A further look to the popular Z-Match circuit

Claude Frantz

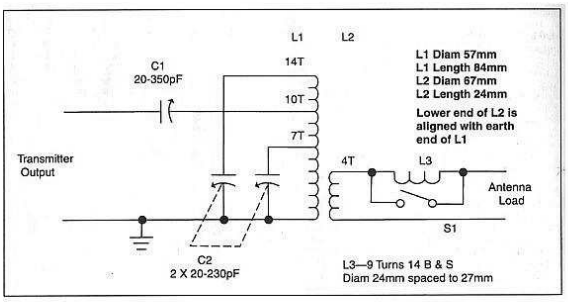

Fig. 1. The "normal" version of the Z-Match circuit

***Abstract*—Because of the lack of a band-switch, the Z-Match circuit has become very popular in the amateur radio area as a matching device between the transceiver and the antenna system. Some work around this circuit has be done, especially in the British and Australian area of the world, but some more work is still needed. This present work try to investigate the matching capabilities of the circuit.**

I. Motivation

SOME articles have been published about the very interesting impedance matching device called the "Z-Match", which main advantage is to have no band switch at all. Such band switches, used in antenna matching devices, have usually to support large currents and large voltages, depending on the impedances to match. Therefore, such switches have to be large and they are then expensive. An attempt to avoid such switches has resulted in a matching device in which one the switch has been replaced by a plug connecting field, which reduces the cost and requires less space [1]. As a drawback, the handling becomes not so easy as with switched devices.

Some statements encountered in the many articles about the "Z-Match", were surprising or a further explanation was simply missing, so that contradictions or erroneous statements could no more be excluded. It becomes clear that further work was necessary in order to verify. This article reports about such a further work. It is in no respect all-embracing. Further work is still needed.

II. History

As usual, in the amateur radio area, it is not really clear at which time, the circuit now called "Z-Match", has been used for the first time. In the year 1948, King reports about using a parallel arrangement of a serial LC circuit and a parallel LC circuit as a tank circuit in a transmitter [2]. In this manner, the tuning becomes possible using only the variable capacitor, for a coverage of the then usual five short wave bands from 80 to 10 meters. In another article, Johnson returns on this idea and reports further about the using of an arrangement using only a tapped coil in place of the two not coupled coils [3]. Although used in commercial equipment by Harvey Wells and the World Radio Laboratories, the above-mentioned arrangement used as a tank circuit, has been the target of many criticisms. At first, it was mentioned that the Q of the circuit cannot be controlled over all the working range, with all the drawbacks which results from using a wrong circuit Q. Secondly, it was reproached that the circuit has a second high Z resonance (anti-resonance) at a not very easily controllable frequency at which one the attenuation is negligible. Further, the output coupling cannot be performed in the same manner for all bands, so that a switching becomes necessary here although it was the main goal to avoid switches.

Only a short time later, King proposed to use the circuit in an antenna matching unit, i.e. independently of the tank circuit [4]. A switching is still necessary at the output because the arrangement is using two not coupled coils. Using the alternative realization form already proposed by Johnson [3], on an antenna matching unit, resulted in the now called "Z-Match" circuit.

It is interesting to note here, that the "Z-Match" arrangement has been used first as a tank circuit, i.e. as a combined tuned loading and matching circuit and it has been used later as a matching only circuit. In the case of the very common π circuit, this sequence of events was reversed.

III. The circuit

A. The structure

Fig. 1 shows the "standard" Z-Match circuit as found in the WWW version of Butler's article [5]. It is called "standard" here because it is the most commonly encountered variant, the one to which one the authors refer mostly to when talking about the Z-Match circuit. This will be the base of our further examination here. There is what we will now call "the central circuit" having the taped coil L1 and the double variable capacitor C2. Therefore, it is the alternative arrangement as proposed by Johnson [3]. Further there is a transceiver side coupling by the variable capacitor C1 going to a tap of L1 and an antenna side coupling by the L2 coil. At first, the optional inductance L3 will be ignored, we will consider the switch around it as closed. In order to try to understand the behaviour, we will now perform some circuit transformation on the "central circuit" using common techniques as explained e.g. in [6]. Fig. 2 will shows the performed steps. There is, at first, the starting central circuit (a) having the taped coil which can be considered as two serial connected coupled coils

This present work has be performed using only free software, e.g. spice3, acmi, xcircuit, GNU octave, Xmaxima, g77, gnuplot and LaTeX. Please support the development and use of free software.

