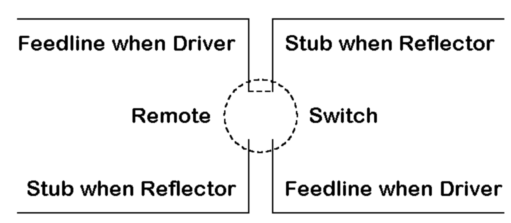
The trends for virtually all operating parameters are opposite for the two types of configurations possible in 2-element Yagis. You should feel free to develop further models with different spacings to test these conclusions and to develop expectations for the rates of change for each of the major specifications. Element spacings for reflector designs have ranged from 0.1 to 0.25λ, while director designs have used spacings from 0.05 to 0.125λ.

18-2		**Reference Data**				
Frequency MHz		**Forward Gain dBi**	**Rear Gain dBi**	**F-B dB**	**Source Z R ± jX Ω**	**50-Ω VSWR**
28.0	18-2	5.60	- 6.84	12.44	31.9 - j20.0	
	18-2-1	5.71	- 6.97	12.68	35.1 - j18.9	
28.2	18-2	5.93	- 9.74	15.67	27.5 - j12.7	
	18-2-1	6.03	- 9.21	15.24	31.3 - j11.9	
28.4	18-2	6.30	-15.12	21.42	22.9 - j 4.2	
	18-2-1	6.36	-11.58	17.94	27.0 - j 3.9	
28.6	18-2	6.67	-17.05	23.72	18.6 + j 5.0	
	18-2-1	6.71	-10.72	17.43	22.9 + j 5.1	
28.8	18-2	7.03	- 8.40	15.43	14.8 + j15.4	
	18-2-1	7.02	- 6.49	13.51	19.1 + j15.0	
29.0	18-2	7.29	- 2.84	10.13	11.7 + j26.6	
	18-2-1	7.26	- 2.40	9.66	15.8 + j25.9	

18-3.NEC: A reversible wire Yagi for 10.1-10.15 MHz

Although aluminum Yagis are available for use on frequencies below 12 MHz, fixed-position copper wire Yagis often serve important communications functions. The principles of operation are identical to those employed with Yagis using larger diameter elements, although the operating bandwidth of a wire Yagi may be relatively smaller. Wire Yagi installations often prompt the use of elements of identical lengths, with a reflector electrically lengthened by the insertion of an inductive reactance. Although inductively reactive loads can significantly reduce gain when applied to the driven element, their use in parasitic elements with lower current levels produces few noticeable ill-effects.

Run model 18-3.NEC, a 2 element #12 AWG copper wire beam with a design center frequency of 10.125 MHz. This free space model has identical 46.24’ elements spaced 14.2’ (slightly less than 0.15λ) apart. The reflector is center loaded with a type 4 reactive load of 75Ω. You should obtain a free space gain of about 6.07 dBi and a front-to-back ratio of about 10.90 dB, with a source impedance of 43.5 - j 0.1 Ω.



18.3 Reversible 2-Element Yagi

The question is how best to implement the required load. We might add an inductance to the reflector. However, let's consider another option. If we use a transmission line stub, either shorted or open, we can make the Yagi reversible. By adding stubs to each element and bringing them to a central point--either elevated or near the ground--we can use one line as a stub and the other as a section of the system feedline. A simple remote switching system would permit role reversal for the two sections of line. The system is sketched in **Figure 18.3**.

Since we may use either a shorted stub or an open-ended stub to accomplish the same loading task, we may choose the stub type that results in the best length for the installation. Refer to the chapter on reactive loads for information on calculating suitable stubs.

Models 18-3-1.NEC through 18-3-3.NEC provide examples of stubs suitable for use in such an installation. 18-3-1.NEC, shown at right, uses a 15.21' (4.636 m) shorted stub of 50-Ω transmission line (VF = 1.0). (Note that you may have to enter transmission line data in meters even if the antenna dimensions are in feet or inches. As well, you may have to separately calculate the effects of the line's velocity factor on the physical length of the stub.)

```
CM 2-el bi-directional Yagi: 10.1-10.15 MHz
CM Shorted stub load on reflector
CE
GW 1 13 -23.12 0 0 23.12 0 0 3.36778215223097E-03
GW 2 13 -23.12 -14.2 0 23.12 -14.2 0 3.36778215223097E-03
GW 3 1 -.2 -14.2 -20 .2 -14.2 -20 1.05643044619423E-03
GS 0 0 .3048
GE 0
EX 0 1 7 0 1 0
LD 5 1 1 13 5.8001E7
LD 5 2 1 13 5.8001E7
TL 2 7 3 1 50 4.636008 0 0 10000000000 10000000000
FR 0 6 0 0 10.1 .01
RP 0 1 360 1000 90 0 1 1
EN
```
18-3: 1-3

Model 18-3-2.NEC is identical except for the use of a shorted stub that is 63.78' (19.44 m) long. At the design center frequency, this line is exactly 1/2λ longer than the preceding model's stub. Note once more that since NEC-2 transmission lines are mathematical rather than physical, they do not account for losses in the line. Model 18-3-3.NEC uses the same antenna dimensions with a transmission line stub that is open and 39.48' (12.034 m) long.

Apart from slight differences in losses within each length of stub, the choice of stub type and length should have no affect on antenna performance. Rather than presume that this claim is a fact, let's model each of these systems and run a frequency sweep from 10.1 MHz through 10.15 MHz in 0.01 MHz steps.

For each model, record for each frequency step the free space forward gain, the rear gain, the 180° front-to-back ratio, the source impedance, and the 50-Ω VSWR. Use the table at the top of the next page for your data.

