THE MONOLITH HORN

By Bruce C. Edgar
Contributing Editor

After my "Show Horn" article appeared (*SB* 2/90, p. 10), I received a number of inquiries about designing a bass horn that would go down to 30–40Hz. One *SB* reader, Fred Ireson, requested a 40Hz horn for a 15" driver, and I have been refining the design and construction details ever since.

The 40Hz horn is shown in *Photo 1*. Since the structure is rather imposing, I have nicknamed it the "Monolith." Despite some unusual features, such as a mouth that exhausts out of the bottom and a top-mounting driver compartment, the modular construction is well within the capabilities of a skilled home craftsman with a table saw.

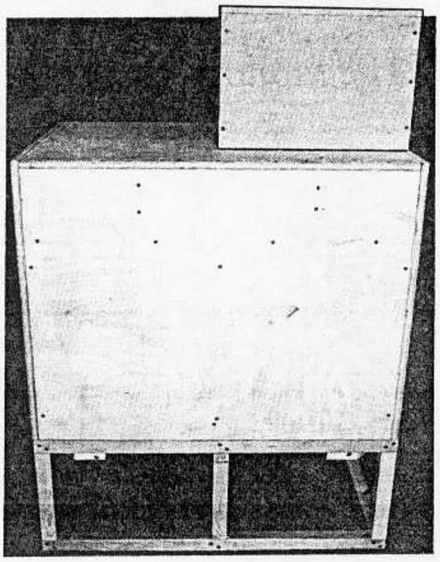

PHOTO 1: The Monolith Horn.

EXPERIMENTAL STAGE

Experimentation helped me avoid potential problems. Since bass horns can be huge, designers try tricks such as 180° folds, reducing the mouth size, and shortening the length in an effort to keep the overall volume to reasonable proportions. Unfortunately, if they are not applied intelligently, these techniques can lead to numerous response anomalies.

One of the classic horn-folding designs utilized a series of 180° folds that approximated an exponential flare in steps.[1] The overall response of the rear-loaded bass horn (*Fig. 1*) rolls off above 200Hz, and it is unclear whether this is due to the cone mass or the folds. If we move the rolloff up to 400Hz, however, we can achieve good wide-band performance with a reduction in volume.

Before conceiving the "Show Horn," I was asked by a reader to design a 50Hz corner horn with the smallest volume (for shipping overseas) plus a wide bandwidth to mate with a 500Hz midrange horn. In my naïveté, I set off on my mission not realizing the potential conflicts in the design requirements. To attain the 500Hz bandwidth, I chose to use the EVM 12L driver, which has a mass rolloff over 500Hz. *Figure 2* is a design sketch featuring several 180° folds with a top-mounted driver and a bottom exhaust mouth—precursor to the Monolith.

I proceeded to build the bass horn and measure its response (*Fig. 3*). You can see the big 20dB "hole" between 300 and 400Hz, which is clearly unacceptable. At first, I didn't have a clue as to the root cause, but after some discussion with Dave Rowe and other colleagues, we arrived at the concept of placing the corner reflectors along the diagonal. When I replaced the existing corner reflectors with larger ones, the response hole partially filled up (*Fig. 4*), indicating that this approach was leading in the right direction.

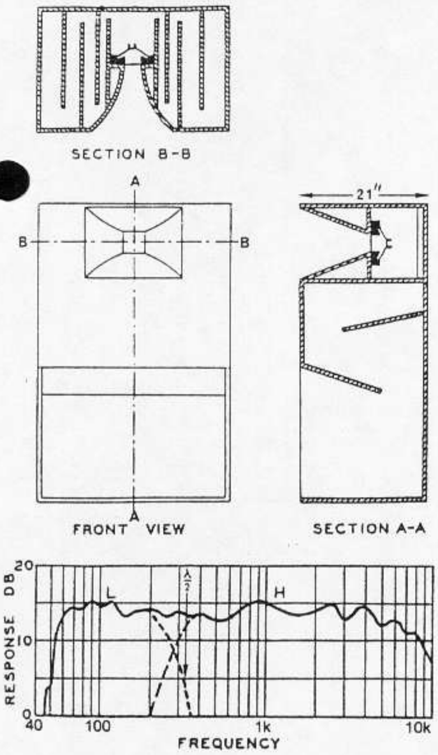

FIGURE 1: Olson and Massa's 1936 horn.

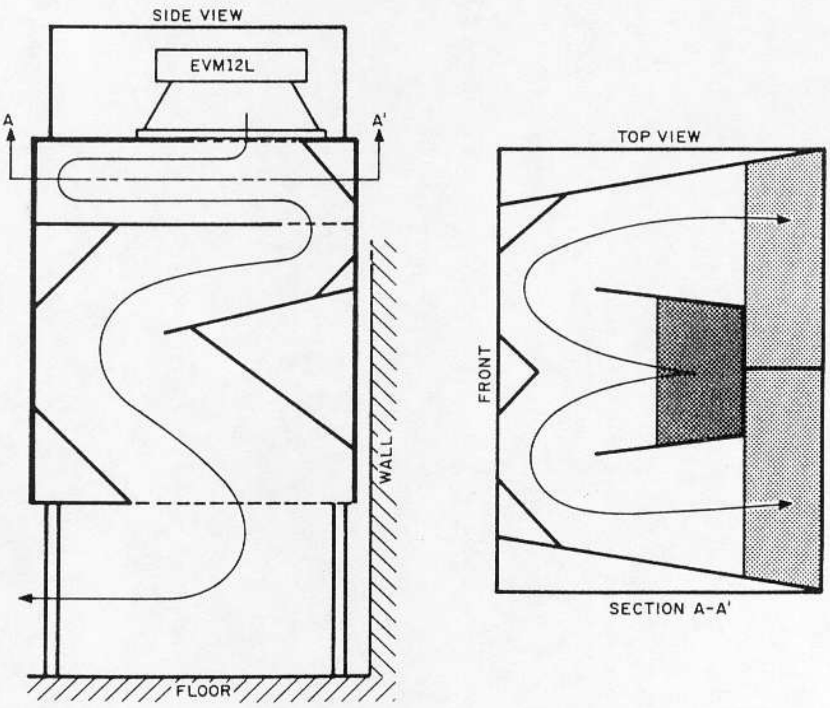

FIGURE 2: An Edgar experimental 50Hz horn design circa 1984.