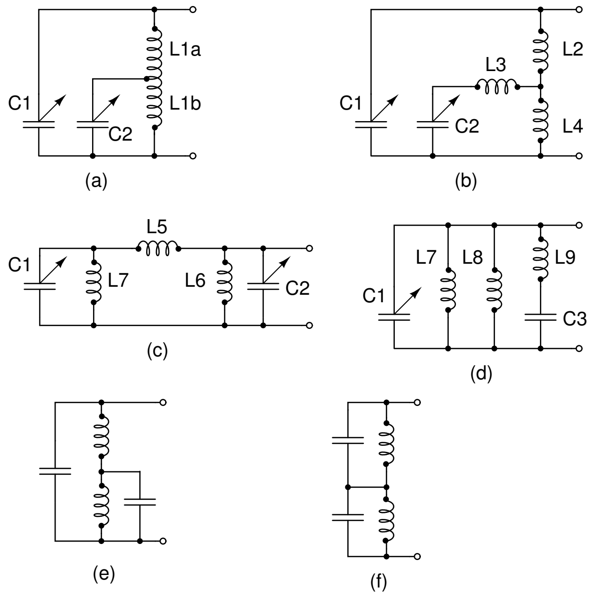

Fig. 2. The equivalent circuits of the central circuit

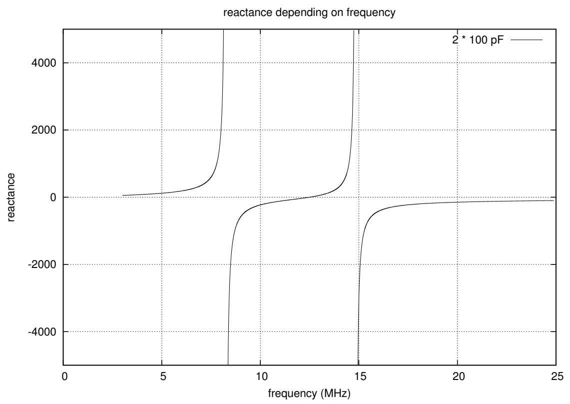

Fig. 3. The impedance of the central circuit vs. frequency

L1a and L1b. Now, at (b), the tapped coil will be split in an equivalent T arrangement of not coupled coils L2, L3 and L4. In the next step (c), this T arrangement will be converted to an equivalent π arrangement of the no coupled coils L5, L6 and L7. At next, the substructure including L5, L6 and C2 will be converted to an equivalent sub-circuit including L8, L9 and C3. The result is (d), which still includes L7 and C1. Now, we recognize the parallel connected two LC circuits: L9 connected in serial with C3 and L7 and L8 (which can be shrunk to an unique one) connected in parallel to C1. This confirms the statement of Johnson [3], that both arrangements are equivalent. Further classical transformations show that (e) and (f) are equivalent circuits too [6]. Note that [6] contains errors in the formulas of Table 10.1(2), to which one we refers especially here. In contrast to some other analysis found elsewhere, this one is not concentrated on an unique frequency.

B. *The behaviour*

The impedance vs. frequency behaviour of the central circuit obeys to very general rules as proved by Foster [7]. We will examine this behaviour a little bit more specifically here, as related to the central circuit. The behaviour at the zero frequency can be found while replacing every inductance by a short-circuit and while ignoring all capacities. The central circuit has zero impedance at the zero frequency. The behaviour at the infinite frequency can be found while replacing every capacity by a short-circuit while ignoring all inductances. The central circuit has a zero impedance at the infinite frequency. According to [7], there are 3 singularities between the zero and infinite frequencies. In the sequence of increasing frequency, we will find an anti-resonance (parallel resonance), a resonance (serial resonance) and another anti-resonance. Fig. 3 shows this graphically when C2 of Fig. 1 has a value of 100 pF. When C2 is changed, the frequencies at which ones all these 3 singularities occur change too. But since only the component values changes while the structure of the circuit remains the same, the sequence at which ones the singularities occur remains the same. Fig. 4 shows how the frequency of the singularities changes when C2 is changed.