Note that the models do not use a length of transmission line on the driven element of these driver-reflector designs. However, as a supplementary exercise, you may add such a line and run it to an added short wire, placing the source on the new wire. These additions will not add materially to the run-time for the modified models. Note especially if the length of line makes a significant difference in the source impedance.

18-3			**Test Data**		
Frequency MHz	**Forward Gain dBi**	**Rear Gain dBi**	**F-B dB**	**Source Z R ± jX Ω**	**50-Ω VSWR**
10.10 18-3-1 18-3-2 18-3-3					
10.11 18-3-1 18-3-2 18-3-3					
10.12 18-3-1 18-3-2 18-3-3					
10.13 18-3-1 18-3-2 18-3-3					
10.14 18-3-1 18-3-2 18-3-3					
10.15 18-3-1 18-3-2 18-3-3					

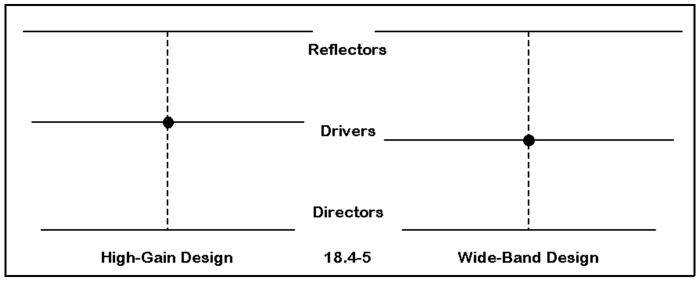
Comments: As we expected, there is no significant difference in the performance of the simple Yagi with any of the stub-loading systems used. Consequently, you can choose whichever of the three (or other) stub type and lengths that will provide the correct length to reach the design position of the remote switching box. Of course, you should independently take into account losses in the stubs, especially as their length increases to over 1/2λ.

The narrow band of frequencies over which the beam is expected to operate simplifies the design considerations for this array. However, you may well revise the frequency span to test the antenna over a wider range of frequencies.

As wire beams, the designs in 18-3-1.NEC through 18-3-3.NEC will not have as broad a set of responses as antennas using larger diameter elements. Indeed, you may wish to redesign the antenna using either larger monotapered elements or tapered-diameter elements to simulate an aluminum Yagi for this band. You may use either an unloaded or a loaded reflector for your aluminum version of the beam. Once you have effected the design changes, compare the results with those you obtained for the wire models.

18-3		**Reference Data**			
Frequency MHz	**Forward Gain dBi**	**Rear Gain dBi**	**F-B dB**	**Source Z R ± jX Ω**	**50-Ω VSWR**
10.10 18-3-1	6.18	-4.60	10.78	41.3 - j 4.3	1.24
18-3-2	6.22	-4.48	10.70	40.6 - j 4.4	1.26
18-3-3	6.20	-4.53	10.73	40.9 - j 4.4	1.25
10.11 18-3-1	6.14	-4.72	10.86	42.2 - j 2.6	1.20
18-3-2	6.16	-4.65	10.81	41.8 - j 2.7	1.21
18-3-3	6.15	-4.68	10.83	42.0 - j 2.6	1.20
10.12 18-3-1	6.09	-4.80	10.89	43.1 - j 0.9	1.16
18-3-2	6.10	-4.79	10.89	43.0 - j 0.9	1.17
18-3-3	6.10	-4.79	10.89	43.0 - j 0.9	1.16
10.13 18-3-1	6.05	-4.87	10.92	44.0 + j 0.7	1.14
18-3-2	6.04	-4.88	10.92	44.1 + j 0.7	1.13
18-3-3	6.05	-4.87	10.92	44.0 + j 0.7	1.14
10.14 18-3-1	6.00	-4.91	10.91	44.9 + j 2.4	1.13
18-3-2	5.98	-4.92	10.90	45.3 + j 2.4	1.12
18-3-3	5.99	-4.91	10.90	45.1 + j 2.4	1.12
10.15 18-3-1	5.96	-4.93	10.89	45.8 + j 4.0	1.13
18-3-2	5.92	-4.94	10.86	46.4 + j 4.0	1.12
18-3-3	5.94	-4.93	10.87	46.1 + j 4.0	1.12

18-4.NEC and 18-5.NEC: High-gain and wide-band 3-element Yagis for 14.175 MHz



In this exercise, we shall examine two contrasting designs for 3-element Yagis, both consisting of one reflector and one director. They reflect two different design philosophies, sketched in **Figure 8.4-5**. One design tries to achieve the maximum gain possible (with a reasonable front-to-back ratio) for the given boom length (23'). The compromise for this "high gain" version of the Yagi is that it must hold the gain as well as possible over a frequency spread from 14.0 MHz through 14.35 MHz.

The second design strives to achieve wide-band operation, with stable (although lower) values for gain, good front-to-back ratio, and a direct match across the operating bandwidth with a 50-Ω system feedline. The sketch of the two antenna layouts reveals the different element positioning required to achieve this goal.

