A 21 MHz Four Square Beam Antenna

This popular antenna for the lower bands, can also work well on 15 meters.

Garth Swanson, G3NPC

The four square beam is a square array of four vertical elements whose radiation pattern can be rapidly switched in direction by altering the relative phases of the four driving currents. The main beam relies on constructive interference of the signals from the elements. The relative phase of waves from an element of the array is made up of the phase shift of its drive current and the phase shift associated with the additional path length due to its spatial separation from the lead element.

At low frequencies, where mechanical rotation is difficult for large structures, phase control is an attractive possibility. This makes a four square popular with contesters and DXers on 160 through 40 meters. The elements are generally positioned at the corners of a ¼ wavelength square. At 21 MHz the antenna is more compact and can be easily accommodated in smaller yards allowing changing directions without a tower or a rotator. The array maintains the low angle radiation characteristic of a simple ¼ wave vertical monopole but is able to offer forward gain and reject noise and unwanted interference that is outside the main lobe.

This practical description of my antenna is based on my article in the current issue of *QEX*, which includes the theoretical basis for many of the design choices presented here.[1]

The Antenna Array

The array is formed of four ¼ wave vertical monopoles located at the corners of a ¼ wave square. Although a maximum radiation efficiency of 80% can be achieved with a monopole at 21 MHz with 13 or more ground radials, eight radials per monopole were selected for this design. This was done purely for convenience but had the effect of reducing the radiation efficiency to 65%, equivalent to a small eventual loss of array output of 0.9 dB. Each of the four elements had its own set of ¼ wavelength radials lying on the ground, now buried at a depth of about ¾ inch.

The basis of the array is the ¼ wave vertical and a first step is to carefully characterize this element to ensure that its driving point impedance is known across the band ensuring that it is resonant at the center of the band or at a frequency of interest. This should be done in isolation either without installing its three neighbors or, if they are present, by open circuiting their neighboring driving points during the measurements.

The design was centered on a frequency of approximately 21.2 MHz using elements adjusted to be resonant in isolation with a length of 10.95 feet. The monopoles consisted of three telescoping aluminium sections with an insertion length of about 4 inches locked by stainless steel screws. Each was topped by a short telescoping whip that allowed fine adjustment of the overall length. The details of its construction are shown

[1]Notes appear on page 00.

Table 1
The Phases of Unit Element Currents Needed for Broadside and Diagonal Firing

Element	NW	NE	SW	SE
Broadside (S firing)	0°	0°	–90°	–90°
Diagonal (NE firing)	-90°	–180°	0°	–90°

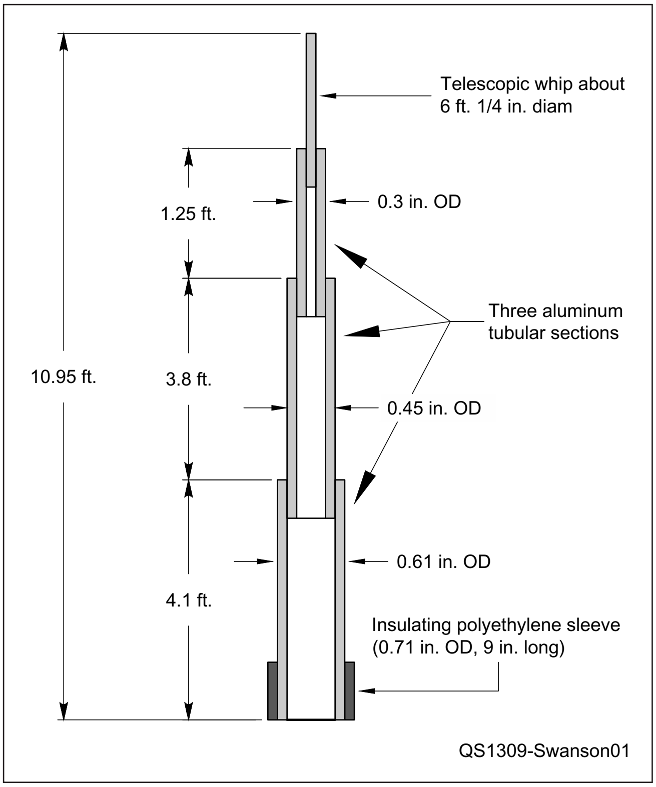


Figure 1 — Constructional details of the monopole. The dimensions were converted from the author's metric sizes. Use available telescoping tubing of similar size.

