Impedance And Coupling Measurements On A 80m 4-Square
A Cautionary Tale!

Rudy Severns N6LF
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It's well known that towers in the vicinity of a vertical array can interact with the array degrading its performance. This interaction will show up in impedance measurements of the array elements. Coupling between the elements in an array is covered in some detail in both the ARRL Antenna Book and Low Band DXing by ON4UN but these discussions are mostly theory. These discussions are certainly helpful but what's missing is an example of actual measurements on a real array with it's imperfections and in the presence of nearby towers.

The following discussion tries to fill this gap by reporting the results of such measurements on an actual array which certainly has a tower coupling problem.

The array at NK7U

In the fall of 2008 George Cutsogeorge, W2VJN and I, N6LF, were helping Joe Rudi, NK7U, with his new 80m 4-square. With some input from George and me, Joe erected the new array. He wanted the array optimized for the CW end of the band (3.510 MHz) so the element lengths and spacing were chosen for that frequency. The vertical elements were made from 4" diameter irrigation tubing. At 3.510 MHz a 1/4-wave = 70' (in free space) so the element spacing on the sides of the square was set to 70'. This resulted in a diagonal spacing of 99'. The elements were made 67' high, about 4% less than a free space 1/4-wave. Each element had sixty insulated #14 radials, each 70' long. The radials overlapped in the interior of the array but were not connected at the crossing points. Joe did an exemplary job fabricating the array. Every element was very close to the same height and plumb. The layout and symmetry were also close to perfect.

In October George and I drove over to Joe's QTH to make a series of measurements on the array, as built, so we could design a feed network for it. What follows is a description of those measurements and what they told us about the array. The object of this is to show you just how strongly nearby towers can interact with an array. Until these interactions are greatly reduced you cannot design a feed network which will allow the array to operate as expected.

When we arrived Joe's new QTH which we had not seen before, we had an uh-oh moment! Joe has been building a first rate contest station so in addition to the 80m 4-square he has three towers with multiple Yagi's and slopers attached but his new QTH is restricted to a 5 acre site so within 100' of the 80m array there is a 70' and a 150' tower. 100' is less than 1/2-wave on 80m so the probability of serious interaction between the towers and the array was almost a certainty. The measurements were to bear out our worst fears!

Array measurements

The plan was to make a series of impedance measurements on the array which would allow us to accurately characterize the array for the design of the feed network. In theory only ten measurements are required, four self impedances and six coupled impedances. However, to minimize errors it's always wiser to make the coupling or mutual measurements in both directions: for example, at element 1 with element 2 shorted (s/c) at it's base and then go to element 2 with the base of element 1 s/c. This pair of reciprocal measurements should be identical within the accuracy of the instrumentation even if the array is seriously asymmetric and is a very good check on the test procedure.

To design the feed network we needed the four self impedances (Z_{11}, Z_{22}, Z_{33} and Z_{44}) and the six mutual impedances associated with the coupling between the elements (Z_{12}, Z_{13}, Z_{14}, Z_{23}, Z_{24} and Z_{34}). If you are not familiar with this procedure read over the discussion in chapter 11 of Low Band DXing. It's not very complicated and can be very informative.

We made the following sixteen measurements:

1) The feedpoint impedance at the base of each element with all other elements open circuited (o/c). This gave Z_{11}, Z_{22}, Z_{33} and Z_{44} directly.

2) The feedpoint impedance at the base of each element with one other element short circuited (s/c) at its base. This requires six pairs of measurements: [$Z_{1,2}$, $Z_{2,1}$], [$Z_{1,3}$, $Z_{3,1}$], [$Z_{1,4}$, $Z_{4,1}$], [$Z_{2,3}$, $Z_{3,2}$], [$Z_{2,4}$, $Z_{4,2}$] and [$Z_{3,4}$, $Z_{4,3}$]. The notation $Z_{1,2}$ means that the impedance is measured at the base of element 1 with the base of element 2 s/c and the bases of elements 3 and 4 o/c. This is repeated for all the combinations of element pairs. In the following discussion remember that $Z_{1,2}$ is not the same as Z_{12}, etc. The first is the actual measurement and the second is calculated value for the mutual impedance derived from the measurements.

From these measurements we could then compute the values for the mutual impedances which are needed to calculate the actual feedpoint impedances of the array elements when excited with the desired current amplitudes and phases. The feedpoint impedances are a strong function of the element currents and are needed to properly design the feed network. Providing the correct element currents is of course object of the game! The measurements were all made using an N2PK vector network analyzer (VNA).

Results of the measurements

Figures 1 and 2 show the measured resistive and reactive components (R_{11}, X_{11}, etc) for the self impedance of each element.

