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

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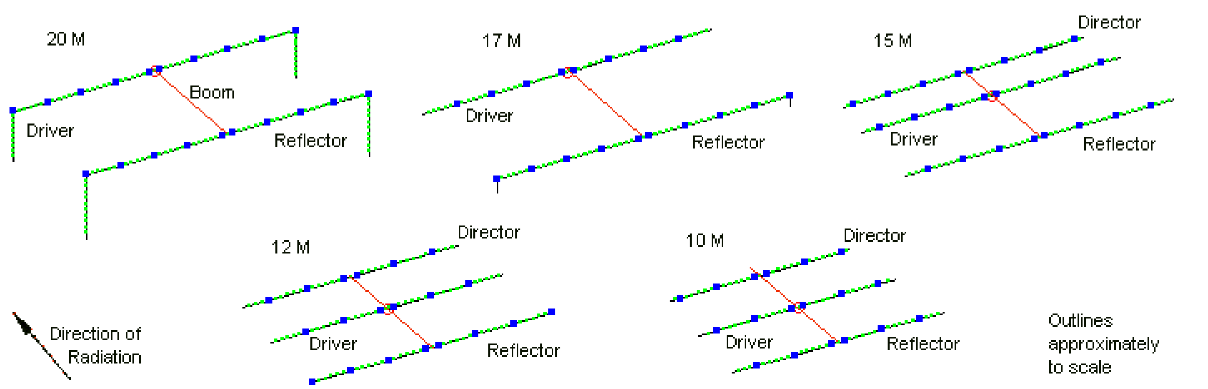
Introduction

This document describes 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.

The electrical aspects of the design appeared in Part 1 of these notes. For reference, we may briefly review an abbreviated version of the collected data from the NEC-4 models. The models use a free-space environment to facilitate a general comparative evaluation. **Fig. 1** provides outline drawings of each beam configuration. The outline sketches are approximately to scale.



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 tables summarize the electrical performance of the antenna on each band as modeled in free-space on NEC-4.

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

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

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

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

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

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.

Mechanical Design of the 2-3-Element Field Yagi

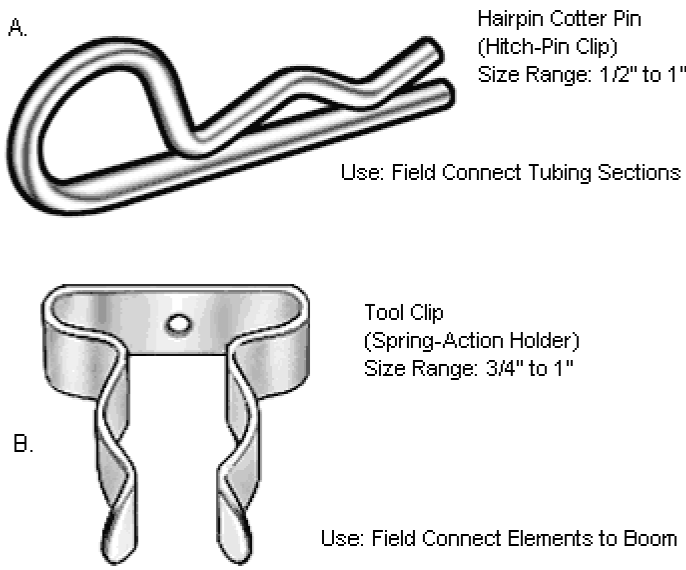
The mechanical design of the field and portable 2-3-element Yagi is subject to numerous alternatives and issues. Therefore, the discussion may prove longer than the text associated with the graphs and tables that provide the modeled performance of the array.

Key Hardware

Central to the no-tool assembly and disassembly of the beam is the use of two items of special hardware not usually associated with Yagi antennas. **Fig. 2** provides sketches of the two items. One item is the hitch-pin clip, also called a hairpin cotter pin. This items links each element section to the next section. It is not usable for a permanent installation, where good electrical contact must exist for years unattended. However, for field and portable operations lasting in terms of days, the element sections make good contact at their junctions and the clip is necessary only to secure the section.