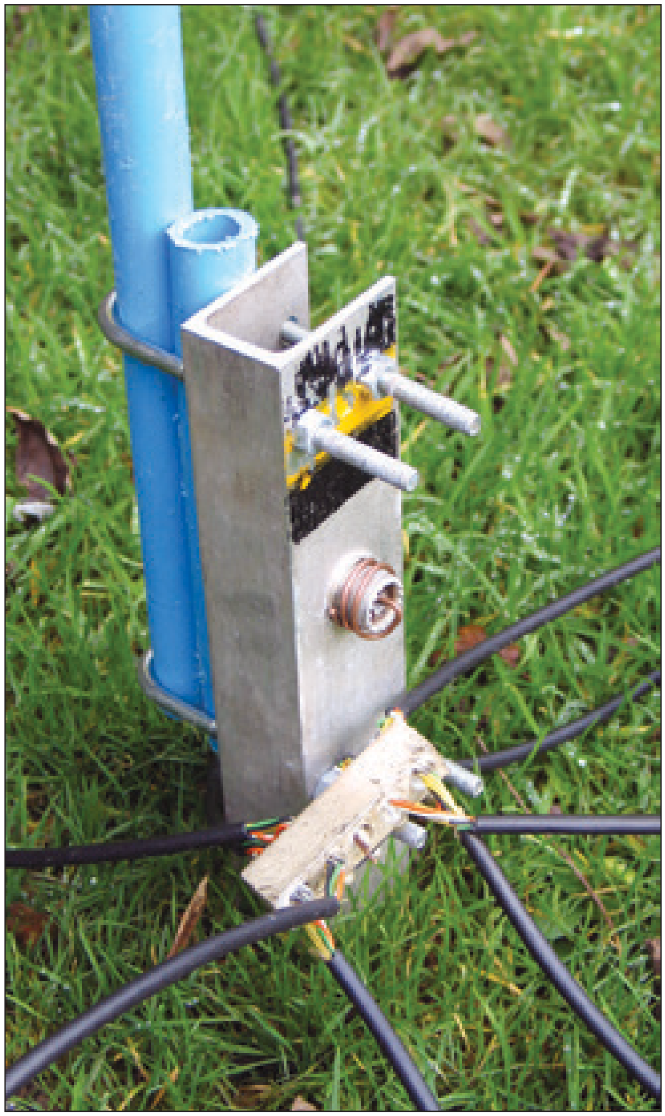


Figure 2 — Details of the monopole mount for each element.

in Figure 1. The element was insulated from an aluminium ground post by a short length of polyethylene water pipe and secured by U bolts (see Figure 2).

Figure 3 shows the parallel electrical response of one of the elements in isolation. These values of impedance are fairly typical, but reflect the eight radials that I used and the ground on which they lay. The elements of an array should be characterized on the ground on which they are to be used.

The side length of the array was 11.64 feet, a ¼ wavelength in free space. In order to ensure, to the extent possible, that the coupling between the elements was only electromagnetic, their radial systems were not connected directly to each other. Each radial set was returned to its own ground mounting.

Taking Into Account Interelement Coupling

Electromagnetic coupling between the four elements means that their properties cannot be considered to be independent of each other. This is most easily seen through the changes in driving point impedance of an element when a similar element is brought near and, more importantly, when that second element is excited.

The related article in *QEX* shows how these measured values of mutual impedance can be used to arrive at the individual element driving point impedances that are defined by the currents flowing simultaneously into the four element driving points.

The choice of driving point currents is determined by the radiation pattern that is sought. Table 1 summarizes two possibilities. The element currents are phase shifted and must be represented as complex quantities in any calculation. Since diagonal firing gives a higher gain and a narrower forward lobe it is this that I have implemented.

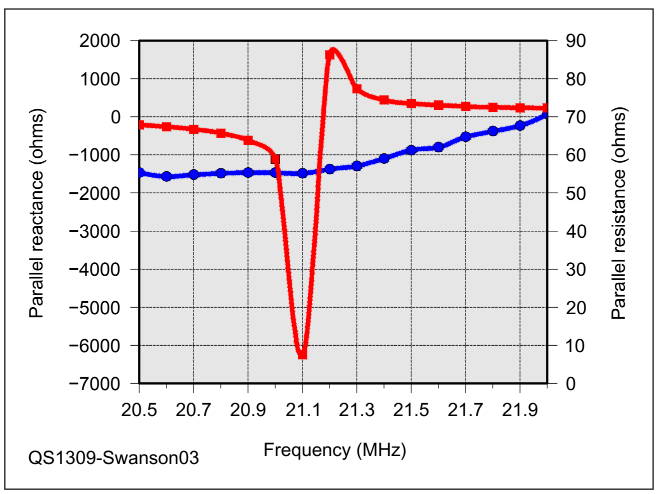


Figure 3 — The parallel electrical response of one of the elements with its eight ground level radials when its three neighbouring elements were open circuited.

Table 2
Calculated Driving Point Impedances for Diagonal Firing

Element	Driving point	impedance (Ω)
Leading	77.5 + j76.2	
Central (off-axis)	66.2 – j18.7	
Rear	1.0 – j31.1	

Table 2 shows the driving point impedances that result from the set of currents chosen for diagonal firing. These values are based on impedance and mutual impedance measurements made on my ground and with eight ¼ wave radials on this terrain.

While these values can be regarded as typical, an optimum design for any other location would require a new set of impedances to be measured using the procedures that have been described in the *QEX* article.

Delivering the Required Currents

As already mentioned, it is the set of drive currents that determines the radiation pattern. The problem then is how to deliver the currents into the four driving point impedances.

A particularly straightforward method that has been chosen here is to make use of a transmission line of an appropriate length to transform the current feeding an antenna element into a voltage that can be preset at the feed point. The method is sometimes called *current forcing* because the length of the feeder, the load impedance and the feeder input voltage completely define the voltage distribution along the feeder and at its termination. It is this terminating voltage that forces the required current to flow into the element driving point.

The four elements have to be individually driven so that four separate feeders of different length are needed to provide the transformations that deliver the complex currents required at each driving point. Ideally the four feeders should be driven together at one point but as Al Christman, K3LC, has pointed out they can only be brought together at a common node and fed from the same source if the voltages at the sending end of the feeders are equal in magnitude and phase.[2] I have demonstrated that in this case, and in others, that points on the four feeders with the same voltage and phase do not always exist and it has been necessary to modify the Christman method.

