Measure characteristic impedance, balance, coupling coefficient, and saturation level accurately

testing baluns

In recent years baluns have become widely used in the antenna systems of most Amateur stations. Because of their popularity, many companies manufacture and advertise baluns regularly; their relative simplicity encourages many Amateurs to wind their own. Unfortunately, very little has been published about the performance requirements of baluns or even about which performance parameters are important. The performance characteristics of baluns *can* be measured, however, and by testing baluns according to the procedures described, users can learn what to expect from the baluns they install in their own antenna systems.

The tests described apply primarily to the familiar 1:1 transmission line balun of either the toroidal or ferrite rod type (see **fig. 1**), but may also be coincidentally appropriate for the 4:1 auto-transformer type balun.

Generally more than one test can be used to measure a given parameter. Most tests can be performed using equipment available to Amateurs. The choice of test will depend, to some extent, on whether the balun is purchased or homemade, since this will determine what terminals are available for testing. Because some tests require that the tertiary winding be disconnected from the top section of the main winding, not all tests can be applied to a purchased balun. All commercial baluns are factory-sealed and cannot be opened without breaking their cases; consequently, it is impractical to open the tertiary junction. With a homemade balun, all tests can be made before the tertiary winding is connected to the circuit.

balun operation

A balun serves two principal purposes. First, it provides two equal and opposite voltages to a balanced load with respect to ground. Second, the balun provides isolation between the balanced load (usually a dipole antenna) and an unbalanced transmission line (coaxial cable). Of particular importance is isolation between the coaxial outer conductor and the half of the dipole connected to the outer conductor. If this isolation is not adequate, then this half of the antenna essentially extends down the outside of the coaxial outer conductor and into the ham shack. This, of course, is undesirable. **Fig. 2** shows the problem graphically.

Your transmitter is actually a generator that drives a coaxial transmission line which is connected to a dipole. Assume the polarity is such that a current, I_1, flows into the center conductor from the left half of the dipole; an equal and opposite current, I_2, flows up the inside of the outer conductor. At the junction point between the outer conductor and the right half of the dipole, current I_2 divides.

Because of skin effect at radio frequencies, the inside and outside of the outer coaxial conductor may be thought of as two separate conductors. The division of the current I_2 into I_3 and I_4 depends on the relative impedances of the right half of the dipole and the impedance of the path down the coaxial outer conductor into your ham shack and through the power wiring to ground. If this length is an odd number of half wavelengths, the impedance will be low compared to the impedance of one-half a dipole (usually taken to be about 35 ohms). Much of the current I_2 will flow back down the outside of the coaxial and I_4 will be relatively high. Consequently I_3 will be low and different from I_1. In addition to causing the antenna to be fed asymmetrically, the outside of the coaxial can also be "hot" inside the shack, which not only creates operational problems, but introduces a safety hazard as well. However, if the length down the outside of the coaxial to ground is

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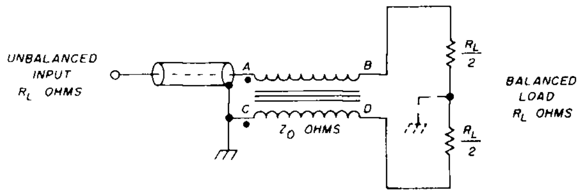

fig. 1. Typical 1:1, two-winding, transmission line balun. The characteristic impedance, Z_0, of the winding should be as close as practical to R_L. This balun will provide isolation, but not a balanced output unless the center-tap of the balanced load is grounded.

an odd number of 1/4-wavelengths, this impedance will be relatively high, forcing I_4 to be small in comparison to I_3 and the balancing dipole. The balun provides isolation between the right half of the dipole and the outside of the coaxial, and at the same time provides equal and opposite voltages and currents to the two halves of the dipole. Let's see how a 1:1 transmission line balun accomplishes these objectives.

1:1 balun

The simplest form of the 1:1 transmission line balun is shown schematically in **fig. 1**. Here a transmission line with a characteristic impedance (Z_0) is wound on a rod or toroidal ferrite core. One end of the winding is connected to the coaxial cable; the other end is connected to the balanced load, as shown. The characteristic impedance of the winding should be as close to that of the coaxial line and the load resistance as practical. One popular balun design[1] uses small 50-ohm coaxial (RG-141) wrapped around a 2-1/2 inch diameter (6.25 cm) toroid.