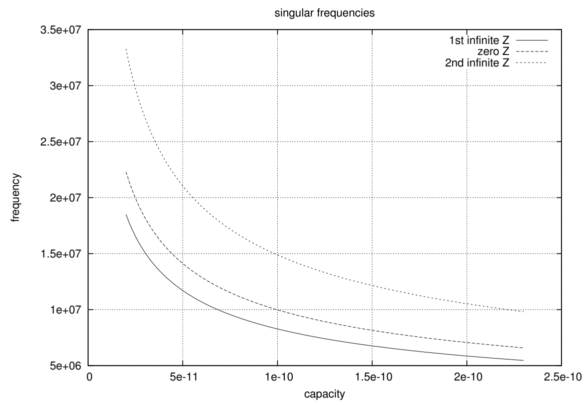

Fig. 4. Changes of the singular frequencies of the central circuit vs. the capacity of the variable capacitor

IV. Investigating the Matching Capabilities

A. *The procedure*

Because all the statements about the matching capabilities of the Z-Match circuit do not allow to see a clear image, it was decided to work further on this subject. The investigation is performed using a simulation method, considering all the components as linear and loss-less. The used values are these found on Fig. 1. The capacity range of C1 will be considered as going from 20 to 350 pF, while the range of C2 is going from 20 to 230 pF. Using the free software named “acmi”, the characteristics of the inductors have been calculated.

In order to investigate the matching capabilities in respect to the very classical reference of 50 Ω source impedance of the transmitter, a simulation model has been built. Although different approaches are possible, the following described one has been preferred. The main problem of the model, is the complex structure of the inductor having two taps on the primary winding and an inductively coupled secondary winding as well. At first, a model of this inductor has been built using the “extended cantilever model” [8], [9], [10] which has become very popular in the power electronics area. There is no limitation which would made its use difficult in the high frequency area, so it was used here. The extended cantilever model of the complex inductor includes only inductors and ideal transformers which are more easy to handle, in the simulation, than non ideal ones. Using the components of the extended cantilever model, an extended admittance matrix has been built according to the rules of the "modified nodal analysis" method [11]. After the inversion of this matrix and the multiplication with the RHS vector, the needed "unknowns vector" has been deduced, using a current source at the input, at first, and using a current source at the output, at second. The result allows now the building of the z-matrix of the Z-Match circuit considered as a 2-port circuit. Using the z-matrix, it was found which load can be matched by the Z-match circuit, resulting in the needed 50 Ω at the transmitter side of the Z-Match circuit. All this work was performed using the open source software named "Xmaxima". Further, the result given by "Xmaxima" was used to build an FORTRAN program allowing to calculate the unknown load corresponding to different frequencies and values of the variable capacitors, in the allowed ranges. In order to display the result in a manner familiar to the electronics engineer, the popular Smith Diagram has been preferred. The excellent PostScript program of Marshall Jose has been used as tool. The value of C1 has been be varied from 20 to 350 pF in 5 pF steps. The value of C2 has been varied from 20 to 230 pF in 5 pF steps. Of course, the Smith Diagram is centered around 50 Ω. For every tried value of the variable capacitor, the impedance has been calculated, which, when it would be connected to the output (antenna) side of the Z-Match, would result in the matching to the 50 Ω at the input (transmitter) side. The found impedance has been marked as a dot on the Smith chart. This procedure has been repeated for every edge frequency of the amateur bands between 80 m and 10 m (ITU region 1). For wider bands, a frequency in the middle of the band has been investigated too. For every frequency, the circuit having the classical 4 turn secondary as well as the special 3 turn secondary have been investigated, with and without L3 in circuit. The Smith charts are attached at the appendix. It will be best to have a look on them, in order the appreciate the Z-Match capabilities.

B. Understanding the results

Looking on the resulting Smith charts, some patterns can be observed. There are regions where dots are clustered together, resulting in a more or less compact black area. Although the variable capacitors have been turned, the impedance which can be matched has not changed notably. The corresponding range of the variable capacitors, can only produce a match in the rather small region corresponding to the clustered dots.

There are other regions where the dots are widely spaced. A small change in the variable capacitors results in a rather large change in the value of the matched impedance. Matching is possible but the value of the variable capacitors must be adjusted precisely. A vernier dial drive is then recommended as mentioned previously by some authors, e.g. in [12].

Further, there are areas where no dot can be found. A matching of the corresponding impedances is not possible there.

C. Looking on the result

It is interesting to observe, that the results are very different depending on the frequency band, the number of turns of the secondary winding and the fact that L3 is in circuit or not. On some charts the area covered by dots is large. The Z-Match is then capable of matching very different impedances. If the spacing of the dots is moderate and if the spacing between the dots does not vary rapidly, the adjustment will be easy.