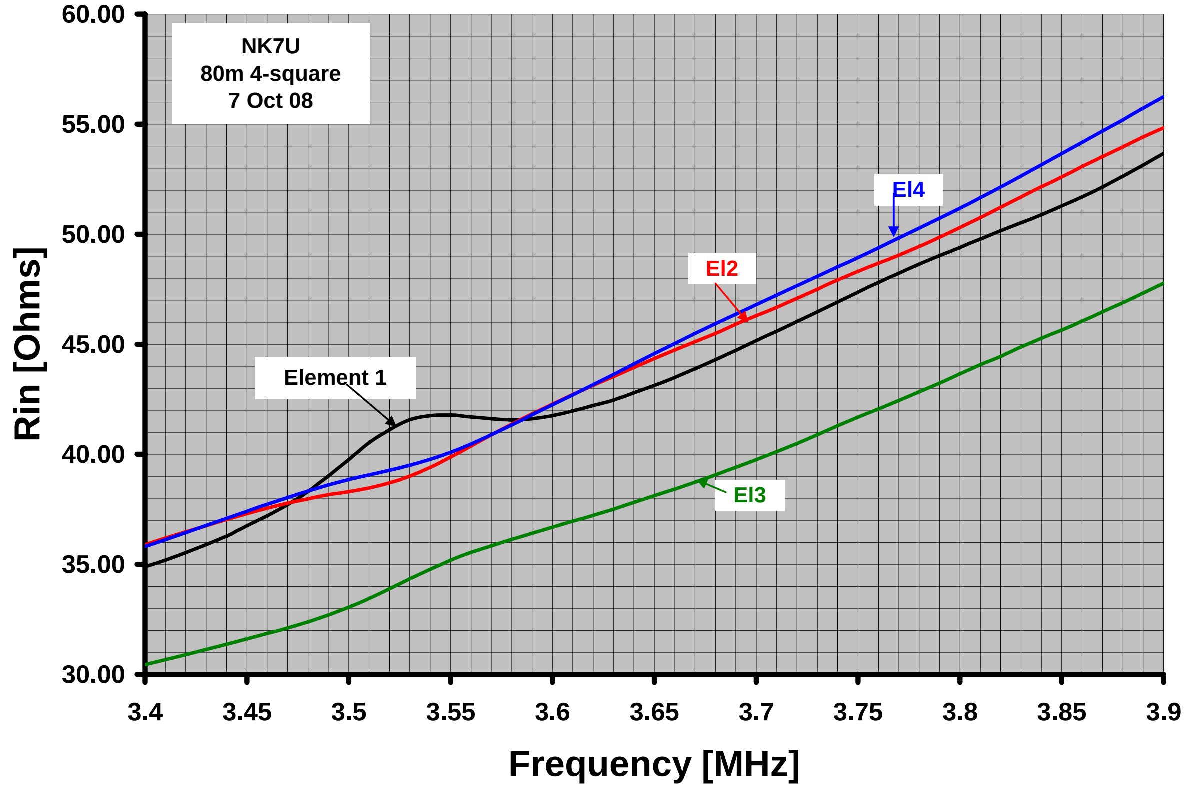

Figure 1, resistive part of the self impedances.