A commonly held view is that the inductance of the winding provides isolation and guarantees balanced voltages across the balanced load. Unfortunately, both these conditions may not occur in this design. The generator currents (I_1 and I_2 in **fig. 2**) are equal and opposite; hence there is no magnetic flux developed in the toroid and the inductance of the balun is essentially zero. The balun merely acts like an extra length of transmission line.

Assume an unbalanced condition, with current I_4 (**fig. 2**) flowing. Since there is no equal and opposite current flow, a magnetic flux will develop. If the inductance of the balun is sufficient, then the resulting counter EMF will limit I_4 and effectively isolate the balanced and unbalanced sides of the balun. The balun will therefore provide isolation. Counter EMFs will also develop on the inside of the coaxial shield and on the coaxial inner conductor; these will be in series opposition and do not affect the balun's operation.

Unless the center-tap of the balanced load is grounded or a tertiary winding is used, there is no ground reference point on the balanced side and no guarantee that the balanced side output is actually balanced with respect to ground. The degree of balance, if any, depends on parasitic inductances and capacitances and is not under control of the user. The only way the user can guarantee a balanced output is to actually ground the center-tap of the load. The lack of balance on a two-winding balun has been verified by actual measurements.[2]

To guarantee balanced output voltages and adequate isolation, it is necessary to provide a path for magnetizing current. Ruthroff[3] has stated that with the balanced load disconnected, there must be dc continuity between the unbalanced input and ground. The two-winding balun does not provide this continuity.

In order to guarantee balanced output voltages as well as provide adequate isolation, a tertiary winding, EF (see **fig. 3**), must be added. Note that the polarity of the tertiary winding is reversed.

If the voltage at the unbalanced input is V volts, the voltage at point B is V/2 volts since point B is halfway down the winding AB-FE with V/2 volts being developed in each winding. This is better shown when **fig. 3** is redrawn as an auto-transformer

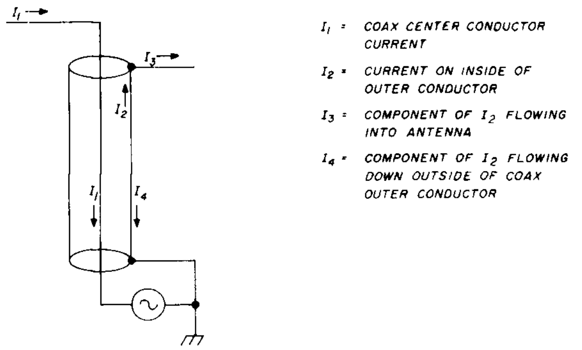

fig. 2. Lack of adequate isolation between antenna and feedline causes I_2 to divide into I_3 + I_4.

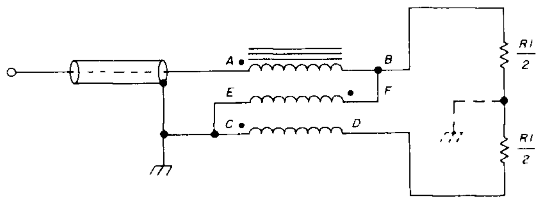

fig. 3. A 1:1 transmission line balun with a tertiary winding E-F. This design provides both isolation and balanced output voltages.

as shown in **fig. 4**. This arrangement guarantees that the balanced output voltages are balanced with respect to ground, provided that the coupling between tertiary and main windings is "tight."

Though **fig. 4** is drawn as an auto-transformer, the balun is nevertheless a transmission line device. Signal currents flow only through the transmission line windings and the input impedance/load impedance relationship follows the transmission line equation and not the auto-transformer law. With this thought in mind we will move on to the actual tests.

dc ohmmeter test

One of the simpler tests, to determine if the balun has a tertiary winding or not, is one that should be performed on any purchased balun. That test is important because a tertiary winding is absolutely essential if the balun is to work properly with most antennas.

This test consists simply of measuring the dc resistance between the unbalanced input terminals and ground with the balanced terminals open-circuited (see **fig. 5**). If a tertiary winding is present, this resistance should be a few tenths of an ohm and will appear on most ohmmeters as a short-circuit. An open circuit reading indicates no tertiary winding.