Hitch-pin clips come in a variety of materials and sizes. I recommend the use of stainless steel versions of the clip to avoid any problems with bi-metallic reactions, which might occur with plated steel clips. Depending on the source, clips may come in specific sizes for each element section diameter, or they may serve two adjacent sizes. I recommend that each clip use an attached flag or tape. The sizes may use separate colors for easy identification. As well, a bright flag will allow easy location of any dropped clips.

The second hardware item is a tool clip, sometimes called a spring-action holder. These devices commonly hold tools with either short or long handles to a mounting board. However, in the present application, they clamp round parts of the antenna structure to mounting plates. For example, they hold both the element and the boom to a common plate. As well, they may hold the boom and the mast to a common plate. Like the hitch-pin clip, tool clips are available in several materials. Again, I recommend stainless steel for its corrosion resistance and absence of bi-metallic reactions.



Key Hardware for No-Tool Field Assembly

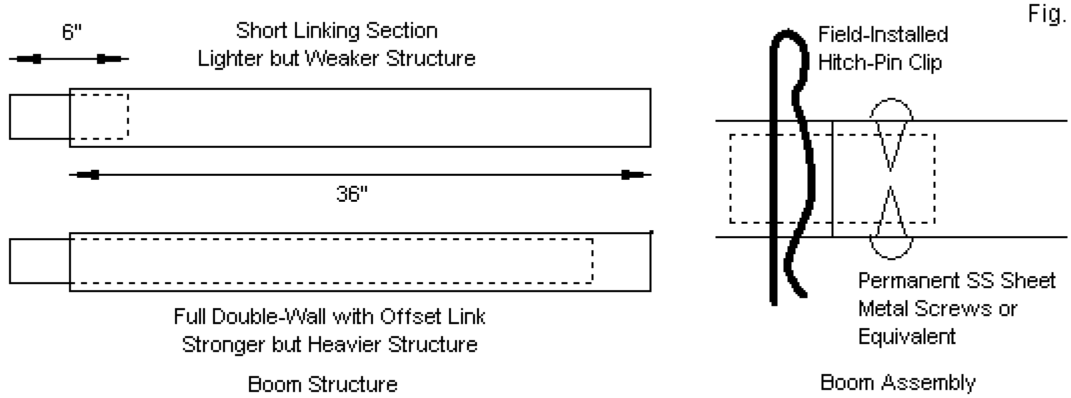
Fig. 2

Unmounted, a tool clip appears to be very open with a large curve in the portion with the hardware hole. However, when mounted securely to a flat plate, the curve straightens, forcing the sides of the clip together. The spring action is exceptionally strong for such a simple device. There is no danger of an element falling through the opening even if suspended beneath the boom. The tool clips mount with a single nut and bolt to a flat plate. The nut and bolt (along with any lock washers) should be stainless steel. All nuts and bolts are permanent fasteners and should never require field adjustment or tightening. Therefore, wherever apt, one may replace nuts and bolts with high-grade rivets or similar permanent fasteners.

The Boom

The electrical design calls for a 12' boom. For transport, we may subdivide the boom into 4 sections, each 36" long plus a linking section. For a lightweight beam such as the present one, the boom may use 1" diameter aluminum tubing. **Fig. 3** shows the structural considerations associated with the boom sections.

Fig. 3



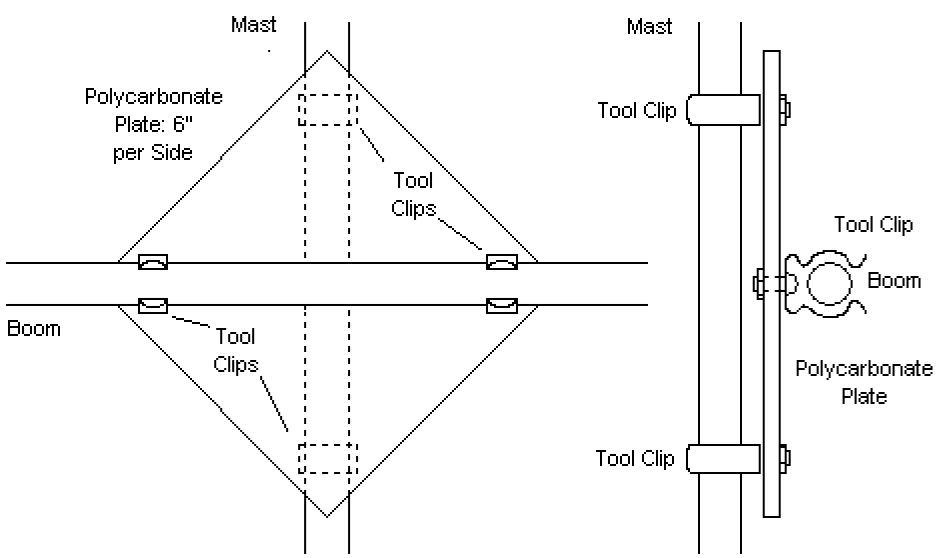
General Outlines of Boom Section Structure and Linking