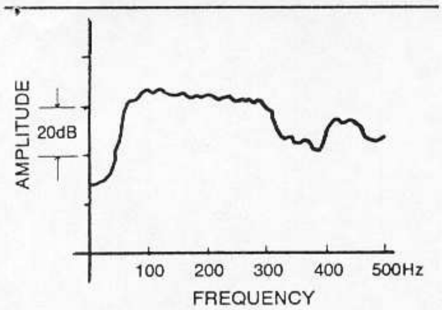

FIGURE 3: Response of the 1984 design with dropout between 300–400Hz.

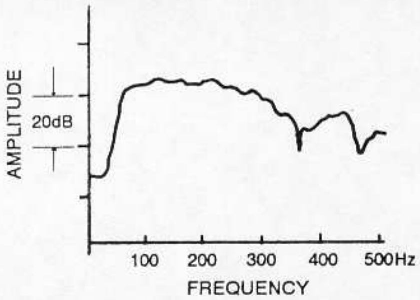

FIGURE 4: Response of 1984 design with diagonal reflectors.

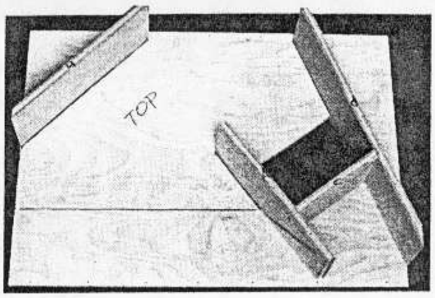

PHOTO 2: Throat partitions mounted to the top.

After the Show Horn article appeared, several people questioned why a diagonal reflector would make such a difference over a radius bend (*SB* 2/90, *Figs. 4* and *5*, p. 14). The radius bend dimensions are still a fraction of a wavelength (45" at 300Hz), which satisfies Olson's conditions for proper horn folds.[2]

If you look at a 90° bend from a short-wavelength perspective, a reflector along the diagonal makes more sense. *Figures 5* and *6* graphically show Huygen's construction principle of wave fronts traversing a 90° bend using both types of reflectors. As you can see from *Fig. 5*, a radius-bend reflector gives both backward- and forward-traveling waves in response to the initial wave fronts, and those coming out of the bend are incomplete. Compare that with *Fig. 6*, where no backward-traveling wave exists, and the forward-traveling wave fronts coming out of the bend are completely reconstructed.

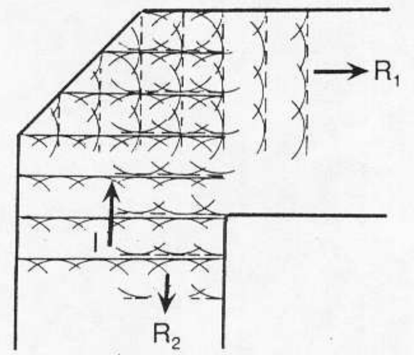

FIGURE 5: Huygen's wavefront construction for a 90° duct bend with a radius reflector. "I" is the incident wave; "R1" and "R2" are the reflected waves.

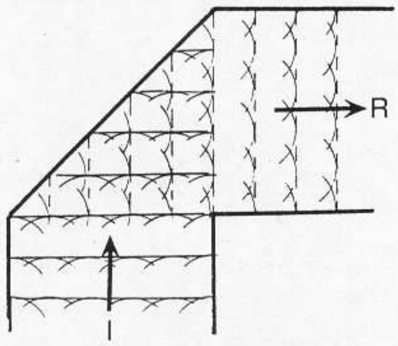

FIGURE 6: Huygen's wavefront construction for a 90° duct bend with a diagonal reflector. "I" is the incident wave; "R" is the reflected wave.

A 180° bend can be modeled as an acoustical inductance, and a horn with many folds can be modeled as a series of acoustical transmission-line strips separated by inductances (*Fig. 7*).[3] At the frequency where the length of the transmission-line strip is half a wavelength (at 300Hz, 22.5"), any transmission line will transfer to the input the impedance seen at the load end.

If a series of transmission-line strips of equal length are separated by inductances, the input impedance at the half-wavelength condition becomes a bunch of inductances in series. In the case of a multifolded horn where the bends are separated by equal lengths, the inductance load condition at the half-wavelength will swamp the mouth impedance and the response is choked off at that frequency.

In mathematical terms, the frequency for the half-wavelength condition is:

$$f = \frac{c}{2 \times l}$$

where:

c = the speed of sound

l = the length of the horn section between bends

In the case of *Fig. 2*, the length between folds was 19½", which corresponds to a half-wavelength frequency of 345Hz—right in the response hole of *Fig. 3*. In the case of Olson's horn example, l = 21", for a null frequency of 321Hz. The bass-horn response has a very sharp rolloff at 300Hz, which leads me to speculate that his horn was indeed affected by the null caused by reflections at the bends and the equidistant spacing between bends.

I discovered during my investigation of horn bends that the same principle is used to design mufflers. A muffler is a series of pipe lengths separated by small volumes which are acoustic capacitances. By adjusting the pipe lengths and volumes, you can design a very effective acoustical stop-band filter. So between 300 and 400Hz, my original horn design was behaving like a muffler!

A diagonal reflector will help, but not completely cure, the response ills occurring with 180° bends. You should first try to reduce their number or make them less severe. You can also use the nulling phenomenon from the bends to shape the horn's upper-frequency cutoff to your advantage, such as in a subwoofer horn.