Using an accurate ohmmeter or Wheatstone bridge can provide other information. With the unbalanced side open-circuited, measure the dc resistance between each balanced load terminal and the grounded side of the unbalanced terminal. Each of these resistances should be one-half the value obtained in the first test. The success of this test ensures that each of the windings is the same length and that the balun is reasonably well balanced, at least in regard to dc.

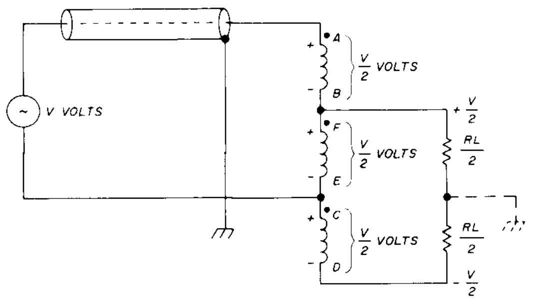

fig. 4. A 3-winding transmission line balun drawn as an auto-transformer. Though shown as an autotransformer it is still a transmission line device. The input versus load impedance relationship follows the transmission line equation and not the transformer law.

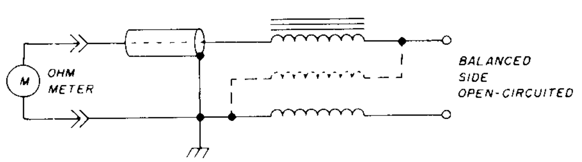

fig. 5. Ohmmeter test to determine if balun has a tertiary winding.

characteristic impedance

One of the most important parameters of any transmission line balun is its characteristic impedance which should be the same as the characteristic impedance of the transmission line with which the balun will be used. If too great a difference between these impedances exists, use of the balun may *cause* more problems that it cures.

There are several ways of measuring the characteristic impedance of a balun. The method used will depend on the measuring instrument available and on whether or not the balun is store bought or homemade.

Perhaps the most straightforward method of measurement is to take advantage of the fact that the characteristic impedance can be found by taking the square root of the input impedance with the far end open-circuited and short-circuited or:

$$Z_0 = \sqrt{Z_{oc} Z_{sc}}$$

While this approach is theoretically straightforward, it presents instrumentation problems. At some frequencies, the input impedance of the line will have a very high or very low resistive and/or reactive component for either an open- or short-circuited condition at the far end with one or more of these components outside the range of the measuring instrument. If it is possible to find a frequency or a test instrument where both open- and short-circuit measurements can be made, this method provides a convenient way to determine the characteristic impedance of the balun.

It is important to note that this test can *not* be used with a tertiary winding connected. If the balun is homemade, make the test with the tertiary winding in place but not yet connected to the main windings. If the balun is commercially made, you may have to figure out a way to open the balun and disconnect the tertiary winding. If this is not practical, use a different measuring technique.

A second method which does not put such severe requirements on the test equipment but is more time consuming is to measure the input impedance of the balun with an arbitrary load impedance as the electrical length of the line changes, or place the value of load resistance across the balanced load that you think the balun characteristic impedance is, or that you would like it to be. Then measure the input impedance of the balun across the frequency range and see how close your guess was. **Fig. 6** shows the input impedance of a transmission line balun with four different values of load resistance: 65, 76, 84, and 101 ohms.

Starting at the top, notice that the input impedance with the 101 ohm load rolls off at higher frequencies. At first glance this roll-off appears as normal high-frequency drop off. However, looking at the 65-ohm load line, we see a "roll up" in the input impedance as the frequency increases. These two input impedance characteristics suggest the impedance inverting effect of a 1/4-wave transmission line whose characteristic impedance, which is what we are trying to find, is between 65 and 101 ohms.

Looking between 65 and 101 ohms, we see that the 84 ohm line rolls off slightly while the 76 ohm load response is practically flat – only a very slight roll-up. This indicates that the characteristic impedance of the balun is just above 76 ohms. If these measurements were made beyond a 1/4-wavelength, the slope of the curves would reverse and the frequency for a 1/4-wavelength could be determined. My equipment does not go high enough in frequency to do this, however.

If a General Radio 821 Twin-Tee admittance bridge[4] or similar instrument is available, a third approach may be used that gives not only the characteristic impedance but the electrical length of the winding as well. If the physical length of the winding (in inches or meters) is known, the velocity coefficient of the winding can also be determined from this data.