Open model 18.4.NEC, the high-gain Yagi. Like its counterpart, it has 1" diameter 6061-T6 aluminum elements and is modeled in free space. You will wish to compare antenna dimensions with the next model. Note especially the spacing of the driven element from the reflector (125.5").

```
CM 3-el. Yagi:  high gain: 14-14.35 MHz
CE
GW 1 21 -207.4 0 0 207.4 0 0 .5
GW 2 21 -198 125.5 0 198 125.5 0 .5
GW 3 21 -186.3 270.5 0 186.3 270.5 0 .5
GS 0 0 .02540
GE 0
EX 0 2 11 0 1 0
LD 5 1 1 21 2.4938E7
LD 5 2 1 21 2.4938E7
LD 5 3 1 21 2.4938E7
FR 0 6 0 0 14 .07
RP 0 1 361 1000 90 0 1 1
EN                                18-4
```

```
CM 3-el. Yagi:  wide-band: 14.0-14.35 MHz
CE
GW 1 21 -215 0 0 215 0 0 .5
GW 2 21 -199 141 0 199 141 0 .5
GW 3 21 -181 271 0 181 271 0 .5
GS 0 0 .02540
GE 0
EX 0 2 11 0 1 0
LD 5 1 1 21 2.4938E7
LD 5 2 1 21 2.4938E7
LD 5 3 1 21 2.4938E7
FR 0 6 0 0 14 .07
RP 0 1 360 1000 90 0 1 1
EN                                18-5
```

Next, open model 18-5.NEC, the wide-band version of the 3-element Yagi. Compare the reflector-driver spacing to that of the high-gain version.

Run the indicated frequency sweep of the two beams from 14.0 through 14.35 MHz in 0.07 MHz steps. Record the same data we have used throughout this exercise.

18-4/5	Test Data				
Frequency MHz	**Forward Gain dBi**	**Rear Gain dBi**	**F-B dB**	**Source Z R ± jX Ω**	**50-Ω VSWR**
14.0 18-4 18-5					
14.07 18-4 18-5					
14.14 18-4 18-5					
14.21 18-4 18-5					
14.28 18-4 18-5					
14.35 18-4 18-5					

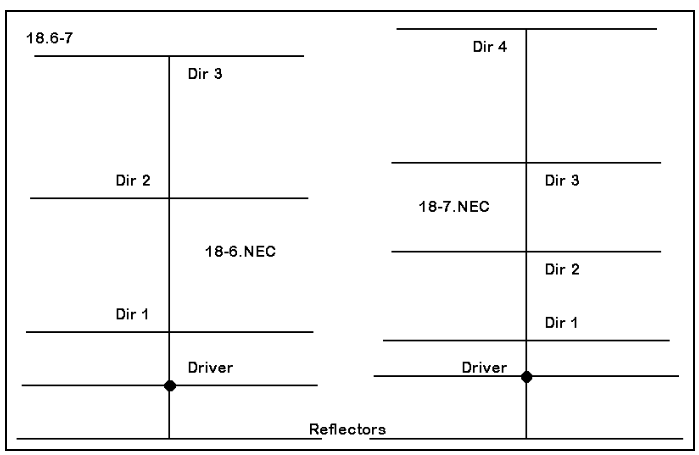
Comments: As we did with the 2-element Yagis, we shall divide our observations of these beams into two categories: how they contrast and what they have in common. The contrast between the beams is especially apparent in the gain column, where the high-gain version averages about 1 dB additional gain across the band of frequencies we swept. The front-to-back ratios are comparable, although the wide-band version shows a smoother curve. (For most Yagi applications, a 20 dB front-to-back ratio is considered adequate in designs with more than 2 elements. However, you may wish to explore the azimuth patterns to ascertain both the front-to-rear ratio and the worst-case front-to-back ratio before making final judgments.)

The wide-band Yagi exhibits a very low VSWR relative to a 50-Ω system feedline, thus simplifying matching the antenna to the line. In contrast, the high-gain version requires the use of a matching network. Any common matching system (gamma, beta, Tee, 1/4λ transmission line) will provide full bandwidth coverage in view of the small changes in both the resistive and reactive components of the source impedance. Whether the advantage of higher gain outweighs the wide-band version's smoother performance curves and direct system feedline match is a decision beyond the scope of this exercise.

18-4/5		Reference Data			
Frequency MHz	**Forward Gain dBi**	**Rear Gain dBi**	**F-B dB**	**Source Z R ± jX Ω**	**50-Ω VSWR**
14.0 18-4	7.94	-12.98	21.92	27.1 - j13.2	2.02
18-5	7.06	-13.47	20.53	47.1 - j 9.3	1.22
14.07 18-4	8.00	-17.39	25.39	26.8 - j 8.5	1.94
18-5	7.08	-13.77	20.85	46.9 - j 5.6	1.14
14.14 18-4	8.07	-20.55	28.62	26.2 - j 3.5	1.92
18-5	7.11	-13.82	20.93	46.5 - j 1.7	1.08
14.21 18-4	8.15	-16.77	24.92	25.3 + j 1.7	1.98
18-5	7.15	-13.59	20.74	45.8 + j 2.2	1.10
14.28 18-4	8.24	-12.51	20.75	24.7 + j 7.2	2.12
18-5	7.20	-13.09	20.29	45.0 + j 6.4	1.19
14.35 18-4	8.34	- 9.31	17.65	22.9 + j13.0	2.36
18-5	7.27	-12.35	19.62	43.9 + j10.7	1.30

What these two beams have in common is that the gain increases and the source impedance decreases across the band of frequencies we swept. Yagis with three elements share this property with the 2-element driver-director design. The phenomena are indicators that, to a very large degree, the directors control the operating characteristics of the Yagi array. The reflector cannot easily be eliminated from Yagi design. To a significant degree, it provides the Yagi with a wide operating bandwidth. Of greater importance is that fact that the reflector length and spacing from the driver controls the source impedance of the Yagi. Although this factor may be modified via the addition of an extra director more closely spaced to the driver, the reflector is an essential ingredient in the determination of the source impedance characteristics of the beam.