DESIGN STAGE

After some discussion with Fred Ireson, we settled on the JBL 2220H 15" pro driver. Using formulas from the Show Horn article, its T/S parameters (f_S = 37Hz, Q_{ES} = 0.18, and V_{AS} = 10.5 ft.³) give an optimum throat size of 56 in.² and a mass rolloff of 411Hz. Even though a

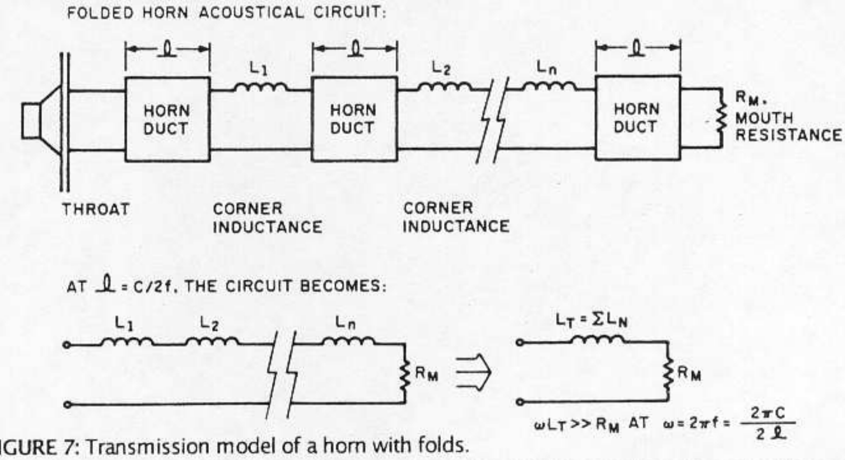

FIGURE 7: Transmission model of a horn with folds.

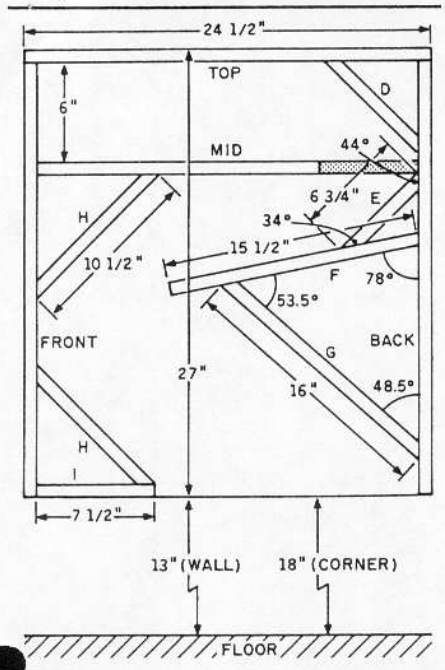

FIGURE 8: Top view of the horn throat manifold.

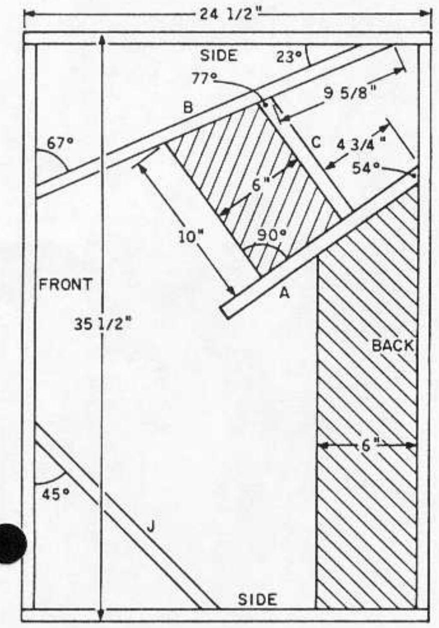

FIGURE 9: Side view of the Monolith bass horn.

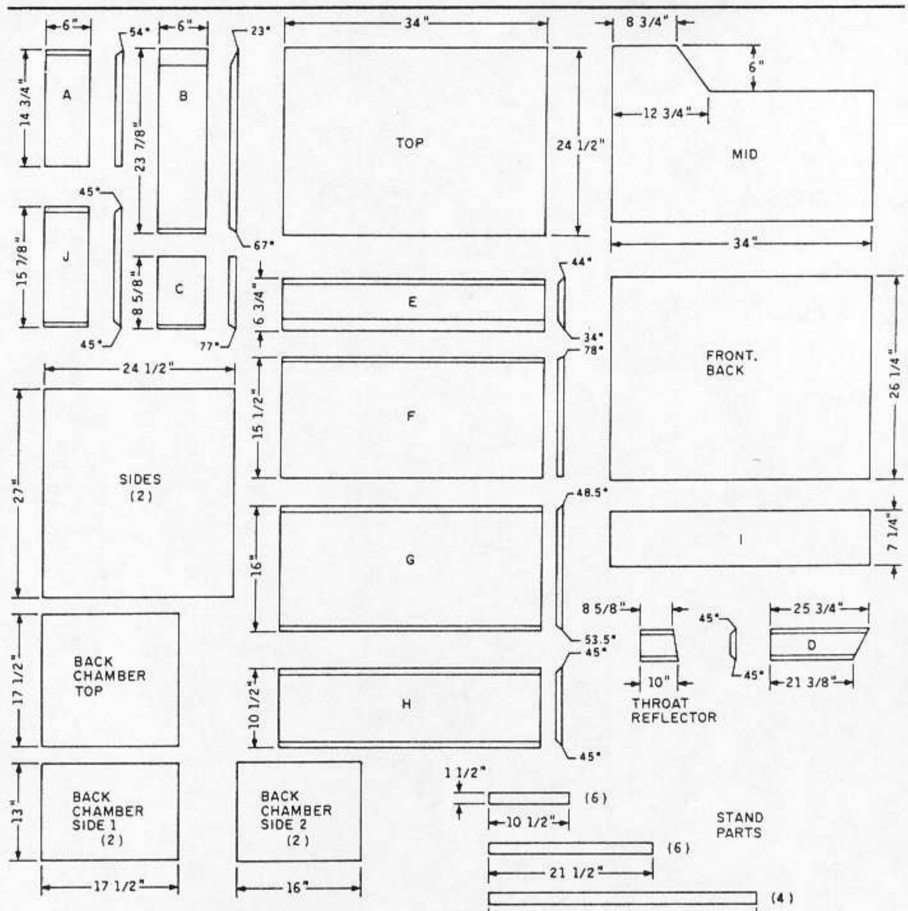

FIGURE 10: Horn parts description.