This test is based on the fact that a short-circuited transmission line 1/8-wavelength long has an inductively reactive input impedance equal to the characteristic impedance of the line. Similarly, if the far end is open-circuited, the input impedance presents a capacitive reactance equal to the characteristic impedance. This can be seen by examining the transmission line equation for the short-circuited case, which is the simplest:

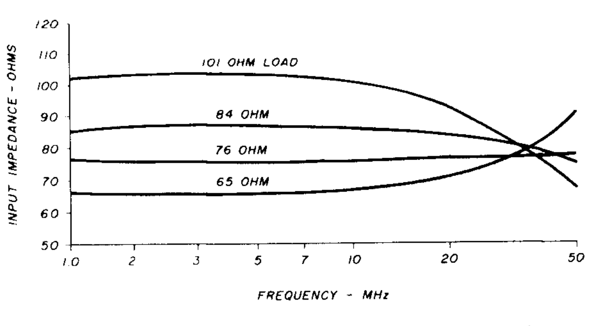

fig. 6. Input impedance versus frequency for 65, 76, 84, and 101 ohm load resistors.

$$Z_{in} = Z_0 \frac{Z_r \cos X + jZ_0 \sin X}{Z_0 \cos X + jZ_r \sin X}$$

when $Z_r = 0$ (short circuit load)

then $Z_{in} = Z_0 \dfrac{jZ_0 \sin X}{Z_0 \cos X} = jZ_0 \tan X$

when $X = \lambda/8 \text{ or } 45°$,

then $(\text{since } \tan 45° = 1)\ Z_{in} = jZ_0$

The open-end and short-circuit values of reactance are plotted versus frequency on the same piece of graph paper; the reactance at which they intersect is the characteristic impedance of the balun. An example of this is shown in **fig. 7**. Also, the frequency of intersection is the frequency at which the balun is 1/8-wavelength long. The electrical length at any frequency can easily be determined from this.

If the physical length of the line is known, the velocity coefficient of the transmission line, k, can be determined by calculating the 1/8-wavelength of the intersection frequency in free space and dividing this into the measured length of the balun winding.

$$k = \frac{\text{measured length winding}}{\text{calculated length } \lambda/8 \text{ free space}}$$

Because this test cannot be used when the tertiary winding is connected, it can be used only on homemade baluns or commercial baluns where the tertiary winding can be opened.

The limitations on the test equipment are that the impedance measuring device must be capable of measuring impedances with high resistive components and measuring reactive components in the range of the expected characteristic impedance at the frequency where the balun is 1/8-wavelength long.

winding inductance

The balun winding inductance is important because it determines the frequency range over which the balun can be used and also determines balun isolation. In general, the winding reactance should be about five times the characteristic impedance for a general purpose balun. You may want to use a factor of ten times the characteristic impedance for a precision or an instrument balun, however.

As the frequency increases, the balun impedance increases until the inductance resonates with the stray capacity across the inductance. At this frequency, the impedance of the winding and the isolation are the highest. As the frequency is further increased, the impedance becomes capacitively reactive and decreases until series resonance occurs and the winding is effectively a short-circuit. The balun is obviously worthless at this frequency as the balun develops no isolation between the balanced and unbalanced sides. There is no problem in operating the balun through parallel resonance, but it should not be operated above the frequency where the impedance falls below about five times characteristic impedance. **Fig. 8** shows a typical inductance curve.

To perform this test, the tertiary winding must be disconnected so you may not be able to make these measurements on a commercial balun. The test arrangement is shown in **fig. 9**.

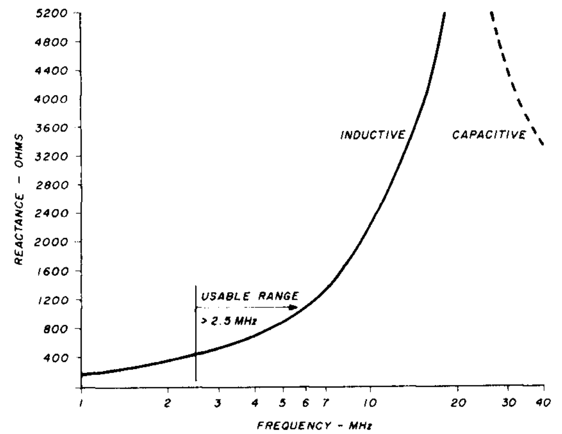

fig. 8. A typical balun reactance versus frequency characteristic. Isolation is at least five times the characteristic impedance from 2.5 MHz to above 40 MHz.