The approach that I have used successfully and recommend is to select points that have the same phase and translate the voltages using transformers. Table 3 summarizes the electrical parameters at the four feeder inputs before making the voltage transformations and shows the lengths of RG-58 feeders that are required to establish the driving point current magnitudes and phase shifts for diagonal firing.

At 9.84 feet for the rear element, 17.06 feet for each of the central elements and 22.63 feet for the leading element, the phase is the same. These feeder lengths would deliver the required complex currents to the element driving point impedances shown in Table 2 and could be driven in common only if voltage scaling were used. This design procedure that takes into account inter-element coupling is a key step in the design of this four square array.

Arranging a Common Feed Point for the Array

The modified Christman method, in which the input voltage of each feeder is scaled to the same value, has also been applied to the four square array as well as to a practical two element design and theoretically to a broadside-firing four square array.

There is a 3% difference in voltage between the required feeder input voltages for the rear and lead elements. This discrepancy is comparable with the accuracy of the calculations so these feeder inputs were simply paralleled. The pair of central element feeders had the same voltage and phase distributions so their inputs could be paralleled together but they did require a voltage about 20% larger, so magnitude scaling was necessary.

Transformers offer a straightforward means of scaling and provide a way of ensuring that the common input impedance of the array is close to 50 Ω. Importantly though, there should be no phase shift in the transformation. A winding of any practical transformer has a leakage inductance due to flux that does not link the other winding. This gives rise to an element of inductive reactance that causes the phase between the winding voltage and its current to be non-zero. The consequence would be an error in the phase of the current delivered to the antenna. This occurs in both

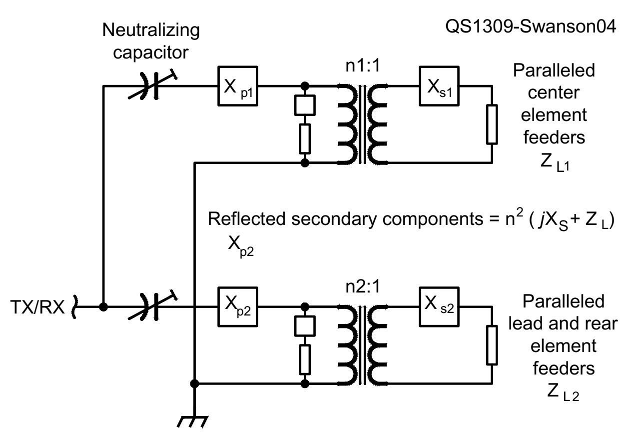


Figure 4 — The interconnection of the feeder transformers.

Table 3
Electrical Parameters at the Equal Phase Points

Position of Feed-Point	*Lead Feeder*		*Central Feeder*		*Rear Feeder*	
Lenth (feet)	**Voltage (V)**	**Phase (°)**	**Voltage (V)**	**Phase (°)**	**Voltage (V)**	**Phase (°)**
9.84					55.0	90.3
17.06			63.4	90.2		
22.63	53.5	90.3				
Input Z of Feeder (Ω)	16.6 – j15.5		46.3 – j21.3		21.0 – j161.6	

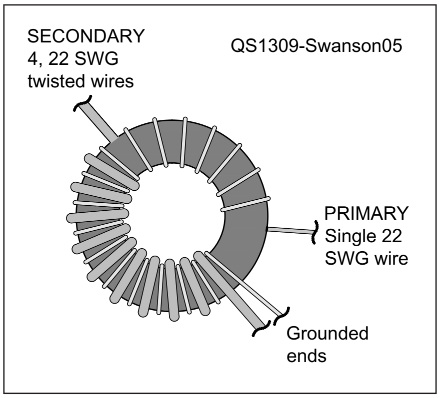


Figure 5 — Transformer winding configuration.

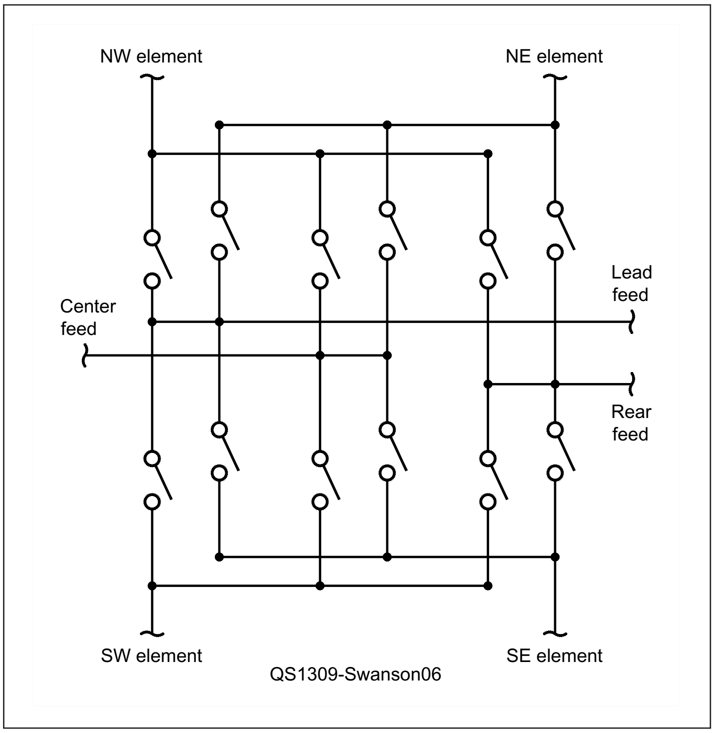


Figure 6 — The schematic router switch array.

windings and it is essential to ensure that the overall phase shift is nulled. Although in principle one transformer could have been used with two secondary windings it proved much easier to neutralise the leakage reactances when one transformer was used for each set of feeders. The calculated individual feeder input impedances are shown in Table 3.