Each 36” section contains a 3” extension of 0.875” tubing. As shown on the right, the extension has permanent fasteners (such as stainless steel sheet metal screws) and becomes a permanent part of the section. (3 of the 4 sections require such extensions.) Precisely aligned holes through the adjacent section outer tube and the extension allow a hitch-pin clip to provide a solid link. The holes should be just large enough to pass the hitch-pin clip straight leg. Excessive clearance will eventually enlarge the holes. Good quality hitch-pin clips have a very strong clamping action that will minimize any potential wiggling of the two sections under the influence of variable loads, such as gusty winds. With a 3” extension, the boom sections are each 39” long (except the extensionless fourth section), which falls within the limits set for the transport package.

The strength of the boom depends upon the wall thickness of the aluminum tube and the quality of the material. The simple short-link version should work well with 6063-T832 aluminum tubing having a 0.056” wall thickness. However, if initial testing of a prototype shows that the boom exhibits too much sag or other weaknesses (perhaps from the use of other tubing materials), then one may use the alternative system. It employs a doubled tube with an offset to create the link between sections. Such a boom will be stiffer and stronger, but nearly double the boom weight.

Fig. 4 shows a usable boom-to-mast assembly. The key element is a ¼”-thick polycarbonate plate that is 6” on a side and arranged for use in the form of a diamond. Tool clips fasten to each face of the plate, with 2 arranged vertically to clamp to a mast and 2 arranged horizontally to clamp to the boom. The strength of the tool clips will support the weights involved with minimal potential for unwanted slippage. However, the use of clips allows a rapid adjustment of position, for example, to best center the weight of the beam after re-configuration for a new band.

Fig. 4



Suggested Prototype Boom-to-Mast Assembly

The dimensions of the plate allow it to fit within the suggested transport package cross section of 6” by 6”. One may round the corners to prevent damage to the package container.

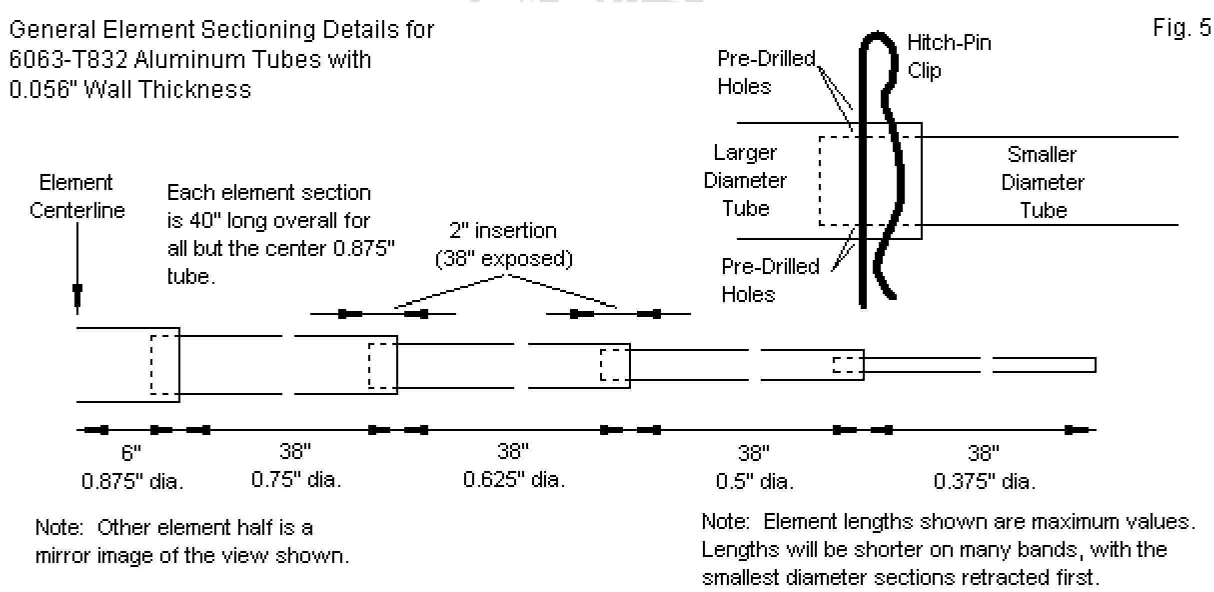
The edge view of the assembly on the right shows a typical tool clip mount, consisting of a single nut and bolt, possibly with the addition of a lock washer. For a ¼”-thick plate, a ½” long #10 bolts is sufficient for a secure mount. In addition, tool clips should not require special treatment of the flat plate surface to prevent twisting, since the mounting surface of the clip itself acts as a compression washer with excellent holding power.