Depending on the charts, the location of the areas of possible matching and non matching can change widely. On the 80 m band, the matching area is rather large, covering very different loads. The dots are not widely spaced, i.e. the tuning is not especially difficult. But there is a non-matching area mostly related to capacitive reactances with a rather small resistance component. This problem, which is not specific to the 80 m band, has been mentioned previously by other authors and two different solutions have been proposed [13]. The first one is to use a 3 turn secondary winding in place of the 4 turn winding. The second proposed solution is to insert a 1.2 μH serial connected inductor in the secondary winding, without coupling with it. Both solutions have been examined and the corresponding Smith charts are included in the appendix. We can see, that every of these solutions, shift the area of non-matching capabilities, in a different manner. None of these solutions can be considered as a solution in a general sense. The use of the switch around L3, is a simple solution to shift the non-matching area, when this results in the coverage of the actual load, by the then shifted matching zone. This apply only for a limited number of possible loads, as this can be seen on the Smith charts.

On no other band is the matching area as large and are the dots as well spaced as on the 80 m band. Depending on the frequency, the dot spacing can become rather large. On the 40 m band, the non-matching is especially large in the capacitive range. In the 30 m band, the matching region becomes rather small. This is the band where the matching is the more problematic with the Z-Match circuit. On the 20 band, the non-matching area is rather large, too, for capacitive loads. The large dot spacing indicates that a precise adjustment of the variable capacitors is necessary. As the frequency increases, for the other bands, the non-matching area becomes smaller but remain located in the capacitive area, while the dot spacing becomes larger, especially in the inductive area.

As we can see, the use of L3 makes not really sense at frequencies greater than 7.2 MHz.

Analyzing the charts is finally a subjective matter. The conclusion will depend on what we are expecting for the situation we are encountering our self. What is not very important for the one observer can be of paramount importance for another one.

V. Conclusion

It is very difficult to compare the performance of the Z-Match to the one of other matching networks. This is mainly related to the fact, that comprehensive data is usually not available. Either only very limited data is available, or the available data is very subjective. In both cases, the data is only of little value. The present work was an attempt to provide data related to the Z-Match circuit. In the lack of information about other networks, the information given here can only the judged by itself.

The Z-Match circuit shows some interesting matching capabilities, but there are limits we have to accept. It is probably a valuable device, but it cannot be called an universal one. A really universal matching device does probably not exist and will probably never exist outside of ads.

In the present work, the components have been considered as linear and having unlimited voltage, current and power handling capabilities. But in our cruel, real world, nothing is perfect nor has it infinite capabilities. This apply to the components used in the Z-Match circuit too. Depending on the frequency, the power, the load, the value of the capacitors, the current flowing through the components and the voltage found on various parts of the circuit, will be very different. Because of the limitations imposed by the components, the power handling capabilities will be limited accordingly. A further work is needed in order to investigate these limitations related to the Z-Match circuit. Another further work would be desirable in order to investigate further the circuit losses because such an investigation has not been available for loads having reactive components [14]. When notable loss is entering into the game, the behaviour can differ in a sensible manner from the loss less case.