Figure 4 shows the interconnection of the two transformers and the placement of the series preset 150 pF neutralizing capacitors.

Design of the Power Splitting Transformer

The ratio of their turns ratios, k, was set by the voltage scaling factor, in this case 0.84. The absolute number of turns in the secondary windings was then determined depending on the number of primary turns that had been selected.

The transformers were constructed on Type 61 ferrite toroidal rings having an outside diameter of 2.4 inches and an inside diameter of 1.6 inches. The primary windings were formed from a single strand of #22 SWG (similar to #21 AWG) enameled copper wire and the secondaries were of four twisted strands of the same wire wound compactly onto the toroid in the same sense and interleaved with the primary turns. Care was taken to begin the ground ends of the two windings at the same position. This helped to minimize the local potential differences between the windings ensuring that capacitive currents between the windings were minimized. The winding scheme is shown in Figure 5.

In practice 20 primary turns were selected for each transformer because these fitted conveniently onto the chosen toroids. The numbers of secondary turns for the two transformers were then adjusted mathematically to achieve a suitable value for the paralleled primary reflected impedances, always preserving the required ratio between the two secondaries. Practical transformers always have inductances due to flux leakage. This inductance gives rise to phase shifts, which in this case, modify the phases of the element drive currents. It is therefore important that they should be removed. This is done by incorporating a capacitive trimmer in series with each primary winding so that it cancels or neutralizes the transformer's inductive reactance. The circuit, in Figure 4, shows transformers individually loaded.

The setting of the trimmers has to be done when the secondary is terminated with a resistance. In this case the load resistance was 100 Ω. When each primary is excited with a voltage at the design frequency the secondary voltage is observed. If a high impedance oscilloscope is available, the phase of the primary and secondary voltages can be compared and the trimmer adjusted until the phase difference is zero. This condition also corresponds to a maximum in the secondary voltage, so that an observation of this RF voltage with a simple diode RF probe and a dc voltmeter would suffice. Once this procedure has been carried out the individual transformers can be connected to the power splitter circuit without further adjustment.

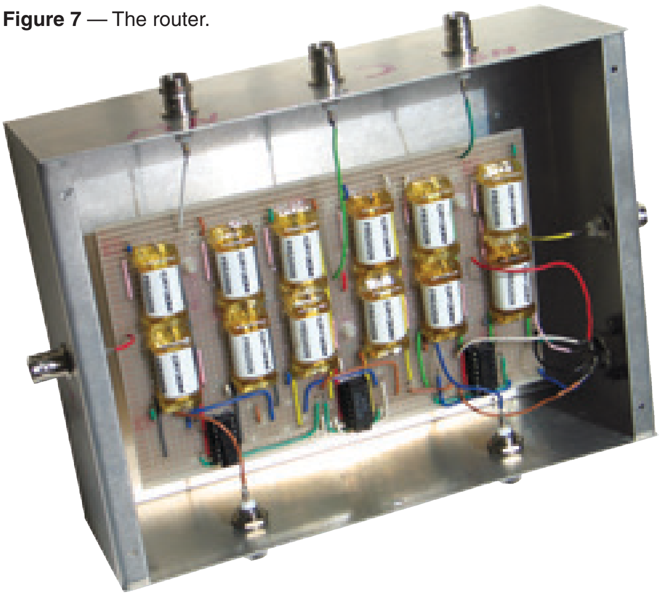
The overall design procedure led eventually to a measured common node input impedance of 51 $-j29$ Ω for the finished array. The details of the transformers are summarized in Table 4.

Table 4 shows that more primary turns were required than had been anticipated by a simple view of transformer design. This could be

Table 4
Details of the Two Transformers Used for Voltage Scaling and Impedance Matching

	Theoretical designs		*Actual Designs*	
	Lead/Rear	Center	Lead/Rear	Center
Primary turns	20	20	23	23
Secondary turns	8.4	10	8	10
Combined input Z (Ω)	51 $-j29$			
Open circuit voltage ratio	2.4	2.0	2.3	2.0
	Required	Required	Measured	Measured

Figure 7 — The router.