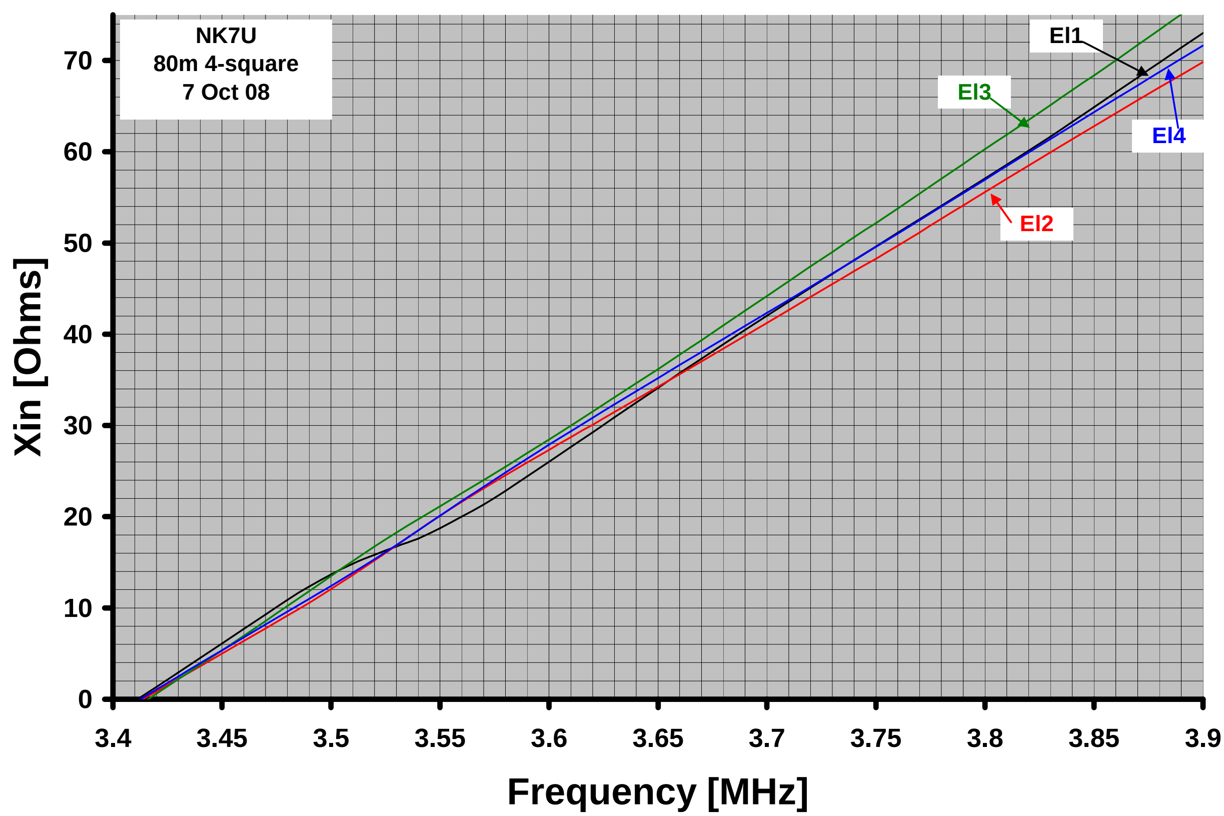

Figure 2, reactive part of the self impedances

From the figures we can see several problems. Ideally all four elements should be identical but they are not. The plot for element 3 is shifted well below those for the other three elements. The individual plots should be essentially straight lines but we can see that there is a pronounced hump in the data from 3.5 to 3.6 MHz. Finally, in figure 2 we see that the self resonant frequencies (Xin=0) are low, about 3.410 MHz or -2.8%.

Coupling to the nearby towers would explain the hump in the data and the differences between element 3 and the other elements but that does not fully explain the low resonant frequency. Examining the elements we noticed two things. First, the irrigation tubing was cut to 67' but the bases of the tubing were another 12" above the radial fan, effectively making the elements 68' instead of 67'. That's about 1.5% taller. In addition the connections from the bases of the tubing to the feedpoint connectors were single pieces of #12 wire. This small wire has significant inductance which further lowers the resonant frequency. We noticed that even small changes in the dress of this lead shifted the resonant frequency significantly. The tubing should have been made shorter and multiple parallel wires used for the connection between the base of the tubing and the feedpoint. The shape of the hump in Rin indicated that at least one of the towers may have a resonance about 3.525 MHz.

If the array were perfectly symmetrical and there were no interfering outside elements, the measurements for $Z_{1,2}$, $Z_{2,1}$, $Z_{1,4}$, $Z_{4,1}$, $Z_{2,3}$, $Z_{3,2}$, $Z_{3,4}$ and $Z_{4,3}$ should be identical as should $Z_{1,3}$, $Z_{3,1}$, $Z_{2,4}$ and $Z_{4,2}$.

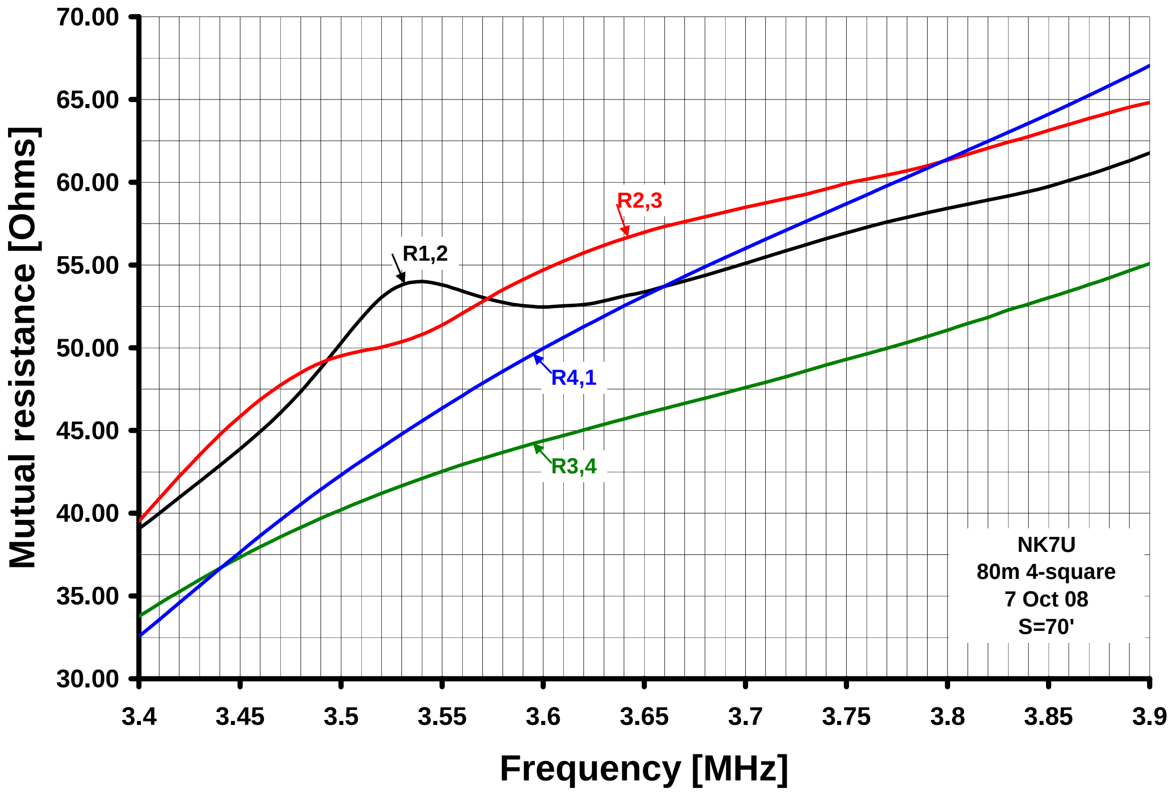

Figure 3, measured feedpoint resistances.