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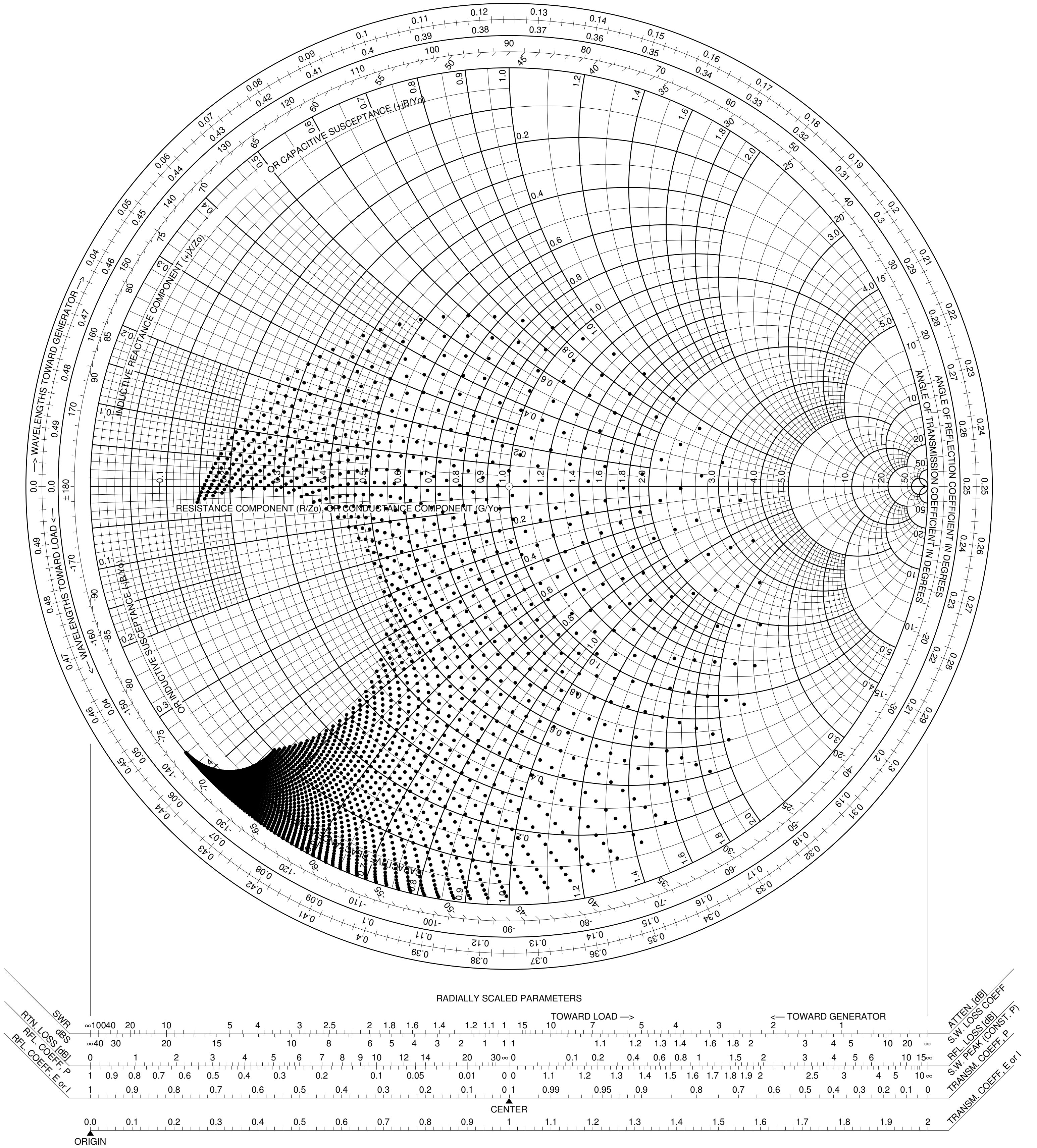
at 3.500 MHz, 3 turn secondary