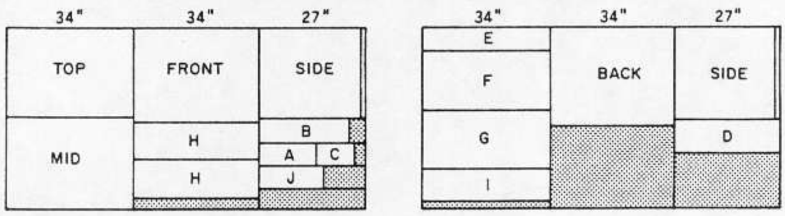

FIGURE 11: Sawing guide for $3/4''$ plywood.

resonance frequency of 37Hz would allow a lower flare frequency, I chose 40Hz to keep the size to manageable proportions. For the best response down to the flare cutoff frequency, I selected a hyperbolic exponential expansion of M = 0.6. Even with a one-eighth-sized horn, the path length is over 7′ and the mouth size is nearly 8 ft.^{2} (1,133 in.^{2}), which gives you an idea of its imposing size.

The concept of a bottom exhaust for the mouth is not new: both the Lowther TP-1 and the Gately Super Horn used it.[4,5] With a bottom exhaust, the mouth can be wrapped around the horn base perimeter. If the two side and front widths add up to a length Lm, then the height (h) of the exhaust opening above the floor is h (in.) = 1,133/Lm.

In the Monolith's case, this distance from the floor turned out to be 13″ for a wall position (two side areas and a front area forming a mouth) and about 18″ for a corner position (one side area and a front area); however, this separation distance can be adjusted for the smoothest response, as we will examine later. The mouth's close proximity to the floor allows for good coupling to the acoustical images below the floor and behind the wall. The formation of these images multiplies the effective mouth area to provide good bass.

TABLE 1

MONOLITH HORN PARTS LIST

PART	DIMENSIONS
A	6″ × 14¾″
B	6″ × 23⅞″
C	6″ × 8⅝″
D	8½″ × 27″
E	6¾″ × 34″
F	15½″ × 34″
G	16″ × 34″
H (2)	10½″ × 34″
I	7¼″ × 34″
J	6″ × 15⅞″
Sides (2)	24½″ × 27″
Top	24½″ × 34″
Front, back (2)	34″ × 26¼″
Back chamber side 1 (2)	12¾″ × 17½″
Back chamber side 2 (2)	12¾″ × 16″
Back chamber top	17½″ × 17½″

MONOLITH CONSTRUCTION

The Monolith's throat manifold layout and side view are shown in *Figs. 8* and *9*, respectively. The former is similar to the Show Horn; however, with the back chamber on top, you can locate the throat and driver in an optimum position and not have to leave room for the back side duct. With a 15″ driver, a top mounting is a decided advantage in reducing the horn's depth. The internal depth

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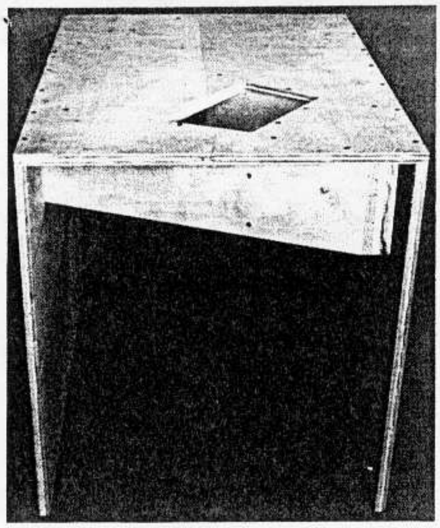

PHOTO 3: Positioning the top piece on the front and back panels.

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of 23" results in a null frequency of almost 300Hz due to the series of 180° bends. A horn with more depth would push the null frequency below 300Hz, which I wanted to avoid. I thought that with the corners properly mitered, the null effects for the configuration could be minimized. The mass rolloff at 411Hz would provide both a graceful attenuation of the response above 400Hz and good mating with a midrange horn above 500Hz.

The Monolith can be assembled from two sheets of ¾" plywood, MDF, or particleboard. I used birch veneer plywood to reduce the weight for shipping. *Figure 10* shows the part shapes, with a plywood cutting guide in *Fig. 11*. The constant-width box design allows for a certain amount of cutting efficiency. If your lumberyard has a good table or plywood saw, have them make the 34" and 27" cuts for easier transportation back to your shop. You can then make the smaller cuts on your table saw. I also recommend redrawing to full scale the plans in *Figs. 8* and *9* as a check on sizes and angles. You can also trace templates for the angles from these drawings.

I first built the horn using only screws, but reassembling it with screws and glue seemed to provide better damping. When I say "attach piece A to B," therefore, you have the option of either using screws and glue or screws only. Begin by cutting the partition pieces (A, B, C, and J) and assembling them to the top piece, as shown in *Fig. 8* and *Photo 2*. Draw out to full scale the throat manifold on the top piece to ensure your angles are cut correctly. Once the throat partition pieces are attached, you can cut the throat opening with a sabre saw. A router with a long, flush cutting head will do a nice job of trimming the throat port flush to the edges of A, B, and C.

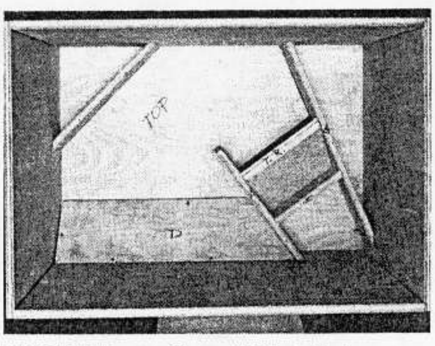

PHOTO 7: Duct reflector "D" installed.