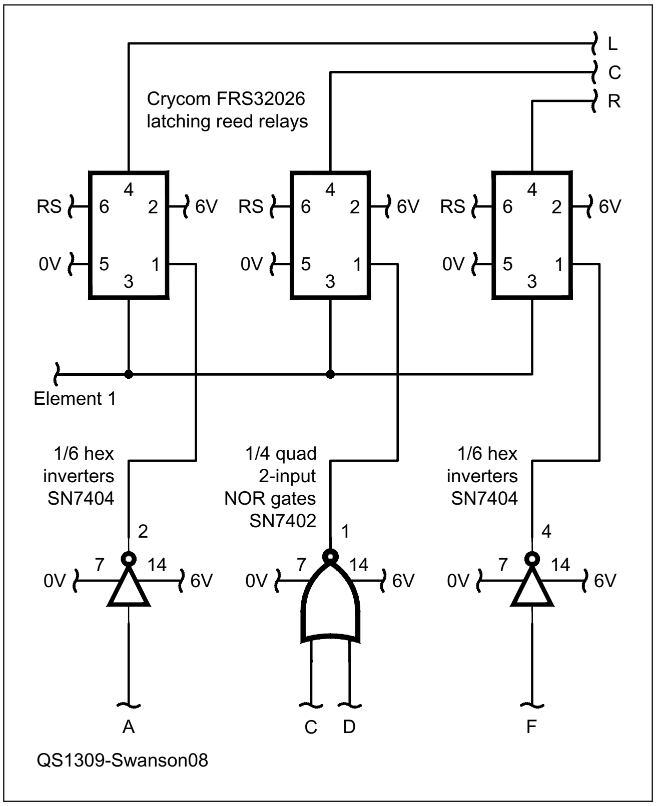


Figure 8 — One cell of the switch array.

due to winding end effects where the end turns coupled inefficiently to the core. Careful adjustment of the number of turns was made as measurements checked the open circuit voltage ratio. Small errors in achieving the specification are due to an inability to realize fractional turns.

The attenuation of each transformer was about 1.2 dB, equivalent to a transformation efficiency of 76%. The realization of the transformers required great care, but there is certainly scope for further improvement here.

The Direction Control System

In order to direct the beam to one of the four diagonal directions the feeds to the elements have to be rerouted, ideally under electrical control. Figure 6 shows the topology of a switching matrix for routing the three possible phase-shifted feeds to the appropriate elements for a particular direction of fire. The switches used were RF latching reed relays with a current carrying rating of 1.5 A and a switching time of 2 ms.[3] They were chosen because of their ability to maintain a particular setting without being continuously energized, and because they were hermetically sealed and suitable for operation outside. The switches had an actuation current of 16 mA suitable for control by TTL pull down devices. This matrix was built on glass-epoxy strip board and the boxed router is shown in Figure 7.

Switching Cell Design

The basis of the design is a group of three switches that are used to attach an individual element to one of three feeders L (lead), C (center) and R (rear). The module for antenna element 1 is shown in Figure 8. The switches used were the Crycom FRS32026 (6) with reset, 6 and 5, and set coils, 2 and 1, that could be operated by the application of 6 V.[3] The reset signal caused the switch to open and remain open on the removal of this voltage. It was then ready for closure on the application of a +6 V potential difference between pins 2 and 1.

The set coils were controlled by either a two input NOR gate or a single logic inverter. If the logical control signals caused an output potential to fall to zero the coil would conduct a current of about 16 mA to ground causing the switch to close. The three reed relay switches in Figure 8 allowed element 1 to be connected to either the lead feeder using logic terminal A, the central feeder with C or D and the rear feeder with F. This allowed the antenna element to fulfil its correct role in any

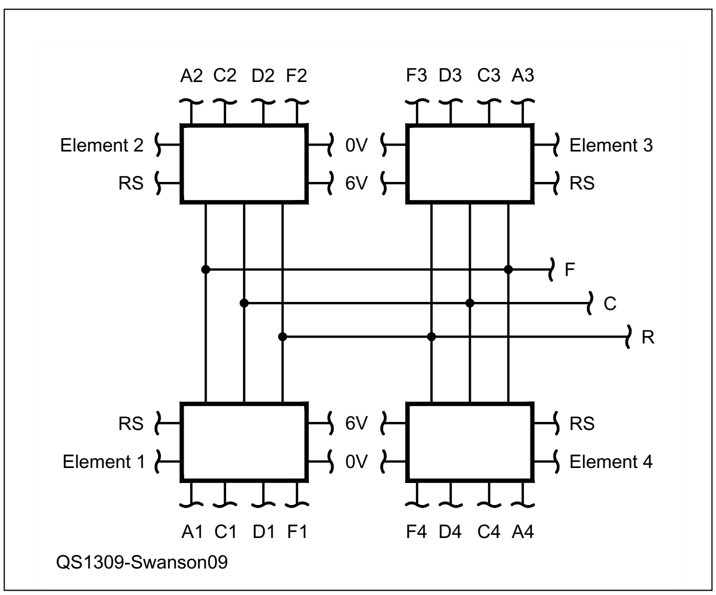


Figure 9 — The interconnection of four router cells.

Table 5
Logical Excitations for Steering

Leading Element	Lead	Center	Rear	Center
1	A1	C2	F3	D4
2	A2	C3	F4	D1
3	A3	C4	F1	D2
4	A4	C1	F2	D3