18-6.NEC and 18-7.NEC: Long-boom Yagis for 14.175 MHz



It is often useful to frequency sweep a Yagi design across the band of frequencies for which it is intended in order to make comparative evaluations of performance potentials. Models 18-6.NEC and 18-7.NEC are both long boom Yagis intended to provide about 10 dBi free space gain with a front-to-back ratio in excess of 20 dB and to be matched to a 50-Ω system feedline. As **Figure 18.6-7** illustrates, they take quite different design approaches to this goal.

```
CM 5-el. Yagi:  14.175 MHz        18-6
CE
GW 1 5 -215.6 0 0 -156 0 0 .3125
GW 2 3 -156 0 0 -120 0 0 .375
GW 3 4 -120 0 0 -72 0 0 .4375
GW 4 13 -72 0 0 72 0 0 .5
GW 5 4 72 0 0 120 0 0 .4375
GW 6 3 120 0 0 156 0 0 .375
GW 7 5 156 0 0 215.6 0 0 .3125
GW 8 4 -205.95 79.8 0 -156 79.8 0 .3125
GW 9 3 -156 79.8 0 -120 79.8 0 .375
GW 10 4 -120 79.8 0 -72 79.8 0 .4375
GW 11 13 -72 79.8 0 72 79.8 0 .5
GW 12 4 72 79.8 0 120 79.8 0 .4375
GW 13 3 120 79.8 0 156 79.8 0 .375
GW 14 4 156 79.8 0 205.95 79.8 0 .3125
```

Model 18-6.NEC is a tapered-diameter 6061-T6 aluminum Yagi with 5 elements, only two of which are shown at left. The design uses the spacing (with attention to element length) between the driver and the reflector as well as the first director to establish a source impedance compatible with a 50-Ω feed system. As we shall see, although the source impedance is adequate, it leaves room for perfection. However, further enhancement of the source impedance would have required additional spacing between the reflector and the driver, requiring a boom longer than the design limit of 45' and would also have required additional spacing between directors. (Impedances closer to 50 Ω have been achieved at the design frequency of 14.175 MHz with booms of 53 to 55 feet.)

Model 18-7.NEC is also comprised of 6061-T6 tapered-diameter elements, this time 6 of them on a 48' boom. Again, only the reflector and driver appear in the description box, since the full model description would be longer than this page. However, you can view the full description via NECWin Plus. The principle behind the design is to use a wider spacing between the reflector and driver to increase the source impedance and to control those characteristics through a close-spaced first director. Attaining the desired gain and front-to-back ratio characteristics requires 3 directors in the remaining boom space, giving the beam a total of six elements. Designs willing to settle for a lower source impedance (in the 25-Ω range) can achieve similar gain and front-to-back ratio results using only 5 elements.

```
CM 6-el Yagi:  14.175 MHz        18-7
CE
GW 1 7 -217.73 0 0 -152 0 0 .25
GW 2 4 -152 0 0 -116 0 0 .3125
GW 3 4 -116 0 0 -72 0 0 .375
GW 4 2 -72 0 0 -48 0 0 .4375
GW 5 9 -48 0 0 48 0 0 .5
GW 6 2 48 0 0 72 0 0 .4375
GW 7 4 72 0 0 116 0 0 .375
GW 8 4 116 0 0 152 0 0 .3125
GW 9 7 152 0 0 217.73 0 0 .25
GW 10 6 -210.7 90 0 -152 90 0 .25
GW 11 4 -152 90 0 -116 90 0 .3125
GW 12 4 -116 90 0 -72 90 0 .375
GW 13 2 -72 90 0 -48 90 0 .4375
GW 14 9 -48 90 0 48 90 0 .5
GW 15 2 48 90 0 72 90 0 .4375
GW 16 4 72 90 0 116 90 0 .375
GW 17 4 116 90 0 152 90 0 .3125
GW 18 6 152 90 0 210.7 90 0 .25
```

Run a frequency scan for both 18-6.NEC and 18-7.NEC from 14.0 through 14.35 MHz in 0.07 MHz steps. Record the forward gain, front-to-back ratio, source impedance, and 50-Ω VSWR for each beam in order to compare the results.

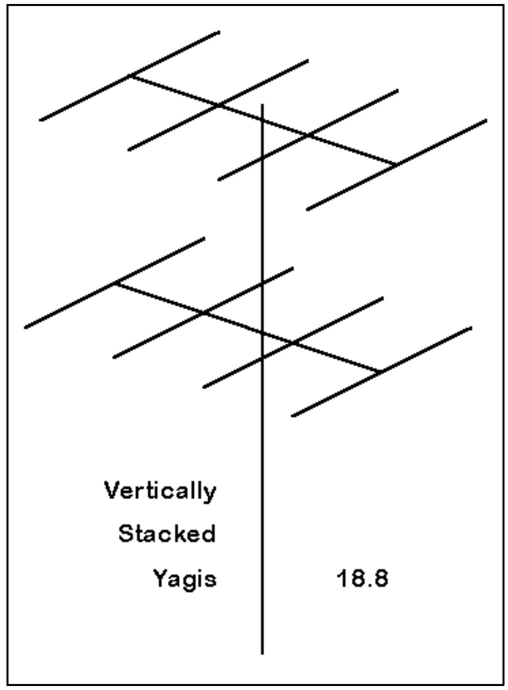
18-6 & 18-7		Test Data		
Frequency MHz	Forward Gain dBi	F-B dB	Source Z R ± jX Ω	50-Ω VSWR
14.00 18-6 18-7				
14.07 18-6 18-7				
14.14 18-6 18-7				
14.21 18-6 18-7				
14.28 18-6 18-7				
14.35 18-6 18-7				