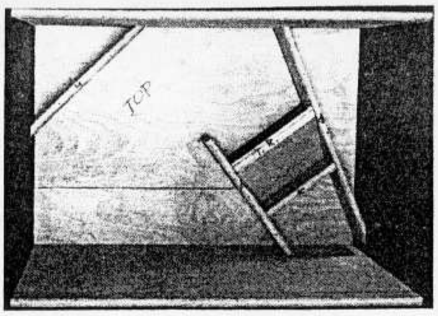

PHOTO 4: Inside view of the throat manifold with attached front and back panels.

Stand the top piece with the throat partitions on the edges of the front and back pieces (*Photo 3*), using corner clamps to hold them together while you attach the top to the front and back. Then add the two side panels, as shown in *Photos 4–6*. Once you have finished assembling the box, finish joining the throat partitions to the back, front, and side panels. Fill any gaps between the throat partitions and sides with a caulking material such as mortite or silicone rubber.

The duct reflector (D) must be fitted next. This procedure is outlined in the Show Horn article. You first determine the compound angle by cutting and fitting scrap pieces which have the same widths and 45° angles as piece D. Once you have determined the proper saw blade and miter gauge angles, make the same cut on D longer than that specified in *Fig. 10*. Keep trimming D until it just fits. Attach the duct reflector to the back, top, and side. To further aid construction, you can fit little 45° trianglar pieces under D for alignment and attachment points. Next, redraw the locations of the throat partition pieces on the midpiece. Slide the midpiece into the box and blind screw it to the throat partitions, then fasten the sides, back, and front to it from the outside.

Make some triangular alignment pieces from scrap stock (*Photo 9*). Attach piece I to one of the H reflectors and set it aside (*Fig. 9*). Slide the other H reflector down into the box and attach it with screws to the midpiece, sides, and front.

With more scrap material, cut the triangular pieces that align panels F and G to the correct angles, then attach them on a flat surface. While the structure is still flat, mount the E reflector to panel F, as shown in *Fig. 10*. Using alignment blocks for E is optional. Place the box on its back and slide the divider structure (F, G, and E) into it. Be certain reflector E is touching the midpiece. Attach the divider structure with screws from the sides, then turn the box over and attach it with screws to the back (*Photo 11*). Attach the H-I reflector to the bottom (*Photo 12*). Finally, install the throat reflector.

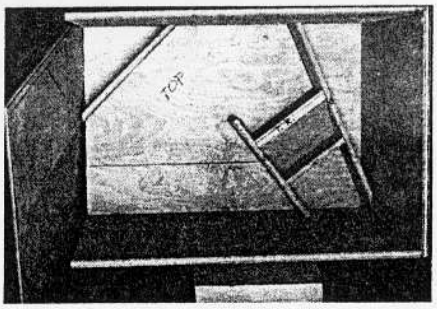

PHOTO 5: Attachment of the side panels.

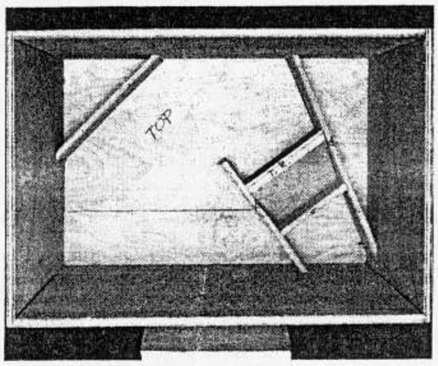

PHOTO 6: Completed horn box.

MAKE A STAND

I constructed the stand from square 1½" stock, which I cut by ripping up scrap 2 × 4s. Begin the assembly by clamping the top frame on a flat surface, then screw it together with 3½" wallboard screws. Repeat the procedure for the bottom frame, and join the frames with the leg pieces. I also added corner braces to correct warping (*Photo 13*). The parts are shown in *Fig. 11*.

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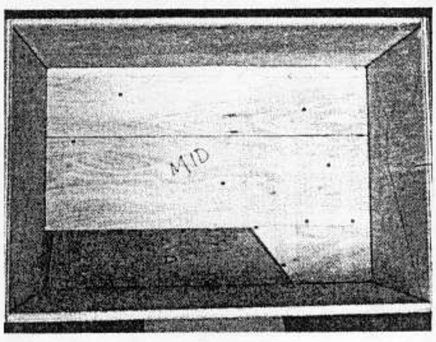

PHOTO 8: Midpiece installed.

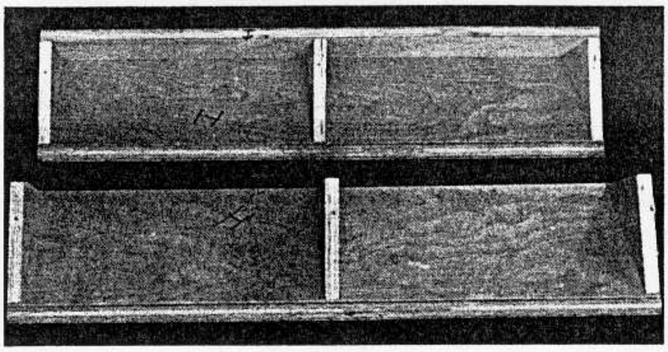

PHOTO 9: Reflectors (H) with triangular alignment pieces.

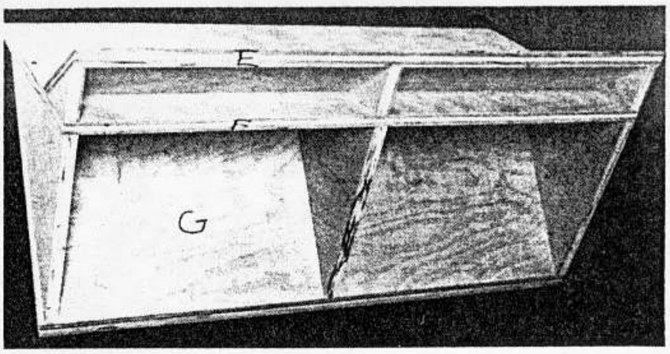

PHOTO 10: Internal divider structure.