An alternative to the suggested boom-to-mast mounting system might be a permanent short section of mast bolted to the plate and used to slip over the top of a field mast. However, this sort of mounting system would enlarge the storage space relative to the transport package cross section. Turning the plate to form a square would reduce the stability that the present separation of boom-holding clips provides.

Elements

The field Yagi package provides the materials for 6 half-elements and 3 center sections: 1 driver center and 2 parasitic element centers. Each half-element—beyond the limits of the center section—uses 4 sections of tubing, each 40” long. The length, which fits the constraints of the transport package, allows for a 2” insertion of each tube into the next larger size tube, with 38” of exposed tubing. Since the half-length of the center is 6”, each half element may be as long as 158” (316” total for each element).

Fig. 5 shows the general structure of the elements. With carefully aligned holes, a properly sized hitch-pin clip fastens each section to the next. All sections should place the hitch-pin holes exactly 1” from the tube end to ensure an equally exact 2” insertion. A hitch-pin clip also secures the largest tube in the half element to the element center, which we shall discuss separately.

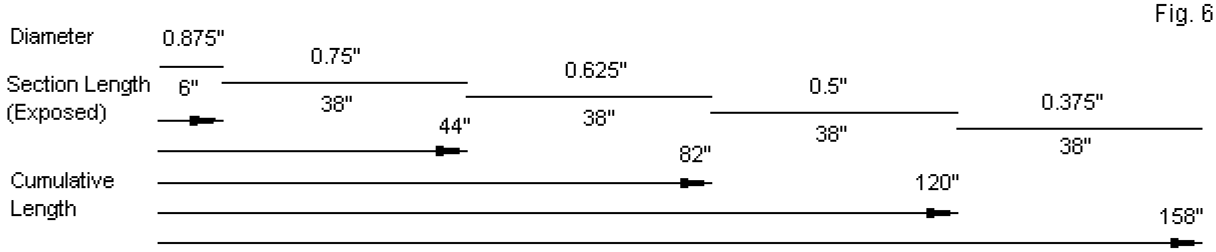


The half-element tubing sizes range from 0.75” to 0.375” in 0.125” increments, using commonly available 6063-T832 tubing with a 0.056” wall thickness. This tubing nests well and closely for good electrical contact with just a hitch-pin clip during the normal duration of field operations. If one chooses to use tubing with thinner walls to save weight, the outer ends should be swaged to provide the necessary contact surface with the inserted tube section. Similar considerations may apply to metric tubing sizes.

When not in use, the half-element sections nest inside each other for packaging, storage, and transport. If the hitch-pin clip holes are well aligned, then each collection of element sections may use a single hitch-pin clip to secure the bundle.

Not all elements use the full available length provided by the sectioning system. **Table 1** shows the variables involved. Only the 0.5" and 0.375" section are involved in variable lengths. The overall section diagram in **Fig. 6** provides a rough guide to the relationship of an element's total half-length and the sections of tubing in the elements.