Comments: By now, you have run enough examples to determine the 180° front-to-back ratio without need for recording the rear gain. You have also experienced the value of using this parameter to determine the frequency of maximum rearward null as a design factor. However, remember that the front-to-rear ratio and the worst-case front-to-back ratio remain equally valuable measures of antenna performance. Clearly, both antennas perform comparably with respect to gain and front-to-back ratio across the band of frequencies swept in the test. However, the source impedance of the longer boom model, with its extra controlling director, is clearly superior with respect to forming a direct match with 50-Ω feedline systems. Losses in the transmission line may be less, especially where long cable runs are required. Moreover, some equipment exhibits great sensitivity in its sensors to even low values of VSWR, reducing the available power output for values as low as 1.5:1. In these and similar situations, the 48' boom design might be advisable. Nevertheless, the 45' boom design would be entirely satisfactory in many other situations.

As the boom length and number of elements in a Yagi increase, it becomes possible to control various of the performance curves and to make them converge within the limits of the frequency coverage of the antenna. The 45' boom Yagi brings the gain and front-to-back curves to near coincidence, although the source impedance continues to rise across the span from 14.0 through 14.35 MHz. In contrast, the 48' boom model achieves a close coincidence of the source impedance and front-to-back ratio curves, while the gain continues to rise beyond the limits of the frequency sweep. Although some design tasks may single out only one of the many performance specifications to optimize--gain, for instance--an ideal Yagi design strives to control as many of the performance characteristics as possible. Although achieving a coincident peak of gain, front-to-back ratio, and source impedance at a desired value is theoretically possible, it is likely to result in a mechanically unfeasible design.

18-6 & 18-7		**Reference Data**			
Frequency MHz		**Forward Gain dBi**	**F-B dB**	**Source Z R ± jX Ω**	**50-Ω VSWR**
14.00	18-6	10.05	21.09	31.6 - j 11.2	1.71
	18-7	10.09	24.64	41.6 - j 0.8	1.20
14.07	18-6	10.13	25.86	31.6 - j 7.7	1.65
	18-7	10.15	28.83	43.1 + j 0.9	1.16
14.14	18-6	10.21	36.69	31.9 - j 3.9	1.58
	18-7	10.20	30.88	44.3 + j 1.9	1.14
14.21	18-6	10.26	31.91	33.3 - j 0.5	1.50
	18-7	10.25	27.90	44.8 + j 2.0	1.13
14.28	18-6	10.27	24.59	33.6 + j 0.5	1.41
	18-7	10.28	24.76	43.8 + j 0.9	1.14
14.35	18-6	10.21	21.45	35.4 - j 3.7	1.43
	18-7	10.30	22.68	39.8 - j 0.9	1.26

18-8.NEC: Stacked 4-element Yagis for 14.175 MHz



A common technique for increasing the gain of a Yagi antenna system without added boom length is to stack 2 or more Yagis of the same design, as illustrated in **Figure 18.8**. Since very long booms result in many mechanical challenges, stacking Yagi beams becomes an attractive design alternative for achieving up to 3 dB gain for each additional antenna.

However, finding the correct stacking separation for maximizing gain becomes a challenge in itself. The optimal stacking distance varies significantly with the gain of the individual antennas and to a lesser extent with the height of the lower antenna above ground. As an exercise in basic theory, you may wish to examine the elevation patterns of many Yagis of varying gain to extrapolate the pattern data necessary to calculate (with due regard for ground reflections) optimal separation for stacks of 2 or more beams.

```
CM 4-el. Yagi 70' up:  14.175
CM Stack of 2, both fed in phase
CE
GW 1 21 -17.38 0 70 17.38 0 70 .04165
GW 2 21 -16.41 6 70 16.41 6 70 .04165
GW 3 21 -16.29 11 70 16.29 11 70 .04165
GW 4 21 -15.26 25.5 70 15.26 25.5 70 .04165
GW 5 21 -17.38 0 123 17.38 0 123 .04165
GW 6 21 -16.41 6 123 16.41 6 123 .04165
GW 7 21 -16.29 11 123 16.29 11 123 .04165
GW 8 21 -15.26 25.5 123 15.26 25.5 123 .04165
GS 0 0 .3048
GE 1
GN 2 0 0 0 13 .005 0 0 0 0
EX 0 2 11 0 1 0
EX 0 6 11 0 1 0
LD 5 1 1 21 2.4938E7
LD 5 2 1 21 2.4938E7
LD 5 3 1 21 2.4938E7
LD 5 4 1 21 2.4938E7
LD 5 5 1 21 2.4938E7
LD 5 6 1 21 2.4938E7
LD 5 7 1 21 2.4938E7
LD 5 8 1 21 2.4938E7
FR 0 1 0 0 14.175 0
RP 0 1 360 1000 81 0 1 1
EN                                             18-8
```

Model 18-8.NEC is a single 4-element Yagi that forms the basis for this small stacking exercise. The version at the left is model 18-8-1.NEC, a stack of two of the beams separated by about 0.75λ, which is optimal for this particular Yagi in view of both its gain and the 1λ height of the lower antenna. The beams are standard 6061-T6 aluminum monotapered 1" diameter element designs, with the lower antenna 70' above average soil using the S-N ground system. Note that the source positions are both on segment 11 of wires 2 and 6, the lower and upper driver, respectively.