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I determined the stand's height with the best response from a near-field response test, using a Sennheiser MD-421 microphone laid on the floor in front of the horn mouth and a Spectrum Dynamics FFT analyzer operating in an averaging mode with a white-noise input to the speaker. A 10½″ stand from a previous project gave me a first trial response. I then shimmed up the horn with a series of scrap ¾″ planks and 2 × 4s and measured the response at each height. The most balanced response occurred with 3″ spacing on the stand, for a total height of 13½″.

Figure 12 shows the response with the horn on a 13½″ stand in a wall position. This "warts and all" response shows much structure in the expanded plot, which is within the ±3dB standard. Above 300Hz, the 3dB drop is probably due to the effects of the 180° bends and the 23″ internal depth, as discussed earlier. The 3dB drop is minor, however, compared to the 20dB hole I experienced in the earlier design.

A one-eighth-sized horn is really intended for corner placement. *Figure 13* shows the white-noise response for a corner height of 21″. Below 200Hz, there is an increase of approximately 3dB above the wall position response of *Fig. 12*. Above 200Hz, the response is quite ragged compared to the wall position response. The horn apparently needs a mouth reflector to smooth out the reflections. *Figure 13* includes the response as measured by an AudioSource octave-band-pink-noise analyzer to demonstrate how deceptive such a coarse resolution measurement can be.

While the white-noise/FFT-averaged response technique works quite well in the midband, it loses resolution at the low end. For example, *Fig. 12* shows that the response at the flare frequency is down some 10dB from the midband bass. Since listening tests did not indicate any serious bass deficiencies, I doubted the validity of the white-noise test at the low end. The Spectrum Dynamics FFT has a transient capture mode, so I decided to use it with a bass pulse. I didn't have a suitable pulse generator, but I found an isolated bass drum pulse on a Telarc CD (#80038, track 3) that made a nice alternative signal. As *Figure 14* shows, the bass drum pulse excites the horn's response down to and just below the 40Hz flare frequency. The response's coarse structure is probably caused by comb filtering in the FFT.

As I looked at the Monolith stored on its side in the corner, I realized that this was the same configuration used by the "Fold and Staple Bass Horn" project, where the mouth exhausts onto the wall.[6] I decided to try it, and *Fig. 15* shows the response plots for several separation distances from the corner. As you would expect, a 5″ separation reduces the output significantly, but the spectrum is markedly more balanced compared to the corner response of *Fig. 13*. Used in the British "Impulse Horn" design, this narrow mouth loading appears to work from a measurement standpoint ("A New Hope," *SB* 4/89, p. 65). A quick listening check tended to favor the larger mouth sizes, although more careful evaluations need to be done. For larger separation distances, the primary differences are in the ripple or standing-wave patterns.

BACK CHAMBER

One of this design's nicest features is the easy-to-access back chamber. I tried a number of test boxes to find two test volumes that would resonate at frequencies below and above the 40Hz flare frequency. To determine the resonant frequencies, I used a signal generator driving the speaker with a 1kΩ resistor

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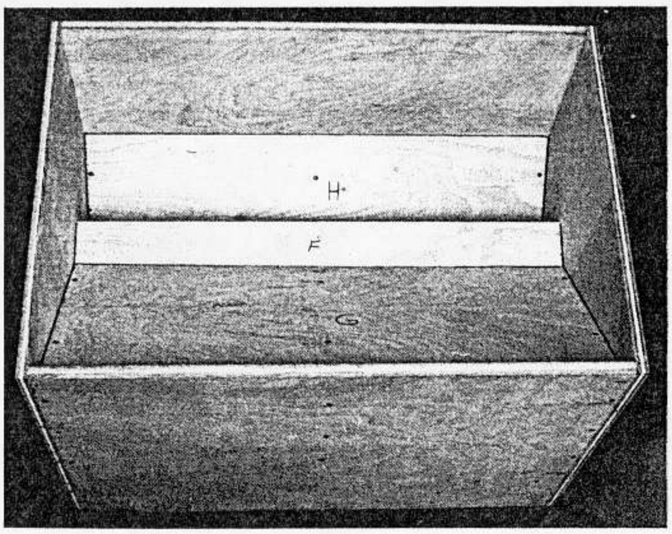

PHOTO 11: Divider structure in place.

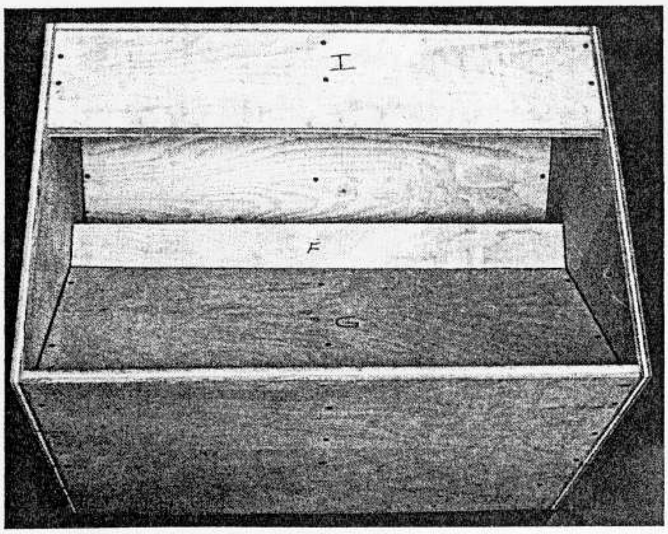

PHOTO 12: Final reflector installed.