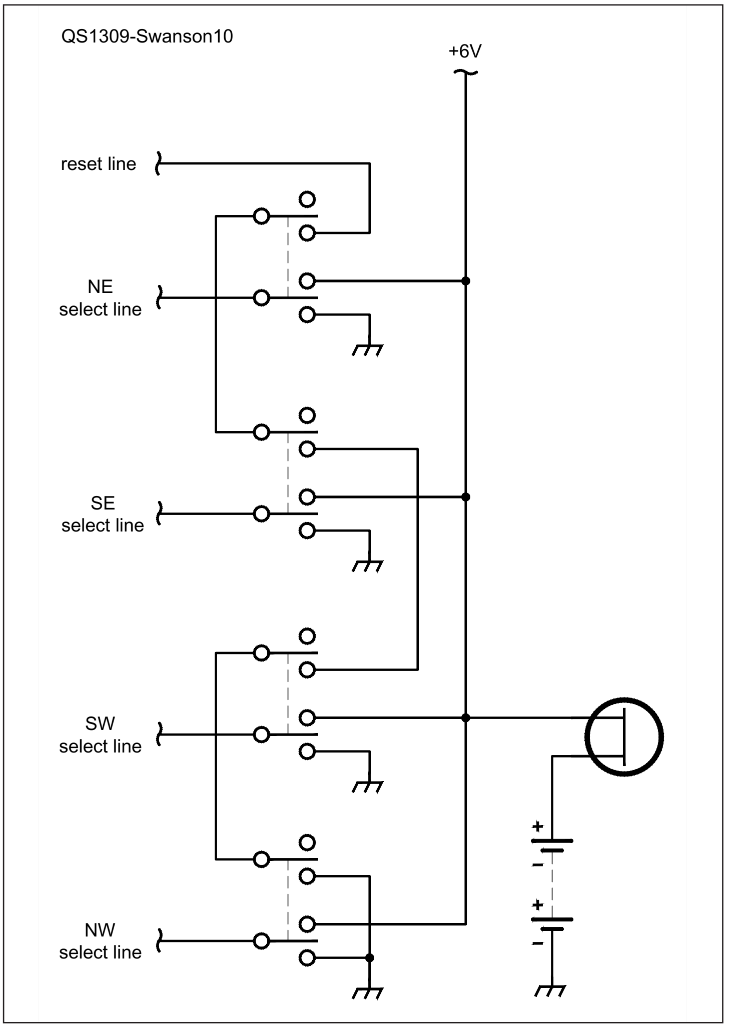


Figure 10 — Control switches at the operating position.

of the four directions of diagonal fire. The relays latching capability allowed it to "remember" either state after excitation of the coils had been removed. Any selection, set, operation had always to be preceded by the reset operation. The logical NOR gates were TTL devices arranged in groups of four, two input devices (SN7402), the inverters were provided by two hex inverters (SN7404).

Control System

The complete router was an array of four such modules, one for each antenna element (see Figure 9). Although shown separately, the reset terminals, RS, were connected together and the complete array of switches was reset simultaneously preceding a change in the direction of fire. The logical excitations necessary for the four directions are shown in Table 5. Notice that each logical input is only used once. This allows the four logical inputs for a particular direction to be hard wired together so that they can be switched together to select a desired direction.

The switch module requires four direction control inputs, ORANGE, BLUE, GREEN, PLUM, the RESET input (yellow) and two supply inputs, +6 V and ground. Figure 10 shows these lines at the operator's position. Before selecting a direction the array of 12 latching reed relays has to be reset. Setting the four DPDT switches down ensures that the yellow RESET line is grounded. When the push switch is actuated, the reset coils are all energized and the switches reset to their open state. A direction is selected by switching one of the DPDT switches up so that its direction control line is energized when the push switch is momentarily pressed. This line is hard wired at the matrix to the logic inputs that ensure that each of the four elements is driven appropriately. In addition, the matrix has three RF inputs and four RF outputs. Because of the low load requirements, the power for the control of the array was supplied by a 6 V battery.

Interconnections

The box was linked to the operating position by a seven conductor cable. The beam was steered by resetting the reed relays and then briefly energising the appropriate direction control line to set the required switch configuration. The 6 V battery that powered the reed relays and the control circuitry was at the operating opposition. All switching was carried out in the absence of RF excitation to avoid the possibility of contact damage due to arcing. The system has been in use for 2 years without any degradation. In principle, the direction of fire could be changed in as little as 4 ms.

Phasing Lines

The antenna design depends critically on RG-58 transmission lines that have definite lengths — 9.84, 17.06 and 22.63 feet. Locating the switching matrix at the center of the array meant that exposed feeders between the matrix box and the elements could be 8.2 feet long with the complementary lengths of 1.64, 8.86 and 13.12 feet, contained within the weatherproof box placed on the ground at the center of the array. This box also contained the power splitter.

The overall measured RF loss from the power splitter output to the elements via the switching matrix was no greater than 0.8 dB and depended slightly on the selected direction. Thus, from the power splitter input to the element inputs, there was a loss of about 2 dB, a feed system efficiency of 63%. Since the elements each have a radiation efficiency of about 70% the effective radiation efficiency of the antenna array measured at its feed point was 42%.

Directional Behaviour

The polar radiation pattern was measured at stations at 22.5° intervals at a radius of 125 feet from the array center. At this distance the phase errors were no greater than 2°, giving a good approximation to the far field pattern. The measurements were made using a tripod mounted field strength meter with a dynamic range of 90 dB based on a design published by the Utah Amateur Radio Club.[4] At each location in turn, the received signal, a relative measure of the signal strength, was recorded for each of the four beam headings with good reproducibility.