Fig. 6



Element Structure from Center to Tip (Full Element Shown)

Table 1. Element structure for each element on each band of operation
Half-elements given from center to tip—see Fig. 7. Add 2" to each element section from 2 through 5 for insertion into the next larger diameter tube.

Section	1	2	3	4	5	Total
Dia. (in)	0.875	0.75	0.625	0.5	0.375	
20 Meters						
Reflector	6	38	38	38	38	158
Driver	6	38	38	38	38	158
17 Meters						
Reflector	6	38	38	38	38	158
Driver	6	38	38	38	36	156
15 Meters						
Reflector	6	38	38	38	26	146
Driver	6	38	38	38	20	140
Director	6	38	38	38	10	130
12 Meters						
Reflector	6	38	38	38	4	124
Driver	6	38	38	35		117
Director	6	38	38	26		108
10 Meters						
Reflector	6	38	38	26		108
Driver	6	38	38	18.5		100.5
Director	6	38	38	9		91

When a tube section is shortened or is not used, it retracts into the adjacent larger section by the required amount. To ensure proper fastening, the smaller diameter tube must have additional holes for the hitch-pin clip to pass through in the new position. Since the requirements for length vary among the reflector, driver, and director elements, one faces the prospect of drilling many holes to make each element half a universal element. Alternatively and perhaps more simply, one may specify the element halves in pairs and designate each pair a reflector, a driver, or a director. Color coding and/or wear-resistant markings are necessary to prevent confusion during assembly. Color-coding should be applied only to the 0.75" tubing in permanently exposed areas. Marking should not increase the tube diameter or add any adhesive so that nesting and un-nesting the sections proceed smoothly.

The element halves are sectioned for the benefit of the storage and transport requirements. They do not adhere to the lengths that might be found in beams that have been analyzed to survive significant wind loads. Therefore, the field/portable beam is useful only in winds ranging from calm to rather gentle breezes. The beam requires disassembly in the event of stronger winds.

20 and 17 meters require extensions in order to achieve resonance and other performance goals within the element half-length of 158". Vertical extensions appear in the electrical specifications. **Fig. 7** provides a system for attaching the extensions efficiently in the field.

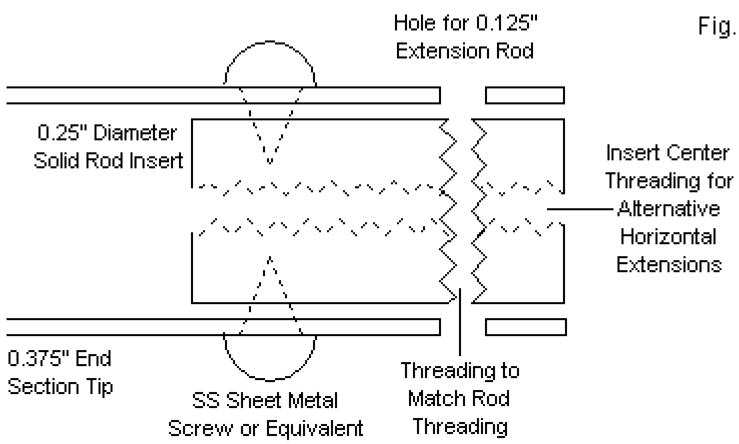


Fig. 7

Possible Element Tip Treatment for Use with Element Extensions on 20 and 17 Meters

Into the end of each 0.375" diameter tube, one may insert a short length of solid 0.25" aluminum rod. The insert requires permanent fastening. If the stainless steel sheet metal screws are used, then the final section will project from the nest bundle by about ½". The bundle will still fit within the overall storage package length. However, one may also consider such methods as sweat fitting or tip brazing as alternatives that do not enlarge the end of the 0.375" tubes.

For vertical extensions, one may drill and thread the insert to receive a threaded rod or end of the extensions. (The sketch also shows horizontal threading in the event that one wishes to use shorter horizontal reflector extensions on 17 meters. However, such extensions would not be self-supporting on 20 meters due to the required length.)