coefficient of coupling

The coefficient of coupling between the main winding and tertiary winding is important because it affects the degree of balance of the balanced output and also limits the high frequency response. To measure the coefficient of coupling, the tertiary winding must be disconnected from the main winding; again, this will restrict the testing to homemade baluns. The procedure is simple; measure the inductance of the main winding as described in the preceding test, with the tertiary winding open-circuited and again with the tertiary short-circuited. Use the equation:

$$k^2 = 1 - \frac{L_{sc}}{L_{oc}}$$

Values of k — not k^2 — should be at least 0.98 to 0.99. If the coefficient of coupling is less than about 0.98, you should expect problems, especially if broadband operation and/or a mismatch condition exists. Since this test involves measuring the inductance of the main winding, it is convenient to do it simultaneously with the inductance test.

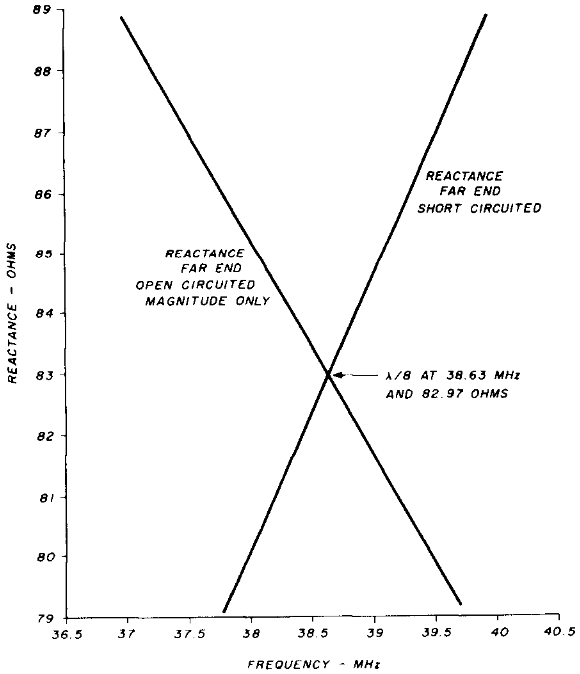

fig. 7. Open/short circuit curves of a balun transmission line showing a characteristic impedance of 82.97 ohms and a *l*/8 length at 38.63 MHz.

achieving a balanced output

A very important performance characteristic of any balun is the degree of balance of the balanced output (assuming a balanced load). Fortunately, the test for this is easy to do, and a number of different approaches are possible.

The simplest and most direct approach is to measure the rf voltage between each side of the balanced load and ground over the frequency range of interest. If the input voltage is held constant, any unbalance or variations in the transmission through the balun will be apparent.

Another approach is to use a dual channel oscilloscope with one channel connected to each of the balanced terminals. This has the advantage that phase differences between the two halves of the balanced output can also be measured by the horizontal displacement of the two traces.

A variation on this test is convenient for measuring the electrical length of the winding; connect one scope channel to the balun input (unbalanced input) and the second channel to the high side of the balanced output of the balun. The balanced voltage to ground at this point should be one-half the input voltage for a 1:1 balun. You will probably want to synchronize the scope on the channel connected to the balun input. The electrical length of the winding can be determined from this measurement from the horizontal displacement of the two traces. Scopes with vertical channel responses of 30, 45, and even 60 MHz are now readily available to Amateurs, making this an attractive method.

The ideal method of measuring the balance is to use a Hewlett-Packard model 8405A vector voltmeter; this instrument measures the magnitude of two voltages and the phase angle between them. Unfortunately, this is a $5000 instrument and very few Amateurs can afford to spend this much for a voltmeter. If you are employed in electronics, see if your lab has one; it's a common instrument in rf labs. The vector voltmeter can also be used to determine the electrical length of the balun.

Another simple and useful test for estimating the degree of balance is to use a balanced load impedance composed of two resistors in series, with each resistor being one-half the value of the desired balanced load. The input impedance is then measured with the center-tap of these resistors both grounded and open-circuited. If the balun and load are well balanced, there will be no change in the input impedance of the balun when the center-tap of the load is grounded or ungrounded. By "grounding the center-tap," I mean connecting the center-tap to the grounded terminal of the unbalanced input. When I have performed this test on a well-designed balun, I have found that the change in input impedance is always less than the width of the calibration line of the dial.