Figure 3 shows some measurement results. The individual impedances are not even close to identical.

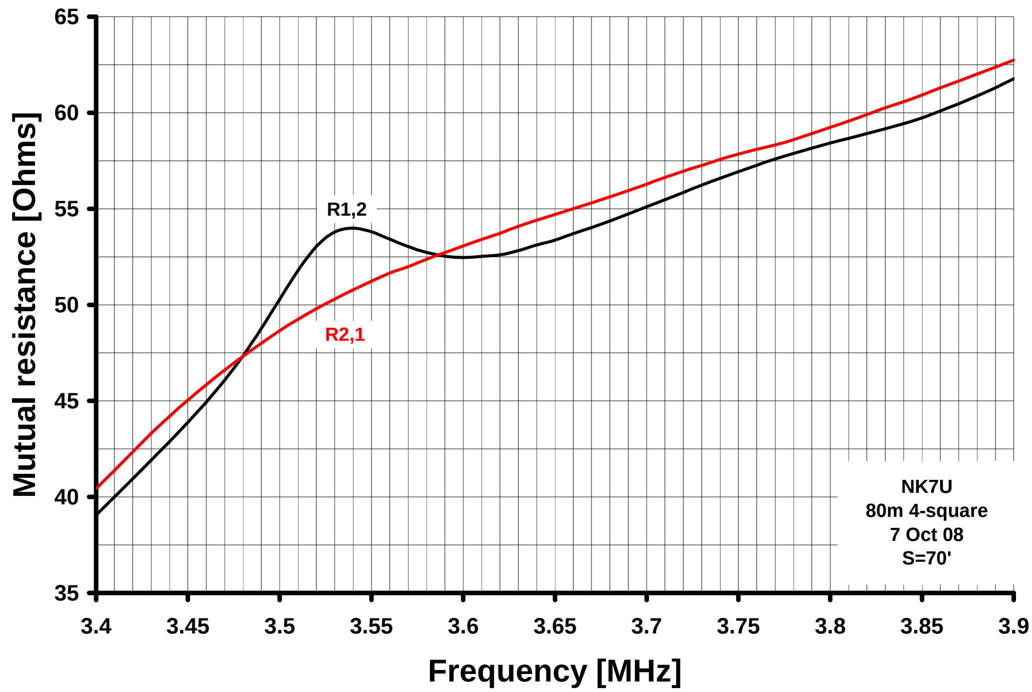

Figure 4, measured feed point resistances at elements 1 and 2.

Figure 4 shows that even the measurements between one pair of elements are quite different!

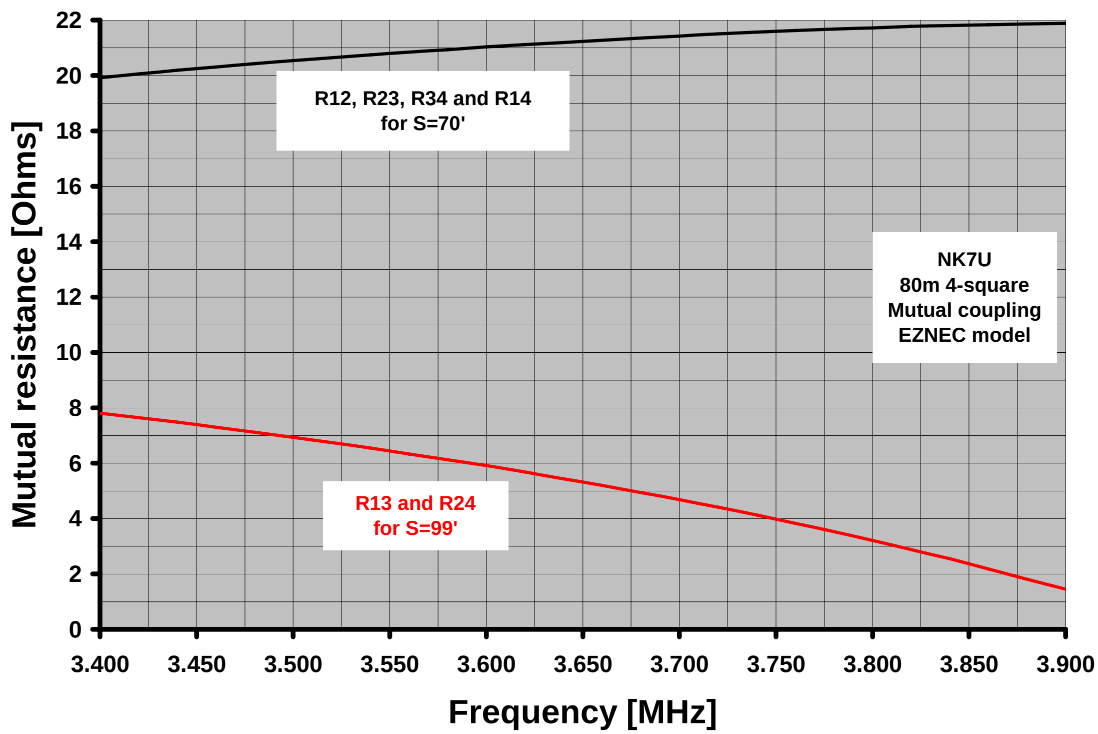

Figure 5, EZNEC results for mutual resistance with S= 70' and 99'.