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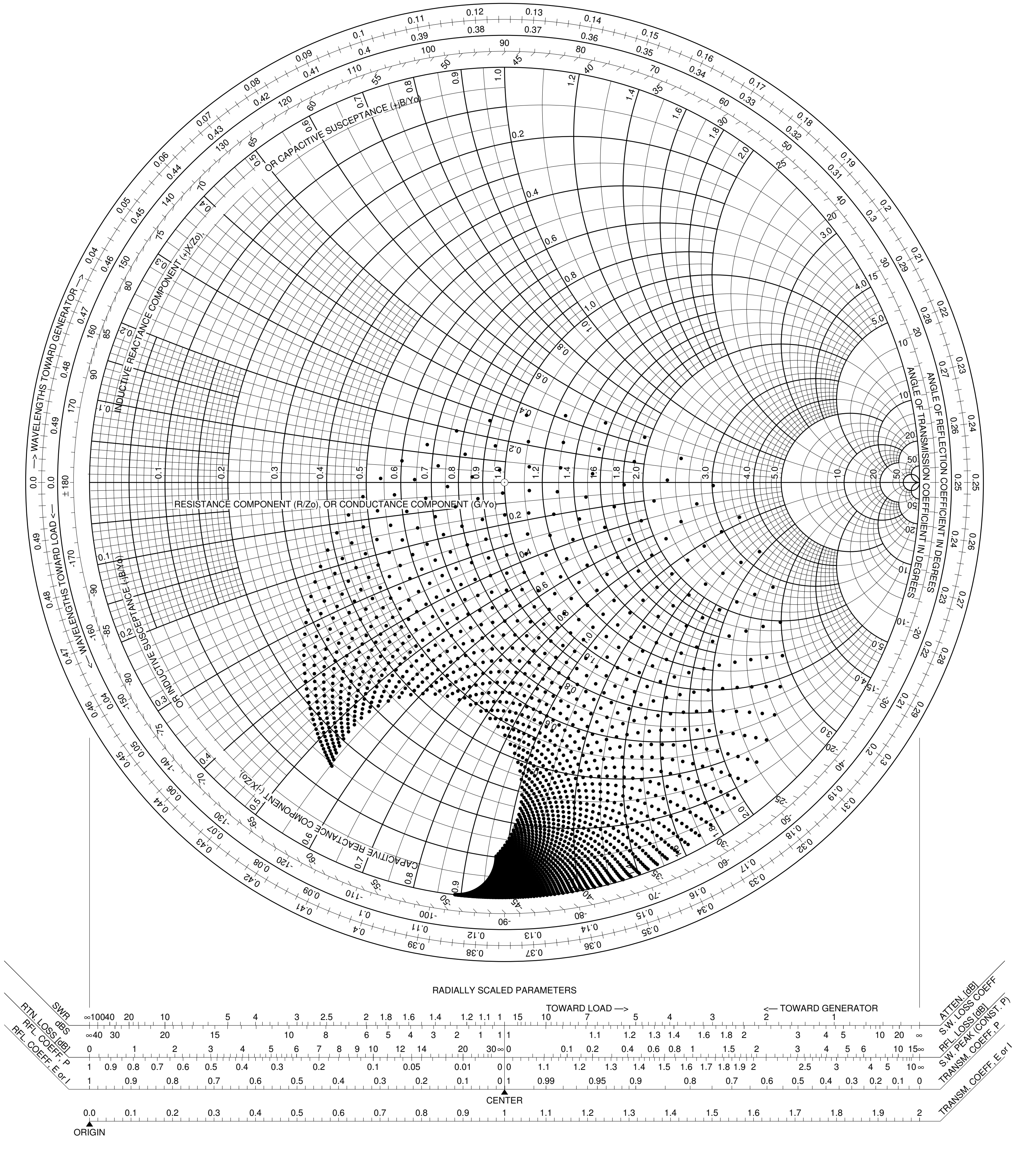