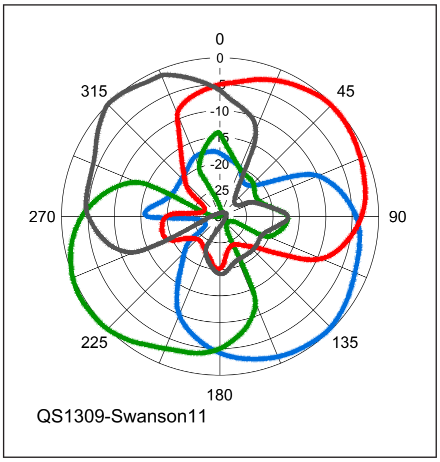


Figure 11 — Measured polar radiation patterns for the four diagonal beam headings.

Table 7 The Actual Measured Elemental Drive Currents with Respect to the Rear Element				
Beam heading	**NE**	**SE**	**SW**	**NW**
NE	1.0, –180°	0.67, –90°	1.0, 0°	0.77, –90°
SE	0.93, –105°	1.04, –165°	0.89, –90°	1.0, 0°
SW	1.0, 0°	0.69, –97°	0.97, –192°	0.70, –90°
NW	0.86, –90°	1.0, 0°	0.71,–90°	1.07, –180°

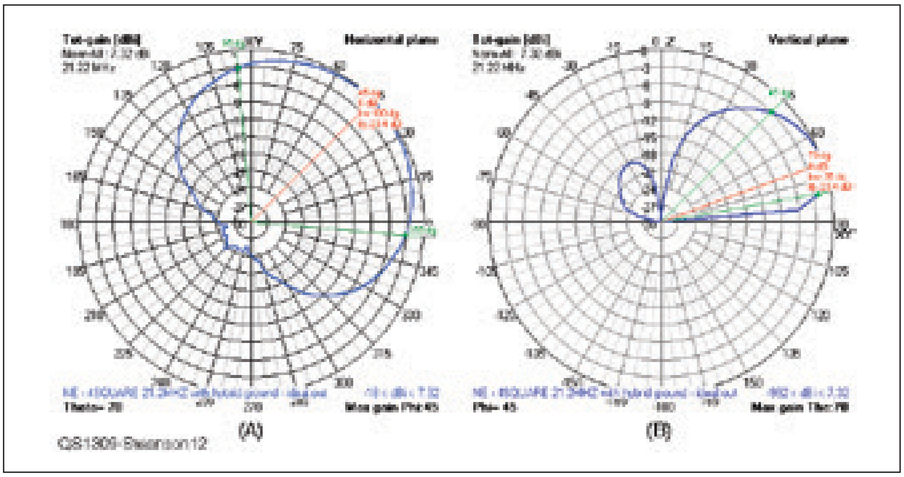


Figure 12 — Computed ideal radiation patterns on the hybrid ground with perfectly defined driving currents.

Figure 11 shows the observed polar patterns for each beam heading. Each is formed from 16 measured points. Because data smoothing has been used to help visualize the patterns, caution is required in interpreting some of the finer angular detail. The patterns are very similar and show clear evidence that switching occurred as intended. They are plots of relative field strength and do not reveal that the maximum signal strength at each diagonal angle was actually the same, ±1 dB. The front to back ratio for each pattern was at least 20 dB. These are logarithmic plots that intrinsically exaggerate detail in the rear sectors, it should be remembered that these features are about 100 times smaller than the main lobes.

Simulated Performance

I used the freely available *4NEC2* package based on the *NEC2* electromagnetic modelling code to simulate and predict the behaviour of the array. *4NEC2* has the advantage of being able to set current as well as voltage excitations and offers the use of a hybrid ground in the simulation. The detail of my approach to modeling this 4-square with its ground level radials uses a concentric hybrid ground, the inner disc-like region being more conductive because of the radials. The outer zone has the properties of the actual terrain extending to infinity. The appropriate two-zone parameters for the hybrid ground are stated in Table 6, they represent the behavior of the monopole with eight radials operating at 21.2 MHz on the imperfect ground.

Table 6 The Hybrid Ground Electrical Parameters Used for Simulation		
Region	**Relative permittivity**	**Electrical conductivity (S/m)**
Inner zone	73	0.75
Outer zone	42	0.088

Figure 12 shows the computed behavior of the antenna on the hybrid ground when driven with the ideal perfectly defined set of drive currents; it provides a basis for comparison when the actual currents were used.

For comparison the measured complex drive current for each element at the four beam headings was used in a similar simulation to arrive at the calculated polar patterns for the four directions, again on the hybrid ground. The normalized currents which sometimes deviated from the intended values are listed in Table 7, the reasons for this will be discussed later.

The modeled polar patterns using the actual drive currents are shown in Figure 13. There is good agreement between these and those that were measured, Figure 10. The front to back ratios span the range from 20.6 to 14.7 dB and are somewhat smaller and less consistent than those measured. The beam widths are in very good agreement with the measurements. Predicted, but not measured, are the forward gains. These are very similar for the four directions, ranging between 7.00 and 7.36 dBi.

The simulation also provides the elevation of the main lobe above the horizon. Although the only pattern presented here, Figure 15, is for the NE direction, the peak elevation is close to 20° for all beam headings, with a half power vertical beam width of 35°.

A very useful indication of the insensitivity to frequency across the 21 MHz band is provided by the two NE polar patterns in Figure 15. This 2% change of frequency caused a change of only 0.5 dB in the front to back ratio and a negligible change in gain of only 0.05 dB.