Despite the above asymmetries we would expect that the mutual impedances between a given pair of elements would be close to identical. For comparison purposes I modeled the NK7U elements using EZNEC. The mutual resistances for 70' and 99' spacings (S) are shown in figure 5. This represents an "ideal" array.

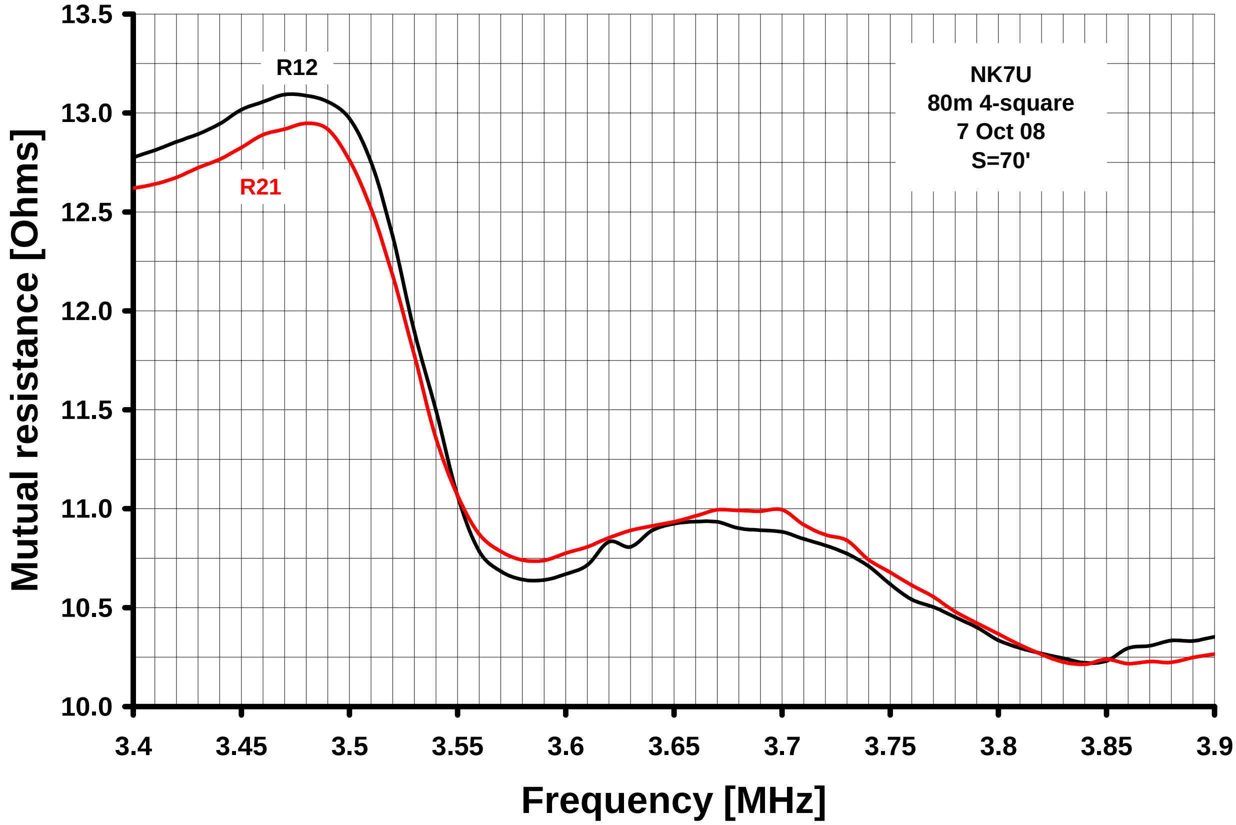

Figure 6, R12 and R21 derived from measurements.

Now for the real array. Figures 6-10 show the mutual resistances derived from measurements on the actual array. Note, there is only one trace on figure 9, I screwed up and repeated the same measurement twice rather than the reciprocal! From the graphs we can see that the reciprocal measurements agree fairly well but are not as good as they should considering the instrumentation being used. It's clear I need to make improvements in my technique!

More importantly, figures 6 through 9, which are for S= 70', do not resemble the plot on figure 5 for S=70' and they do not even resemble each other! The graphs for S=99' in figures 10 and 11 are much more similar to each other but still not exactly the same. These badly distorted plots (in comparison to figure 5) show that there is definitely something going on between 3.5 and 3.6 MHz.