Our interest in this stack will be confined to the ways in which the antennas can be operated. We may feed both together in phase, both together out of phase, the lower beam only, or the upper beam only. Run all 4 configurations at the design center frequency of 14.175 MHz. Either modify model 18-8-1.NEC or use check models 18-8-2.NEC through 18-8-4.NEC to achieve the desired set-up. Note that setting one source at 180° relative to the other source results in a negative value for the source voltage in the EX line of the model description.

18-8		Test Data		
Feed System	**TO Angle degrees**	**Gain dBi**	**F-B dB**	**Source Z R ± jX Ω**
Both in phase				
Both out of phase				
Bottom only				
Top only				

Comments: Note that only the scheme of feeding both antennas in phase results in additional gain for the assembly. The other schemes show gain ranging from 2.4 to 2.9 dB less than the in-phase combination. However, raw stack gain is not the only parameter worth noting.

Under various ionospheric conditions, the required take-off angle for transmission and reception may vary considerably. The use of the remaining stack options, especially the "bottom-only" and the "out-of-phase" options, results in a variety of angles for the strongest lobe of the array. It is possible to design not only a manual switching system, but as well, an automated system to switch to the option resulting in the strongest received signal.

18-8		Reference Data		
Feed System	**TO Angle degrees**	**Gain dBi**	**F-B dB**	**Source Z R ± jX Ω**
Both in phase	9	16.58	23.14	25.9 - j30.4 L 25.2 - j30.4 U
Both out of phase	22	13.73	21.39	27.5 - j27.3 L 26.9 - j27.5 U
Bottom only	14	13.77	21.35	26.8 - j28.8
Top only	8	14.17	24.66	26.1 - j29.0

Note: L = lower antenna; U = upper antenna

Note that feeding both antennas in phase results in a slightly lower elevation angle of maximum radiation than feeding the top beam only. This result will hold true of any stacking arrangement, since the composite pattern results from combining the top beam output with that of a beam with a much higher take-off angle relative to the horizon. The difference is real, although it has little operational significance.

Numerous follow-up exercises are possible and advisable. You may wish to perform frequency sweeps across the 20-meter amateur radio band to determine whether the anticipated results from the stack are frequency specific or more general. Additionally, you may wish to experiment with the spacing of the two beams in the stacked array to determine whether the present separation is indeed optimal from both the gain and front-to-back ratio perspectives. Few beams exhibit maximum front-to-back ratio and gain at the same separation. The disparity between optimum, heights for both varies widely from one design to another, and you may wish to model numerous Yagi designs to determine what patterns, if any, can be extracted from the exercise.

18-9.NEC: A non-interlaced multi-band Yagi for 18.2 and 24.95 MHz

The next stage in Yagi design involves achieving desired levels of performance on multiple separated frequencies with one set of elements, some of which may have principle duties on only one of the bands. The simplest type of set-up is to have two (or more) Yagis on the same boom, such that each set of elements is relatively independent of the other set.

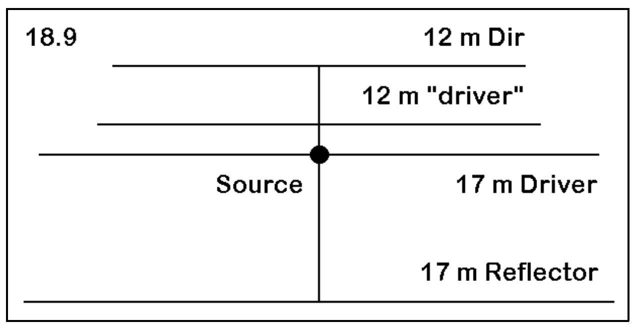


Figure 18.9 shows one such system for the amateur radio 17 and 12 meter bands. The forward (shorter) elements form a 2-element driver-director array for 24.95 MHz. Since this allocation is only 100 kHz wide, the driver-director arrangement has sufficient band width to cover the entire band. The rear (longer elements) form a driver-reflector array for 18.112 MHz, with more than enough bandwidth to serve another 100 kHz allocation. The spacing was selected for a source impedance compatible with a 50-Ω system feedline.

The only "oddity" in this simple design is the use of open sleeve coupling between the lower frequency driven element, marked with a source position, and the higher frequency driver. By close coupling and careful adjustment of the 12-meter driver length and spacing from the 17-meter driver, a single feedpoint may be used on the 17 meter driver for both bands. On the higher frequency band, the single driver exhibits close to a 50-Ω source impedance and the forward elements operate as a normal driver-director array. The model, 18-9.NEC, has tapered-diameter 6061-T6 elements, with all dimensions shown in meters.

Because of the length of the model description, only the rear elements are shown to the right. The model is initially set up for a 3-step frequency sweep from 18.068 to 18.168 in 0.05 MHz steps. After making this modeling run, change the frequency (but not the source location) to create a 3-step frequency sweep from 24.89 through 24.99 MHz in 0.05 MHz steps. Record the forward free space gain, the 180° front-to-back ratio, the source impedance in terms of resistance and reactance, and the 50-Ω VSWR for the two sweeps.

```
CM 4-el Yagi:  12 m & 17 m                     18-9
CE
GW 1 5 -2.8956 .94488 0 -1.9812 .94488 0 .00476
GW 2 5 -1.9812 .94488 0 -.762 .94488 0 .00635
GW 3 2 -.762 .94488 0 -.3048 .94488 0 .00794
GW 4 3 -.3048 .94488 0 .3048 .94488 0 .00953
GW 5 2 .3048 .94488 0 .762 .94488 0 .00794
GW 6 5 .762 .94488 0 1.9812 .94488 0 .00635
GW 7 5 1.9812 .94488 0 2.8956 .94488 0 .00476
GW 8 5 -3.0419 .10668 0 -1.9812 .10668 0 .00476
GW 9 5 -1.9812 .10668 0 -.762 .10668 0 .00635
GW 10 2 -.762 .10668 0 -.3048 .10668 0 .00794
GW 11 3 -.3048 .10668 0 .3048 .10668 0 .00953
GW 12 2 .3048 .10668 0 .762 .10668 0 .00794
GW 13 5 .762 .10668 0 1.9812 .10668 0 .00635
GW 14 5 1.9812 .10668 0 3.0419 .10668 0 .00476
```