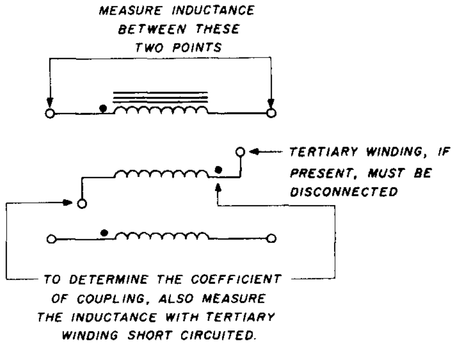

fig. 9. Circuit for measuring balun inductance and calculating the coefficient of coupling between main and tertiary windings.

As the balance test must be made with the balun in its final operating configuration, it can be made on commercial baluns as well as homemade ones. This is one of the simplest and most effective tests I am aware of for determining the effectiveness of a balun. As the balun test involves only measurements of input impedances, it is convenient to check balance when the input impedance is measured. To demonstrate the benefit of a tertiary winding, try making this test on a 1:1 balun without a tertiary winding.

short-circuit test

This test was first described by Reisert.[1] Readers have often called it to my attention after publication of my previous articles about baluns.[2,4,5] Basically, this test is intended to give an estimate of the isolation provided between the balanced and unbalanced sides of the balun.

This test is performed by measuring the input impedance at the unbalanced terminals with a normal balanced load connected to the balanced side. The input impedance is again measured when each of the balanced terminals is shorted to ground. If baluns provided perfect isolation, there would be no change in the measured input impedance; but because nothing is perfect, some change in input impedance should be expected. Despite extensive reading in the field, I have not yet discovered what constitutes an acceptable change in input impedance, but I would assume that a change of ten percent or less is acceptable. This would suggest that the series impedance of the balun is at approximately ten times its characteristic impedance.

However, this test must be approached with extreme caution. First, if the balun has a tertiary winding, shorting the high side of the balanced terminal to ground will also short-circuit the tertiary winding. As the tertiary winding is tightly coupled to the main windings, this will effectively short-circuit the main winding, thereby ruining the balun action. If the balanced-load center-tap is grounded, shorting either side to ground will also short-circuit one-half of the load resistance, which will obviously affect the input impedance.

My principal objection to this test, however, is that the test conditions alter the operating conditions of the balun. Grounding either balanced terminal provides a path for the magnetizing current (a dc path to ground) and also increases the voltage across the main winding by a factor of two — from V/2 volts to V volts where V is the unbalanced input voltage. For these reasons, I am not convinced that this test is really a reliable indication of balun performance.

core saturation

One final test that should be mentioned is magnetic saturation of the core. I have not tried this test myself, but it's easy enough to perform, at least in theory. Wrap three or four turns of insulated wire around the balun core and connect it to an oscilloscope. If the waveform on the scope is a sine wave, the core is not being saturated. The test must obviously be made at full power while connected to the actual load. This presents some practical as well as safety problems.

summary

I have briefly discussed the purposes and operation of a 1:1 transmission line balun and described seven tests that can be used to measure the characteristics of the balun. The tests include:

1. tertiary winding (using an ohmmeter)
2. determination of characteristic impedance
3. isolation determination by winding inductance
4. balance
5. coefficient of coupling of tertiary winding
6. electrical length
7. core magnetic saturation

The tests described above do not appear to require specialized test equipment or training and I feel that balun vendors should list the various technical parameters as do manufacturers of other products. This information would benefit the users because they would be better able to choose the balun that best met their requirements. Perhaps if balun manufacturers were to share their test results with consumers by including technical specifications in their promotional materials, users could be spared some of the time and effort testing requires. Armed with such information, users would be better able to choose the balun that best meets their needs.

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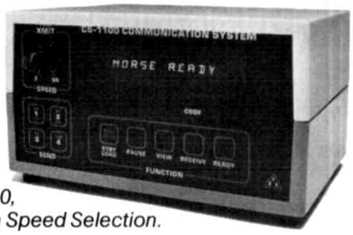

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