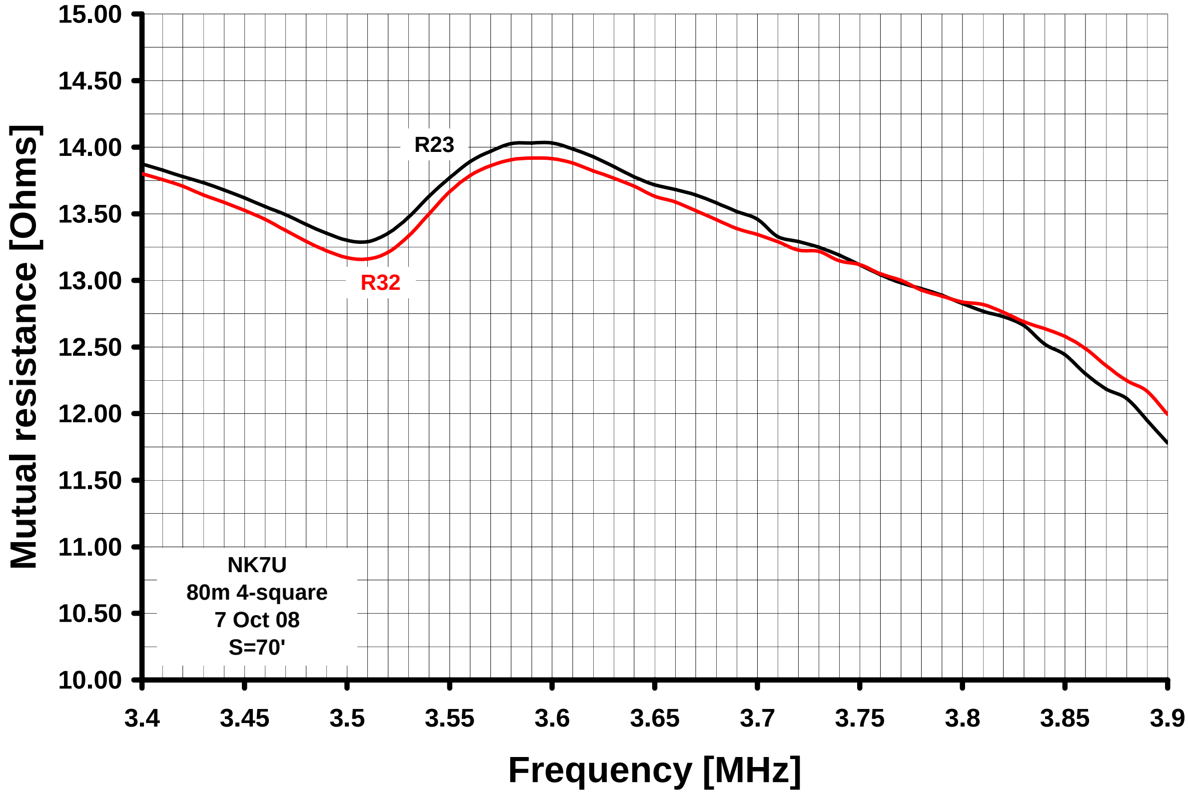

figure 7, R23 and R32 derived from measurements.

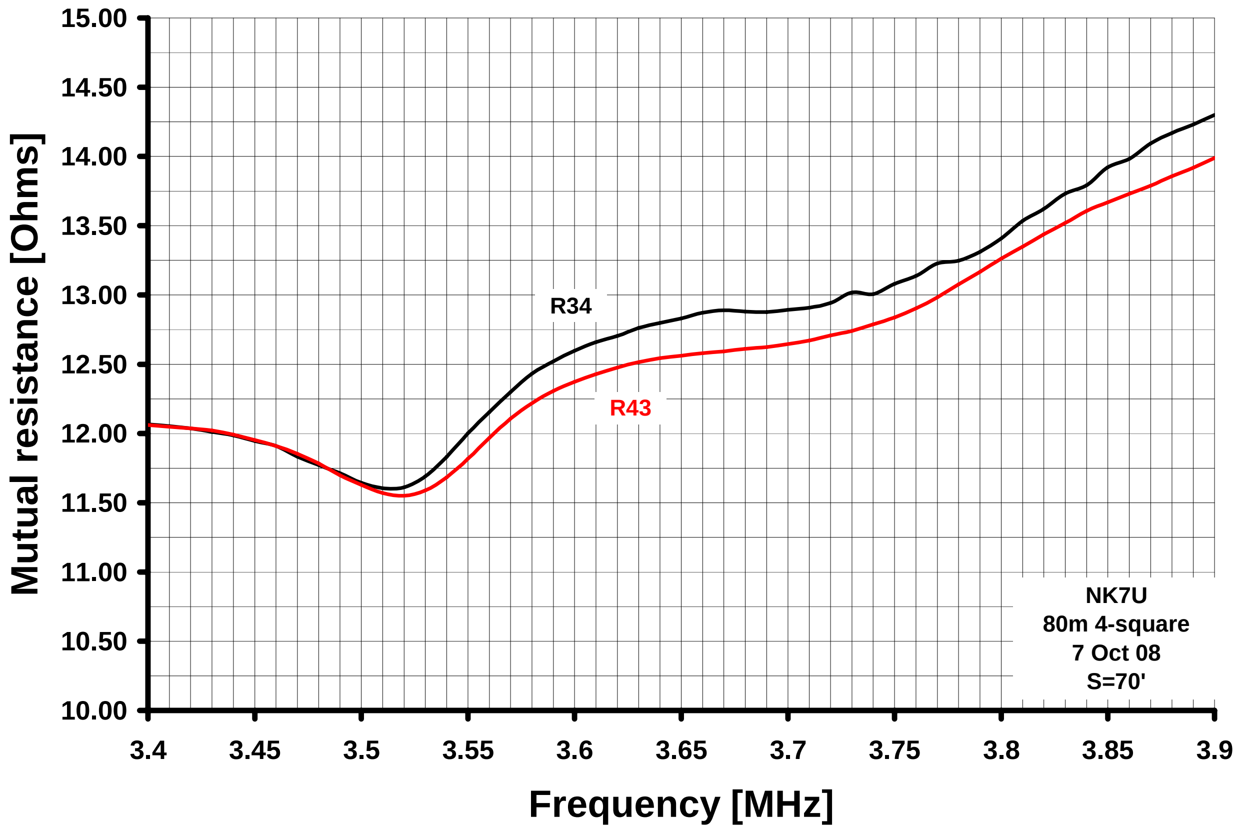

Figure 8, R34 and R43 derived from measurements.