18-9	**Test Data**		
Parameter	**18.068**	**18.118**	**18.168**
Gain dBi			
F-B dB			
Source Z (R±jXΩ)			
50-Ω VSWR			
	24.89	**24.94**	**24.99**
Gain dBi			
F-B dB			
Source Z (R±jXΩ)			
50-Ω VSWR			

Comments: In principle, this antenna is very easy to create, both as a model and as a physical reality. Its performance shows higher than normal gain on the lower frequency span. On the upper band, gain is also higher than one might normally expect. Part of these figures owe to the fact that the 12-meter elements act partially as directors on 17 meters. As well, on the 12 meter band, the 17 meter elements act somewhat as reflectors. You may examine the current table for the antenna to verify that the current on the seemingly inactive elements is not quite low enough to count as wholly negligible.

However, part of the unexpectedly high performance owes to the close spacing of the two driver elements, which are also unequal in length. As we noted in a past set of exercises, NEC-2 tends to produce higher than normal gain figures for such situations, along with source impedance figures that may be inaccurate. In this case, the 17-meter gain may be up to 0.15 dB higher than reality, which the 12-meter gain may be as much as 0.5 dB higher than one can attain with a physical implementation of this antenna. Nonetheless, even when figures are reduced by these amounts, the antenna produces very respectable 2-element-per-band performance on a 10' boom.

18-9	**Reference Data**		
Parameter	**18.068**	**18.118**	**18.168**
Gain dBi	6.56	6.49	6.42
F-B dB	11.40	11.50	11.53
Source Z (R±jXΩ)	41.1 - j 1.5	43.7 + j 1.2	46.3 + j 3.7
50-Ω VSWR	1.22	1.15	1.12
	24.89	**24.94**	**24.99**
Gain dBi	6.92	7.00	7.09
F-B dB	24.32	27.84	33.08
Source Z (R±jXΩ)	63.6 - j 1.9	55.9 - j 1.9	47.7 - j 0.3
50-Ω VSWR	1.27	1.12	1.05

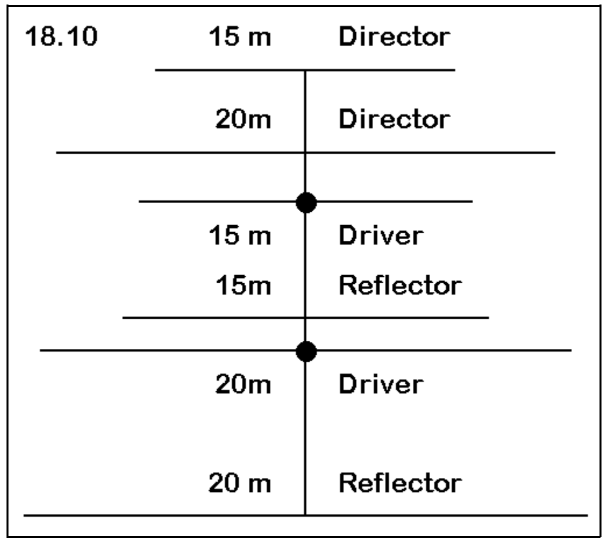
Because the model may yield incorrect source impedance figures, the lengths of the direct and the coupled drivers may not be exact, nor might the spacing be correct. However, both specifications will be close enough to allow experimental determination during construction of the correct values. Remember that when using open sleeve coupling, the coupled driver length will affect both the resistive and reactive components of the source impedance at the higher frequency. In cases like this one, the model provides a guide to the start of experimentation, but not a wholly reliable model of all construction and performance details.

18-10.NEC: Interlaced Yagis for 14.175 and 21.2 MHz

High gain multi-band Yagis cannot easily use the principle of separation (sometimes called "forward stagger" employed in the previous exercise without ending up with long booms that present numerous mechanical challenges. Consequently, some degree of element interlacing is required. Interlacing results in longer director elements for lower bands falling forward of shorter director elements for higher bands. When the elements are for adjacent bands up to a frequency ratio of 1:1.5, the longer elements tend to act as reflectors at the higher frequency, disrupting the function of the higher frequency element.

When bands are harmonically related, the longer element may be excited to a significant current level. The result can be an enhancement of the higher frequency forward gain. However, this function may also limit the higher frequency operating bandwidth, since the lower frequency element tends to be long relative to an antenna element wavelength at the higher frequency. The standard counteragent to such problems is the use at upper frequencies of a higher than normal number of elements for a given level of gain and operating bandwidth.