Discussion

The antenna's behavior on the hybrid ground, but with a perfect set of drive currents, provides a basis for comparison, see Figure 12. It shows that the forward gain should be 7.32 dB, the highest attainable value on this practical ground. The behavior in the rear section is determined by the degree of cancellation of the fields from the four elements. It is here that small differences between the field components become apparent and reflect imperfections in the array and its feed system that cause errors in the drive currents.

Figure 13 (this and the following Figures can be found at w**ww.arrl.org\qst-in-depth**) represents the superimposed data on rectilinear axes to aid comparison. There is significant and consistent detail in the rear sector. The overall impression is of similarity in the main lobes for the four beam headings.

The actual drive currents were inserted into the simulation and the predicted gain values come close to the maximum attainable on the hybrid ground, compare Figures 10 and 11. The observed front to back ratios were at least 20 dB on this ground and Figure 11 suggests that an improvement by 3 to 4 dB might be achievable. Although appreciable, it is questionable if this improvement would have practical value since the ratio was already 20 dB. It is interesting to note that with a perfectly defined set of drive currents and a perfect ground the best possible gain and front to back ratio would be 10.8 dBi and 29.8 dB.

In Table 7 the off-axis element drive currents are highlighted. Firstly they are invariably low compared with the on-axis elements. It should be relatively easy to correct this by increasing the number of secondary turns of the appropriate transformer and should lead to an improved front to back ratio. However this will undoubtedly disturb the transformation of the central element feeder impedances and measures will be needed to ensure that the transformed impedances combine in parallel to approach 50 Ω.

Harder to understand are the off-axis current asymmetries. These elements are driven from the same secondary winding through two feeders that have the same lengths and should deliver very similar drive currents. The asymmetries are not reversed nor replicated if the beam heading is oppositely directed. Had they been due to different local environments for the pair of axis elements the asymmetry would have persisted when the feeders were interchanged, this did not occur.

No account was taken in the design of the delays introduced by the switching matrix. Although they would be relatively small the path lengths through the matrix were not equal for the four signals and depended on the pattern of switch closures. It is possible that this is a source of asymmetry and a careful study of these pathways is needed.

There are strong indications from modeling on a practical ground that the forward gain is between 7 and 8 dBi, but this needs to be confirmed by measurement and would require reference to a standard antenna.

The loss between the common feed point and the element driving points is 2 dB, of which 1.2 dB is attributable to the transformers. The use of iron dust toroids could improve this. The Micrometals mixture 10 offers lower loss than the type 61 ferrite but at the expense of relative permeability.[5,6] A comparison of the two is the subject of current experimentation.

Conclusions

I have shown how to construct an electronically steerable 4-square phased array antenna for use at 21 MHz. The antenna has a diagonal firing configuration with a main beam that can be switched rapidly to one of four orthogonal directions. A novel feed system has been described that uses two RF transformers to ensure that the element feeders can be driven with the same voltage and phase. The overall loss from the array feed point to the element inputs was 2 dB, most in the RF transformers. This elaboration of the Christman method allows it to be used universally in situations where only equal phase points exist on the set of feeders.

On an imperfect practical ground the antenna achieved a measured front to back ratio in excess of 20 dB a value consistent with listening and on-air use that showed differences of between three and four S-units. The forward gain has not yet been measured; however, based upon computer modeling using a hybrid model to represent the practical ground its gain is estimated to be between 7 and 8 dBi. The horizontal and vertical half power beam widths are 90° and 35° respectively, with a vertical beam elevation of 20°. Modeling has also predicted that the antenna characteristics vary only slightly across the operating bandwidth of 0.45 MHz at 21 MHz. The directional properties of the antenna accorded well with computer modeling, potentially pointing the way toward further improvement.

In comparison with a four element Yagi, the diagonally firing four square antenna at 21 MHz is likely to have a gain 2 to 3 dB lower. It has a similar front to back ratio and a half power main beam width that is 30° wider. While there is scope for further refinement of this implementation of the four-square antenna, it is doubtful if the resulting improvements would significantly affect the gain and beam width, but could improve the observed front to back ratio by 3 to 4.

Notes

[1]G. Swanson, G3NPC, "A 21 MHz Four Square Beam Antenna," *QEX*, Sep/Oct 2013, pp xx-yy.

[2]A. Christman, K3LC, "Feeding Phased Arrays — An Alternate Method," *Ham Radio*, May 1985, p 58.

[3]Crycom FRS32026, now replaced by Cynergy3 FRS22012. See **www.cynergy3.com**.

[4]**www.utaharc.org/rptr/wdr_fsm2.html**

[5]Micrometals mixture 10 see **www.micrometals.com/appnotes_index.html** or Fairite mixture 61 see **www.fair-rite.com/newfair/pdf/Broadband.pdf**.

[6]*The ARRL Antenna Book*, 16th Edition, ARRL, 1991.

Garth Swanson, G3NPC, obtained a full transmitting license in 1957 at the age of 16. He earned two degrees from Imperial College London: a BSc (Eng) in 1963 and a PhD in Electrical Engineering in 1967.

He then worked at the Westinghouse Research Laboratory in Pittsburgh for 4 years, working on thin film electronic devices. On returning to the United Kingdom, he spent a year in industry and then moved to a career in academia. He eventually became chairman of the Electrical Engineering department at King's College at the University of London where he was a Professor of Physical Electronics with research interests in electronic and optoelectronic materials. On his retirement in 2001 he became Professor Emeritus at King's College and has pursued an interest in phased array HF antennas.

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