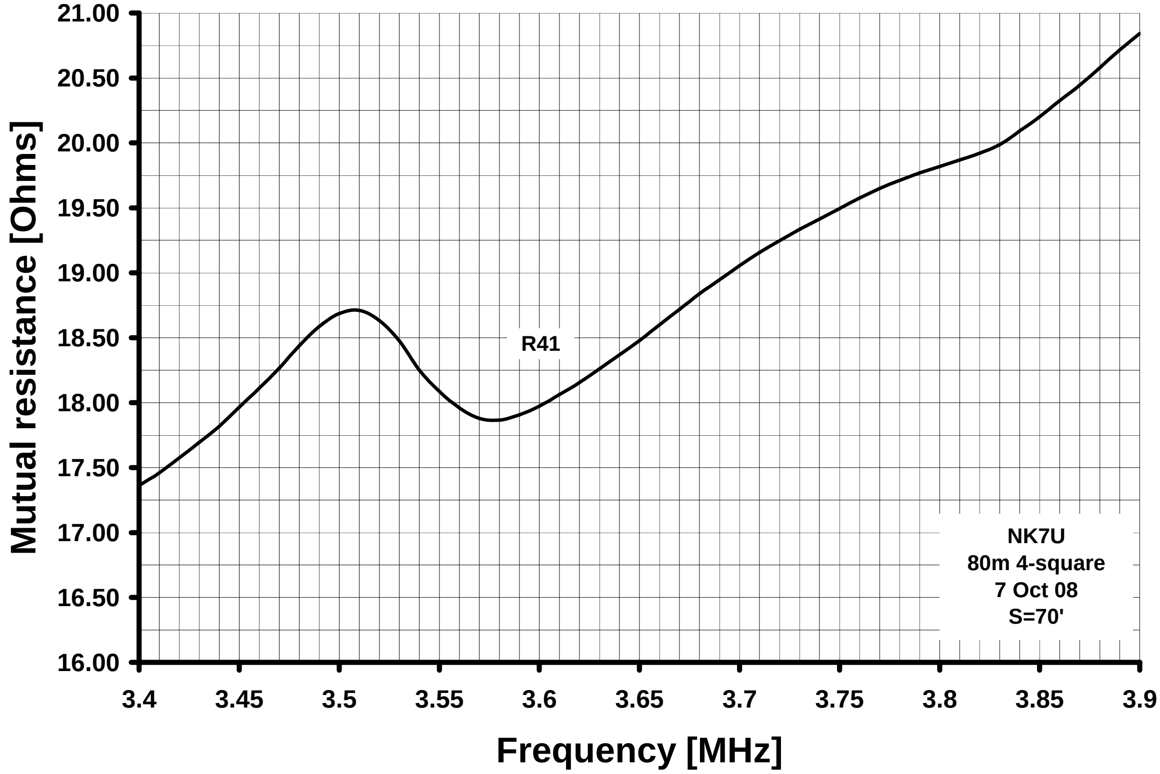

Figure 9, R41 derived from measurements.