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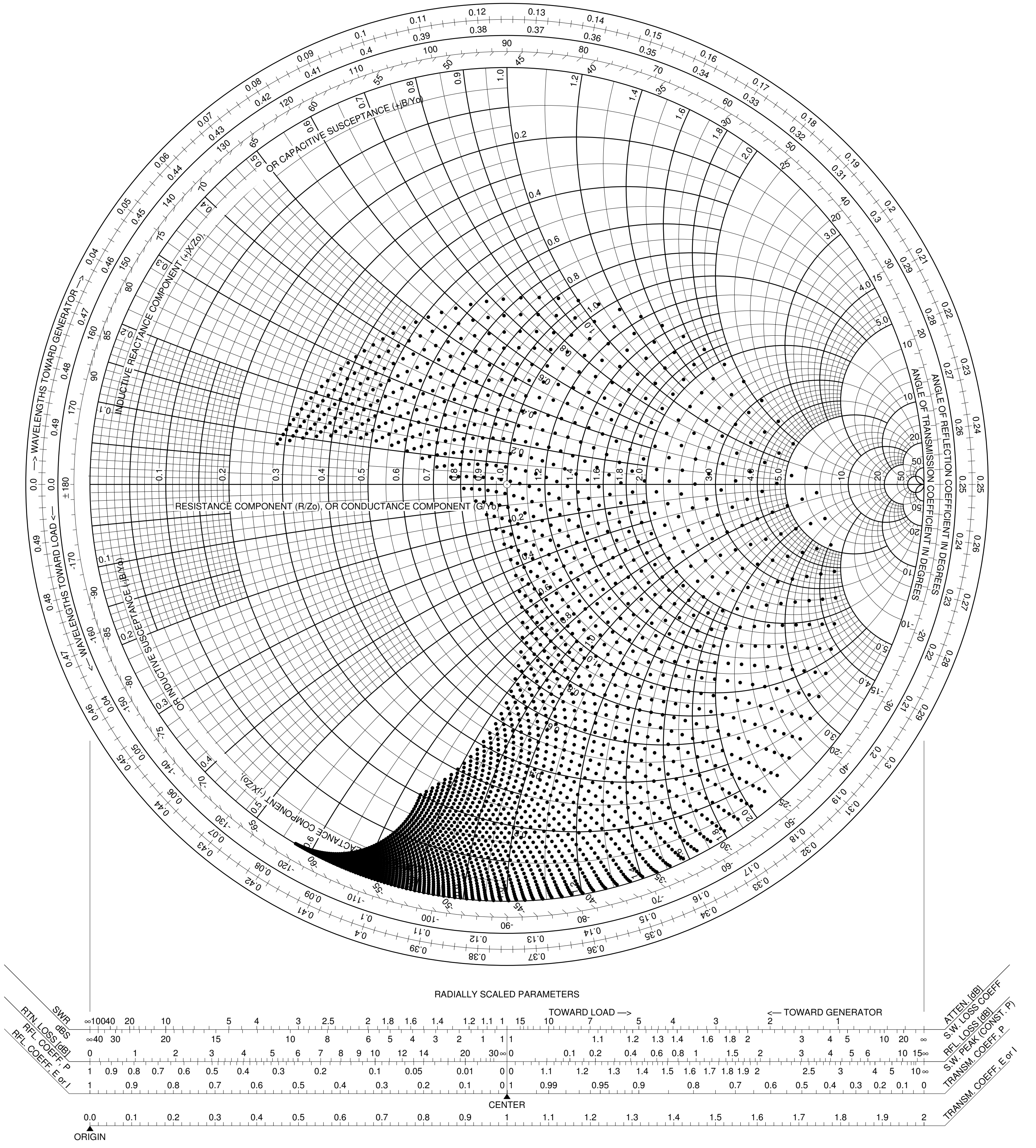