The exact diameter of the threaded hole depends upon the material one selects for the vertical extension. Three alternatives come immediately to mind.

1. The lightest extensions would consist of simple wire, perhaps #14 through #18. These extensions would require that one secure onto one end a threaded headless bolt to fit the threading placed in the element tip with its insert.

2. One may also use 0.125" aluminum rod. This system requires two measures. First, the rod must be cut into sections to fit the storage package. Second, the rod must be threaded at each end. Threaded couplers connect rod sections, and the top-most end threads into the element tip. One weakness of this system is the need to use #6 threading, a situation that is prone to breakage with aluminum rod. However, stronger stainless steel rods would likely add considerable weight to the element ends.

3. The extensions may be created with either stock or custom collapsible whips, commonly used for AM auto radios. Many such whips have threaded. Collapsible whips would suit the needs of the 20-meter driver (about 55") and reflector (about 71") quite well, although a fixed-length extension may still be necessary for 17 meters.

The variability of the potential extension materials means that the extension lengths shown in the electrical specifications are not as firm as the lengths of the horizontal elements. Therefore, whatever material is selected for the extensions will need to undergo prototype trials to arrive at the correct length for proper beam operation on 20 and 17 meters.

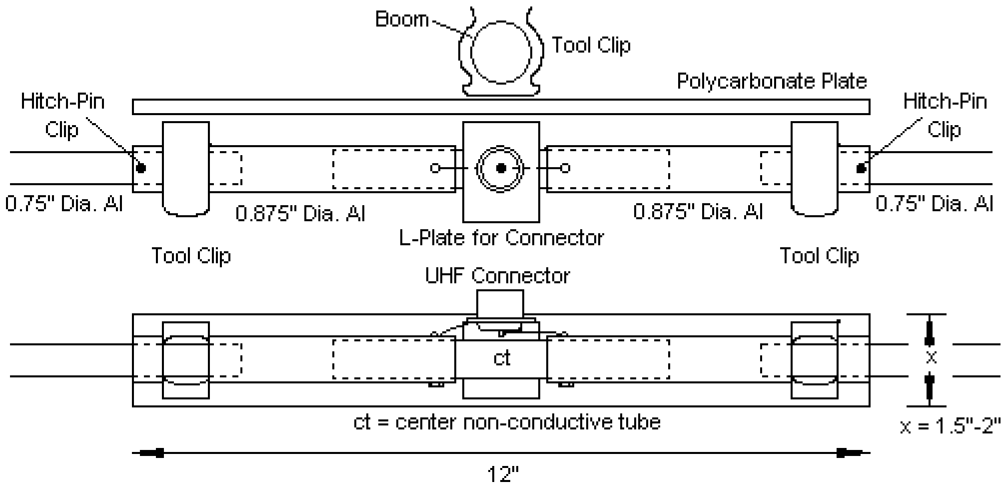
The Element Centers

The element centers perform two essential functions. First, they support the half-elements just described. Second, they contain the tool clips that connect the elements to the boom. One of the centers also provides the gap and coax connector that creates the driver feedpoint. **Fig. 8** shows the details of the driver center. The parasitic-element centers are similar, but consist of a single 12" section of 0.875" tubing with no gap or coax connector.

Each center begins with a ¼"-thick polycarbonate plate that is 12" long by 1.5" to 2" wide. At the center, on one side of the plate, is a tool clip sized to fit the boom. A single tool clip will normally suffice to hold the element beneath the boom. However, if there is any concern about the element weight, then one may widen the plate to about 4" and install a pair of tool clips to clamp to the boom. The suspension of elements beneath the boom assists with horizontal self-alignment during breezy weather.

On each end of the plate on the reverse side are two tool clips sized to grip the element. The tool clips are far enough inboard on the plate to allow for a hole to pass the hitch-pin clip that secures the 0.75" tubing of the half element. Parasitic elements use a 12" center tube, but the driver uses 2 5.75" tubes. Between and inside the tubes is a short section of ¾" outside diameter CPVC tubing or fiberglass rod. This non-conductive piece aligns the two center tube sections and freezes the feedpoint gap. A stainless steel nut and bolt pass through the aluminum and inner tubes to lock the pieces in place and to provide connection points for leads to the UHF coaxial cable female connector.