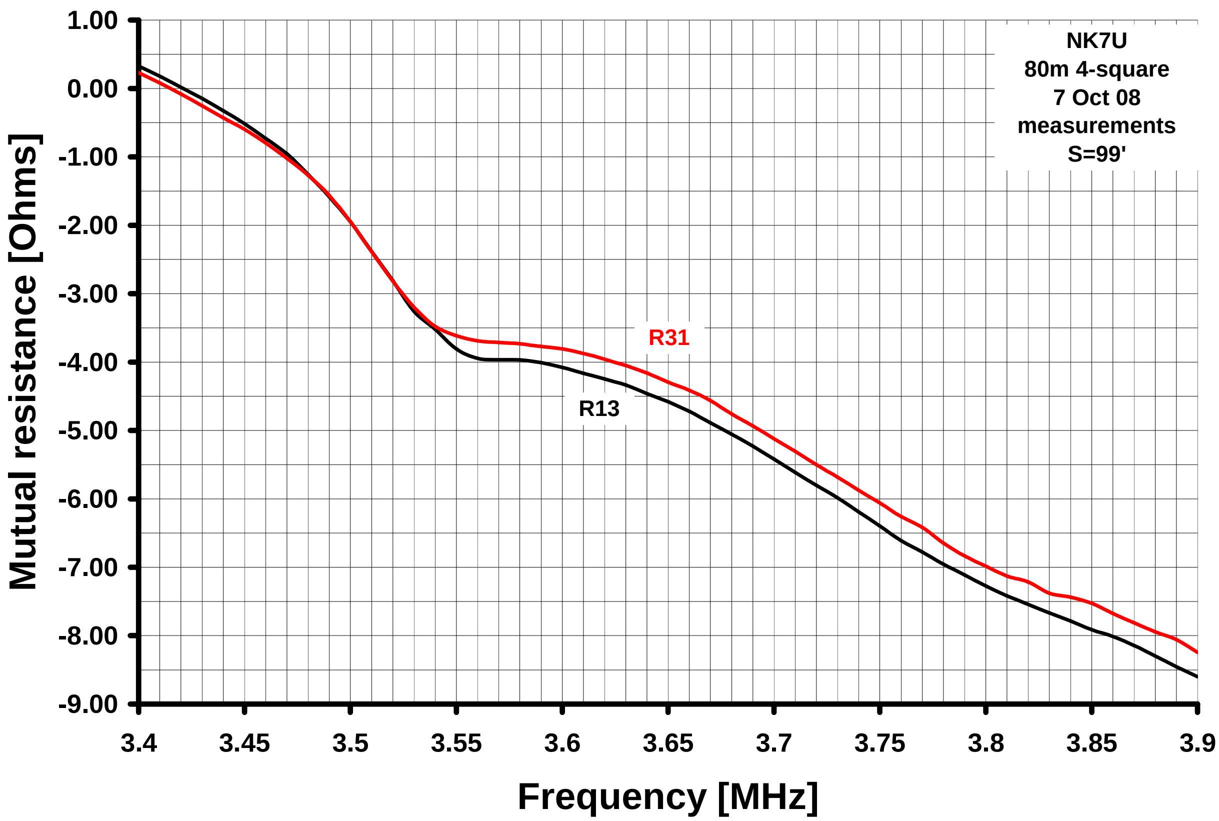

Figure 10, R13 and R31 derived from measurements.

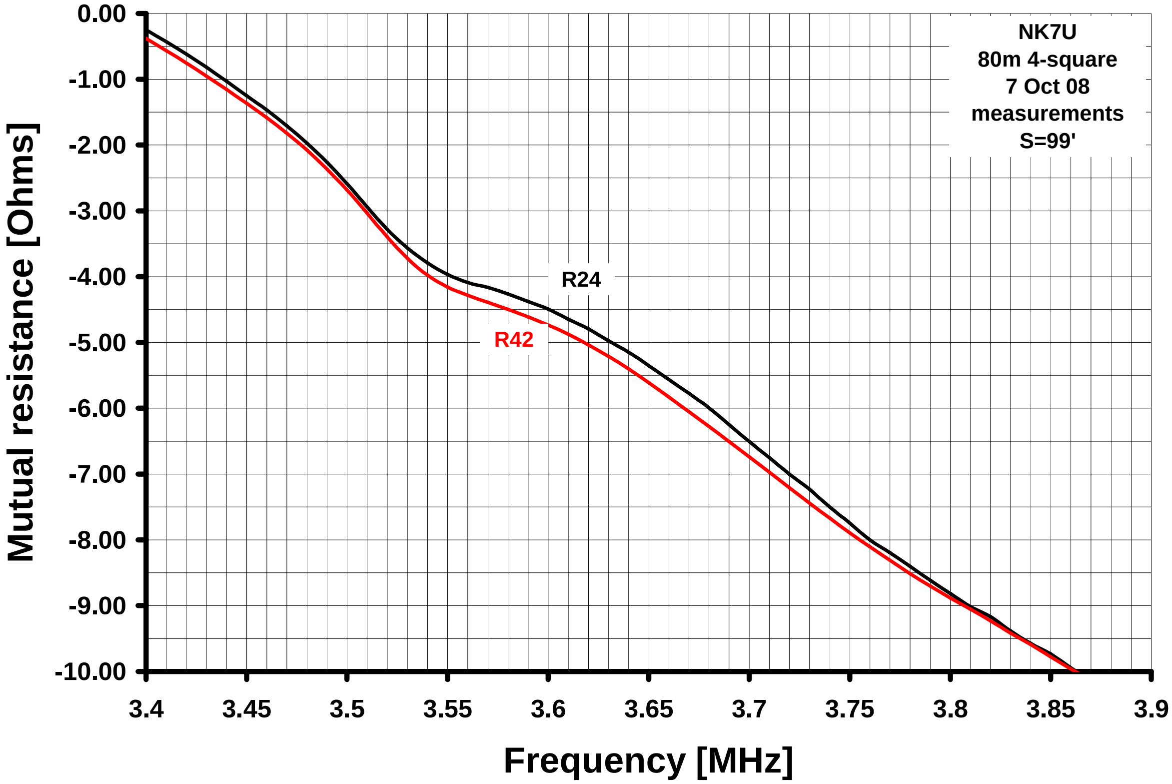

Figure 11, R24 and R42 derived from measurements.

Conclusions

Despite the fact that the array was mechanically very symmetrically it's clear that it's very asymmetric electrically. There's no way to design a feed network which would allow this array to function normally. The tower interaction is simply too strong.

The necessary next step to getting this array working will have to be a determination of which tower(s) is (are) causing the problem and to detune the tower(s). It is likely that most of the problem is coming from one of the towers and that one should be detuned first. Then the array should be remeasured to see if further effort is needed on the remaining towers.