For our exercise, we shall examine a relatively modest interlacing situation for 3-element Yagis, shown in **Figure 18.10**. The goal of the design project was to achieve as short a boom length as possible while preserving as closely as possible the full performance of the independent antennas. If you re-examine the 3-element high-gain Yagi in model 18-4.NEC, you can get some idea of the performance expectations.




```
CM Interlaced Yagis:  20 m & 15 m
CE
GW 1 21 -5.2832 0 0 5.2832 0 0 .008
GW 2 21 -5.0038 3.2258 0 5.0038 3.2258 0 .008
GW 3 21 -4.7752 6.985 0 4.7752 6.985 0 .008
GW 4 15 -3.5052 3.4798 0 3.5052 3.4798 0 .00625
GW 5 15 -3.3147 5.969 0 3.3147 5.969 0 .00625
GW 6 15 -3.1877 8.4836 0 3.1877 8.4836 0 .00625
GS 0 0 1
GE 0
EX 0 2 11 0 1 0
LD 5 1 1 21 2.4938E7
LD 5 2 1 21 2.4938E7
LD 5 3 1 21 2.4938E7
LD 5 4 1 15 2.4938E7
LD 5 5 1 15 2.4938E7
LD 5 6 1 15 2.4938E7
FR 0 3 0 0 14 .175
RP 0 1 360 1000 90 0 1 1
EN                                        18-10
```

Model 18-10.NEC is one solution to the problem of interlacing. Two of the 15-meter elements (reflector and driver) lie between the 20-meter driver and director. Commercial designs tend to group all reflectors behind all drivers, with all directors placed forward of these two element sets. Such design may also cover up to three separate frequency bands.

This 6061-T6 aluminum model uses uniform-diameter elements: 16 mm diameter elements for the 14 MHz and 12.5 mm diameter elements for 21 MHz. An operational version of this array would undoubtedly require tapered-diameter elements. Note that there are separate sources for each band. Be sure to correctly place the source on wire 2, segment 11 for 20 meters and wire 5, segment 8 for 15 meters.

For this exercise, we may simply sample the performance at mid-band and at the band edges. Therefore, set a 20 meter frequency sweep from 14.0 through 14.35 MHz in 3 steps with a 0.175 MHz interval. Then set a 15 meter frequency sweep from 21.0 through 21.45 MHz with a 0.225 MHz interval. Record the gain, front-to-back ratio, and source impedance. We may by-pass the VSWR reading, since each set of elements will require a suitable matching network for a 50-Ω feedline system.

18-10	**Test Data**		
Parameter	**14.00**	**14.175**	**14.35**
Gain dBi			
F-B dB			
Source Z (R±jXΩ)			
	21.00	**21.225**	**21.45**
Gain dBi			
F-B dB			
Source Z (R±jXΩ)			

Comments: Both beams exhibit slightly higher gains than we might expect from monoband models, owing to the "forward stagger effect," which you can confirm from examining the current tables for this model. At the higher frequency range, however, the front-to-back ratio drops, as does the source impedance. Although the figures still represent highly usable performance, they do mark the consequences of interlacing elements. As a supplemental exercise, you may wish to move the 15 meter elements totally forward of the 20-meter elements--making suitable adjustments in element spacing and length--to restore full monoband performance.

18-10	**Reference Data**		
Parameter	**14.00**	**14.175**	**14.35**
Gain dBi	8.12	8.29	8.50
F-B dB	23.05	22.04	15.03
Source Z (R±jXΩ)	23.8 - j 24.9	23.3 - j 10.8	21.7 + j 5.1
	21.00	**21.225**	**21.45**
Gain dBi	8.11	8.16	8.30
F-B dB	16.70	18.45	14.36
Source Z (R±jXΩ)	16.0 - j 23.4	17.8 - j 11.3	17.5 + j 0.5

Often in multi-band Yagi design, some elements require placement at virtually identical positions on the boom. For directors and reflectors, some designers employ traps, although the use of traps in driven elements has diminished, due to their losses in these high-current elements. In addition, driven element designs may use separately fed drivers (often with a remote switch), or they may employ open-sleeve coupling, "log" cells, or directly coupled drivers to achieve single-feedline operation. The variant designs of multi-band Yagis present you with innumerable supplemental exercises.

Summing Up

These exercises have progressed from the simplest Yagi designs to moderate levels of complexity in long-boom designs, stacking, and multi-band considerations. Despite the length and number of the exercises, we have only made an entry into an antenna design realm with almost unlimited diversity. For example, we have not looked in this chapter at methods of antenna element loading, commonly used at 7 MHz and below to make Yagi antennas more manageable mechanically. Nor have we tried to model "linear loads" (folded wire configurations), which NEC-2 does not handle well if the linear load wires are different in diameter relative to the main element diameter. We have limited our investigation to 5 element Yagis, although 7- and 8-element Yagis are used near 30 MHz. We have avoided models using traps and have not directly modeled matching systems. Of course, VHF and UHF Yagis have been reserved for another chapter.

Despite these restrictions, the exercises have introduced you to fundamental properties and behavior of Yagi antennas, including their potentials and their limitations. Understanding the applications of Yagi theory is enhanced by the ability to try out and optimize various designs as models, a much more rapid procedure than building physical models of every design modification. Developing appropriate anticipations about Yagi designs is crucial to choosing quickly the right design directions in development tasks. At the same time, it is important also not to convert anticipations into preconceptions about the limitations of Yagi design. Some of the best recent advances in Yagi antenna performance have emerged from a process of setting aside preconceptions.

The role of amateur radio, with its complex assortment of frequency allocations and operational demands, has made it inseparable from engineering efforts in the search for improved Yagi antennas. Besides some original work developed for these exercises, the designs used as models have been adapted from published designs and models by Brian Beezley, K6STI; William Orr, W6SAI; Jack Reeder, W6NGZ; Jim Breakall, WA3FET; Nathan Miller, NW3Z; and R. Dean Straw, N6BV. The work of other excellent Yagi designers has been omitted, but deserves detailed study by any student both of modeling and of parasitic antenna design.