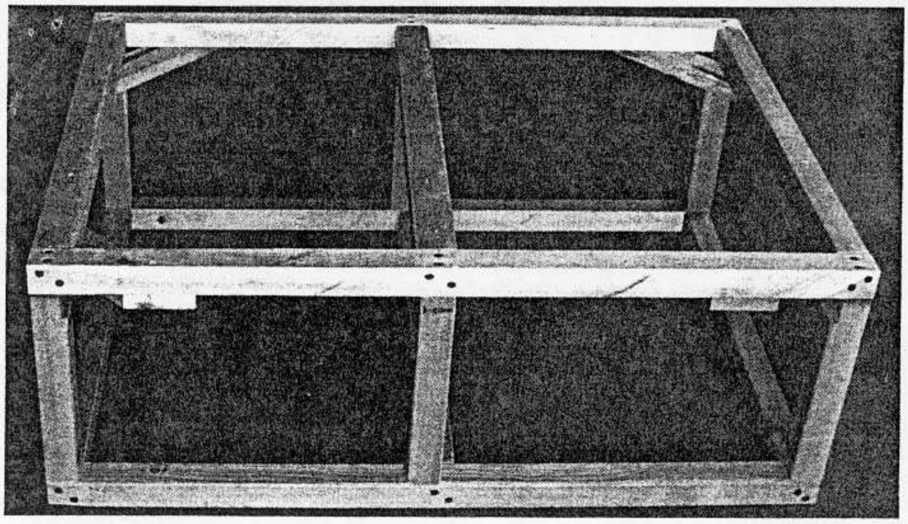

PHOTO 13: Finished 13½″ stand.

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in series and an AC voltmeter across the speaker input. I then plotted the resonant frequencies (Y axis) and their corresponding volumes (X axis) on linear graph paper and drew a straight line between the two points. At the point where the line crossed the 40Hz frequency, I read the required volume off the X axis. With a table saw, I trimmed down the larger of the two test volumes to the required volume. Rechecking the horn/back volume system's resonant frequency showed it very close to 40Hz.

I found the resultant back chamber volume to be 1.81 $ft.^3$, corresponding to an enclosure with external dimensions of 17½″ × 17½″ × 13″. If I had it to do over, I would make the square dimensions slightly rectangular. Feel free to experiment. I calculated the theoretical back volume to be 1.17 $ft.^3$ (based on annulling the throat reactance of an infinite horn by a back volume). Assuming a driver volume of 0.2 $ft.^3$, the experimentally determined back volume is 38% larger.

In my experience, the experimental back volumes for one-eighth-sized horns are always larger than the theoretical ones, sometimes by as much as a factor of two. The fact that the Monolith's back chamber is off by only 38% indicates that it is close to the ideal infinite horn. For one-quarter-sized bass horns, the back chamber is usually much closer to the ideal limit—but at the expense of a much larger horn enclosure.

I used ½-inch-wide foam rubber weather stripping to seal the edge of the back chamber where it mates to the top of the horn. To confirm that reactance annulling actually works, connect a signal generator set at 40Hz directly to the speaker input with the back chamber in place. Adjust the generator output until you can hear the 40Hz signal. Since the horn is very efficient, you don't need an amp for this experiment. Pop the back chamber seal by slightly prying up one side of the box with a screwdriver. As soon as the air seal is popped, the 40Hz signal cannot be heard; restore the air seal and the signal returns.

The back chamber can be firmly attached to the top of the Monolith with L-brackets, or with the more decorative copper-colored chair brackets. I also attached a speaker mounting plate to the top for added mass and strength. You can compensate for the decrease in volume with acoustical stuffing in the back volume.

INTEGRATION AND PERFORMANCE

When I started this project in 1988, the 2220 was a staple of JBL's pro line, but they discontinued the model in late 1992. Some surplus units may be found on the used market, but other models will also work. The EVM15L is the closest to the 2220 with a mass rolloff above 400Hz; the "B" version will have a lower mass rolloff near 300Hz. Drag out any of your old 15″ drivers and try them on the Monolith horn as an interesting experiment. Those designed for direct radiator applications will sometimes work well, but experiments show that a horn needs a driver with a big magnet and light cone. In addition, many different drivers will resonate near 40Hz with the same back chamber.

I compared the relative pink-noise responses between a well-calibrated midrange horn and the Monolith with the 2220 driver. The Monolith in a wall position appears to have a sensitivity of about 105dB, measured with the horn positioned against a wall but close to a corner (4′). Against a long wall, the apparent sensitivity can be lower.

The Monolith appears to be less directional than the Show Horn, because the mouth exhausts onto the floor. This broad radiation pattern can impact the Monolith's integration with a midrange horn. After some experimen-

SOURCE

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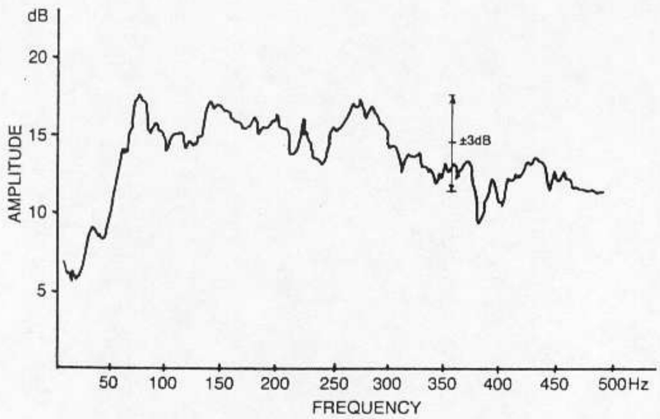

FIGURE 12: Monolith 40Hz horn response with a 13½″ stand, wall position.

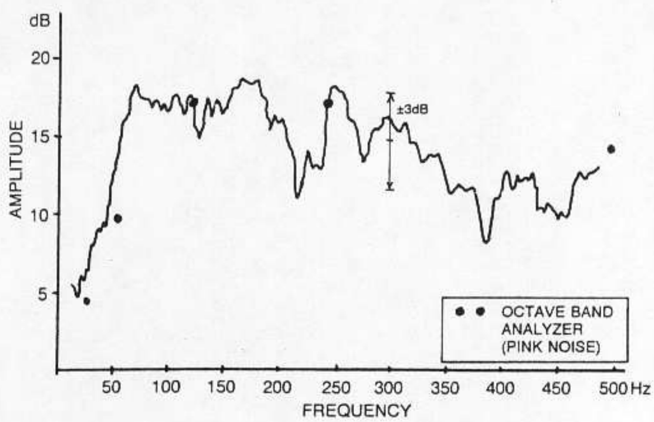

FIGURE 13: Monolith 40Hz horn response with a 21″ stand, corner position.