Boom-to-Element Plate Construction (Driver Element Shown) Fig. 8



Note: Not all hardware shown, specifically, nuts and bolts to mount tool clips, nuts and bolts to mount UHF connector, and details of the hitch-pin clips fastening 0.75" to 0.875" tubes. UHF connector L-shaped mounting plate uses the same hardware as the boom tool clip. Parasitic elements use a simplified mount consisting of a 12" unbroken section of 0.875" tube.

The UHF connector mounts on an L-shaped aluminum plate. In use, the connector would point toward the mast. The connector plate uses the same hardware for mounting as the tool clip on the reverse side of the polycarbonate plate. This connection strategy ensures that the braid of the coax is connected to the boom for eventual system grounding. Leads from the connector center pin and from a grounding point on the connector or the mounting hardware go to the hardware on each short center tube. Stainless steel washers are useful to separate the copper leads from the aluminum tubes.

The center sections complete the required hardware for the beam. In the field, the user would assemble the boom, clip on the center sections needed for the band of operation, and extend the elements to the required and marked lengths for that band. He would then attach (clip) the beam to the top of the mast designed to hold the array. Disassembly is the reverse of assembly and involves unclipping the array, unclipping the elements, and removing hitch-pin clips to reduce the elements and the boom to their storage and transport form.

The storage container may use any convenient package that can contain the beam pieces. For example, one may construct a drawstring bag from toweling or similar utilitarian materials. More formally, one may design a custom carrying case of canvass, plastic cloth, or even hard plastic used for tool storage. A 6” by 6” by 46” package would hold all parts satisfactorily.

Maintenance

All field antennas require inspection and cleaning twice for each use, once prior to the field exercise and again upon return. Besides removing any dirt, the aluminum tube sections should be cleaned with a dry rag. The surface may be smoothed with a plastic abrasive pad, such as those found on some kitchen sponges. (Under no conditions should one use steel wool on the aluminum surface. If a nick in a tube’s surface prevents easy nesting and un-nesting of the element sections, it may be removed with aluminum oxide sandpaper, followed by the smoothing step.) Of course, the inspection should also include assuring that the feedpoint connections are sound and that the UHF connector is properly functional.

Summary of Mechanical Characteristics of the Beam Design

The mechanical aspects of the beam design allow for no-tool assembly and disassembly, as well as for reconfiguring the Yagi for each desired operating band. All screws and all nuts and bolts are permanent parts of the subassemblies. The user need only manipulate a series of hitch-pin clips and tool clips to prepare the beam for use or for transport and storage.

The strength of the elements and the boom depends greatly on the strength of the materials used. The materials listed for the prototype are standard U.S. materials with a long history of successful use in Yagi arrays. The use of different outer diameters for the sections of the element halves will require a re-design session to adjust the performance values listed in the electrical specifications. Thin-wall tubing may require end swaging to effect good electrical contact between element sections. The precise methods used to attach 20-meter and 17-meter extensions to the element ends will depend on the material selected for the extensions themselves. If alternative materials are used for the boom, special attention is required to ensure sufficient strength and to minimize sag at the ends.

Conclusion

The notes in Parts 1 and 2 have described the electrical and mechanical design of a 2-3-element field or portable Yagi that the user may assemble, reconfigure, and disassemble without the use of tools. Hitch-pin clips and tool clips provide both secure mechanical fastening and good electrical contact for the normal duration of a field exercise. The estimated maximum weight of 10 to 12 pounds ensures a relatively modest load to any portable mast system. The components of the array make use of commonly available materials and allow—with suitable caution—the use of substitute materials.

In exchange for the inconvenience of reconfiguring the beam for each operating band, the Yagi offers full performance, since it is based on unloaded elements and on proper element spacing for maximum gain and a 50-Ω feedpoint impedance.

These notes leave an open question: is there a way—without lengthening the boom—to achieve more equal performance among the 3 bands? The answer is *yes*, if we are willing to add two or three components to the overall field package, along with some slight complexity of original construction. Since these notes originated with the idea of creating the simplest possible package, we shall reserve the additions for Part 3.