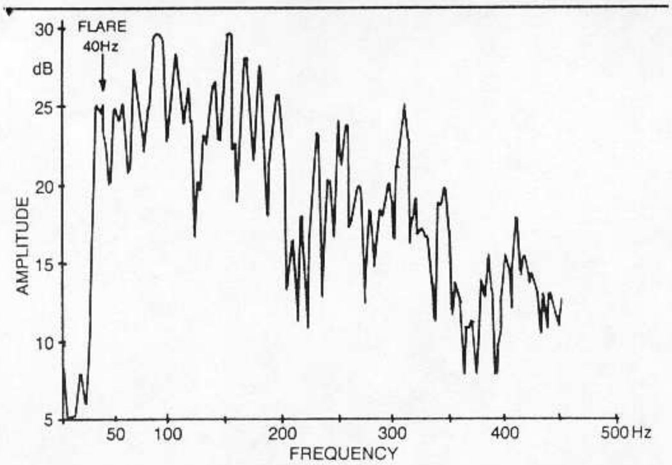

FIGURE 14: Response of the Monolith horn to a Telarc bass drum pulse.

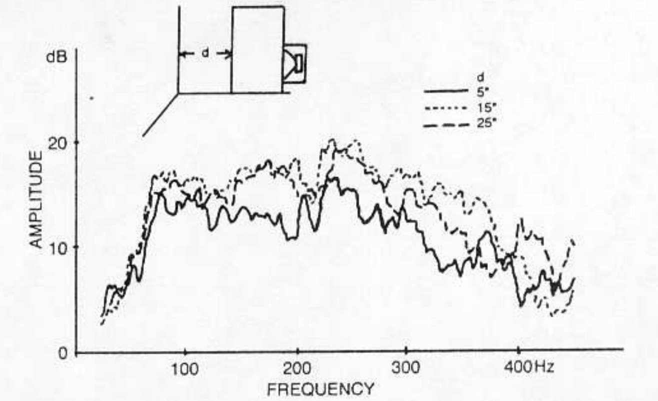

FIGURE 15: Response of the Monolith horn in an upright position for several separation distances from the corner.

tation, I found that the Monolith bass and midrange horns integrated best when the latter's radiation pattern is the broadest in the horizontal plane. For most rectangular-mouth midrange horns, this occurs when the horn's longest axis is horizontal. For the Show Horn, which has a narrower radiation pattern in the horizontal plane, the midrange horn's long axis must be arrayed vertically so the radiation patterns match.

The Monolith stands high, so I do not recommend mounting the midrange horn atop the bass horn—it needs to be at ear level. I usually mount the midrange horn in a separate box and place both it and the tweeter on a 2′ spiked stand in front of the bass horn, as shown in *Fig. 16*.

Finally, you must tune the Monolith. This may be the first time you have heard anyone refer to "tuning a horn" other than adjusting the back chamber system resonance. My friend Barry Kohan of Bright Star Audio has taught me about damping speaker systems with sand loading. The improvements can be dramatic, especially in the bass.

One of the problems with the throat manifold design is an apparent multiple backwave reflection region around the back duct opening (*Fig. 8*). Play any CD with a tremendous bass pulse and place your hand on the top of the Monolith over the back duct. You will definitely feel the wood give and rise up in response to the pulse.

You can damp out this enclosure flexing with mass damping, using a Bright Star "Little Rock" isolation pod on top of the Monolith next to the back chamber (*Fig. 17*). An alternative is to buy several sacks of lead shot and place them on top of the throat manifold. The effect can be dramatic. You can also buy a Bright Star "Big Foot II" sand-filled isolation base and cover the rest of the top plate. A second improvement can be made by loading the top of the back chamber with sand or lead. A "Little Rock" pod or a single bag of sand or lead shot will work.

People have asked me about the advantages of a horn design going down to 40Hz. For many types of music, it doesn't make much difference, but the 40Hz horn does resolve the low end better than a 50Hz horn.

The Monolith horn was a learning project with two main lessons: understanding horn folding problems and sand loading. The effects of 180° bends can be neutralized somewhat by intelligent placement of diagonal reflectors. Sand loading can damp out multiple reflection problems and improve the bass quality. The 40Hz Monolith horn project is complicated, but any good wood craftsman should find it well within his means. Its modular design and construction should lend itself to much experimentation.

ACKNOWLEDGEMENTS

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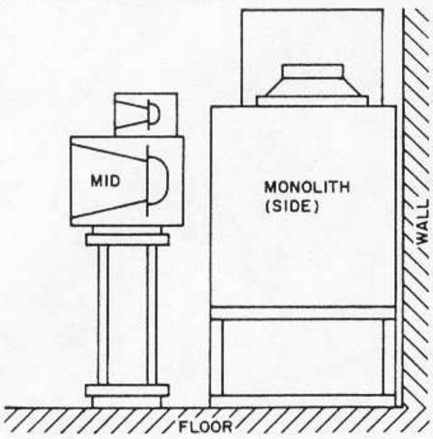

FIGURE 16: Monolith horn with midrange horn configuration.

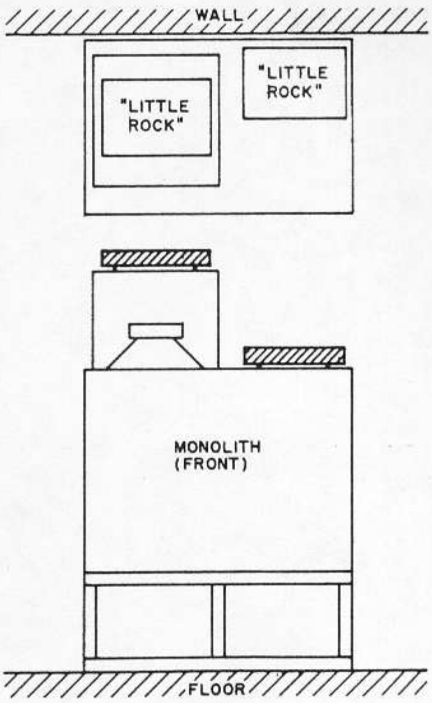

FIGURE 17: Sand loading of the Monolith horn.