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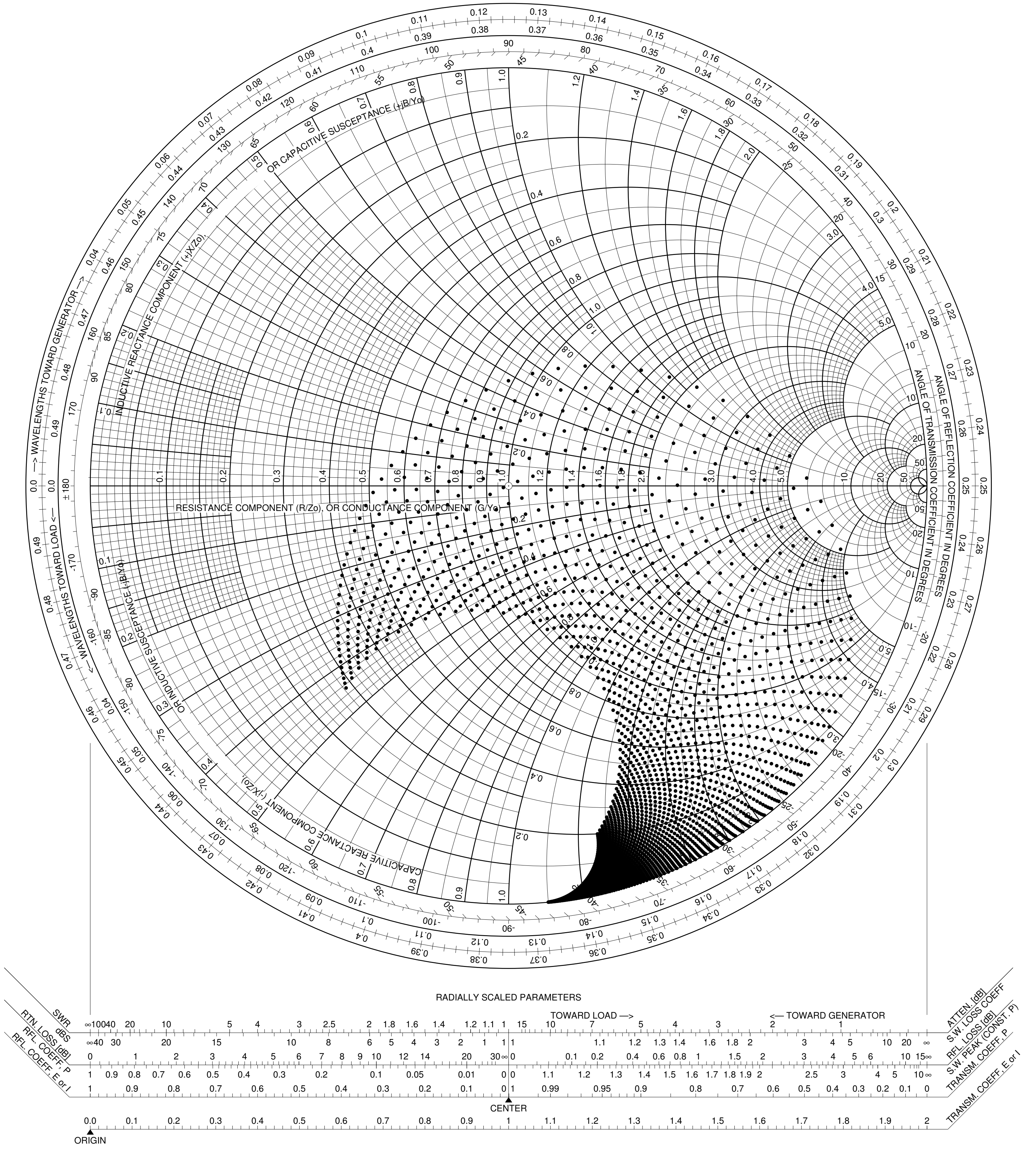
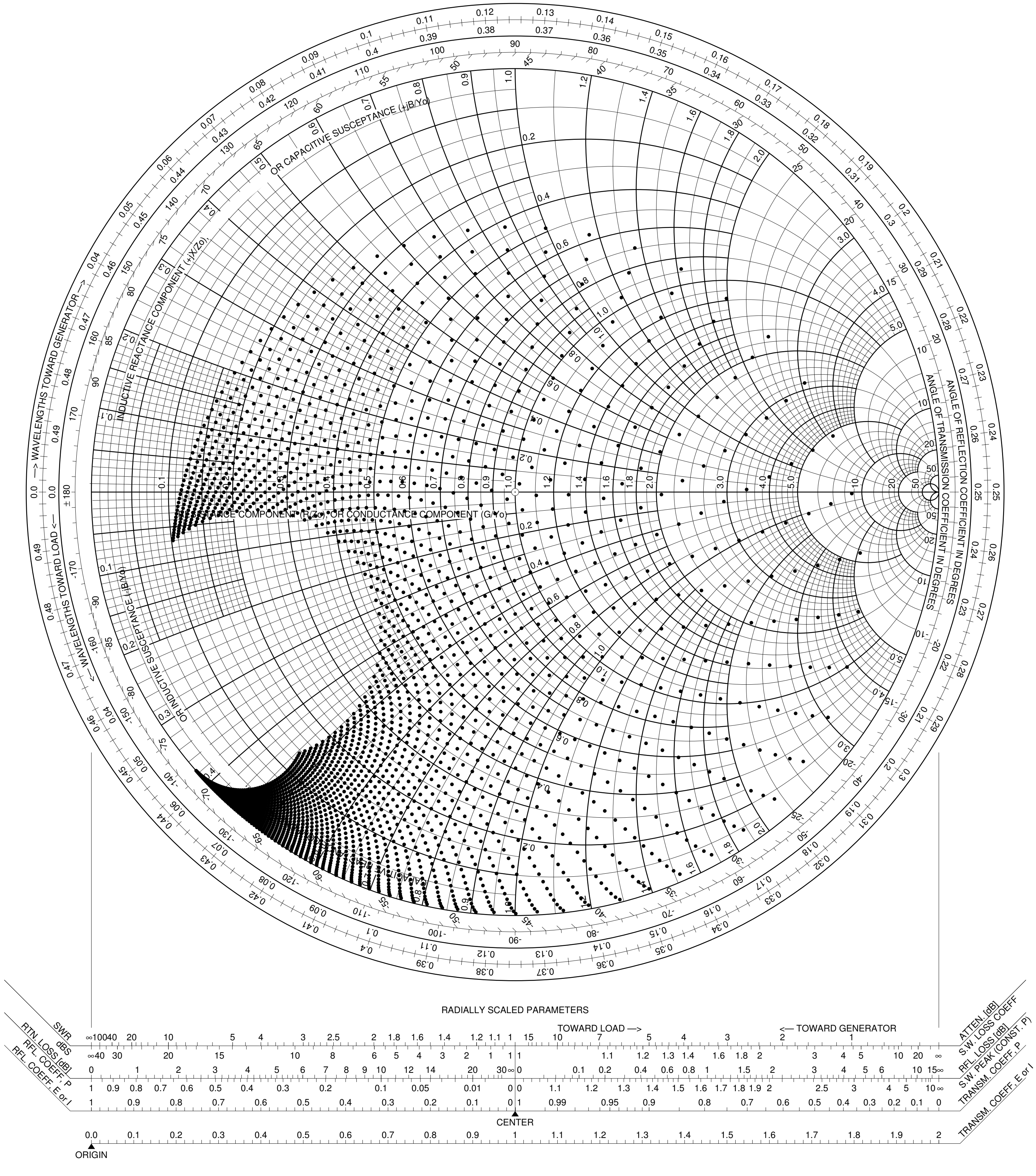


at 3.650 MHz, 3 turn secondary



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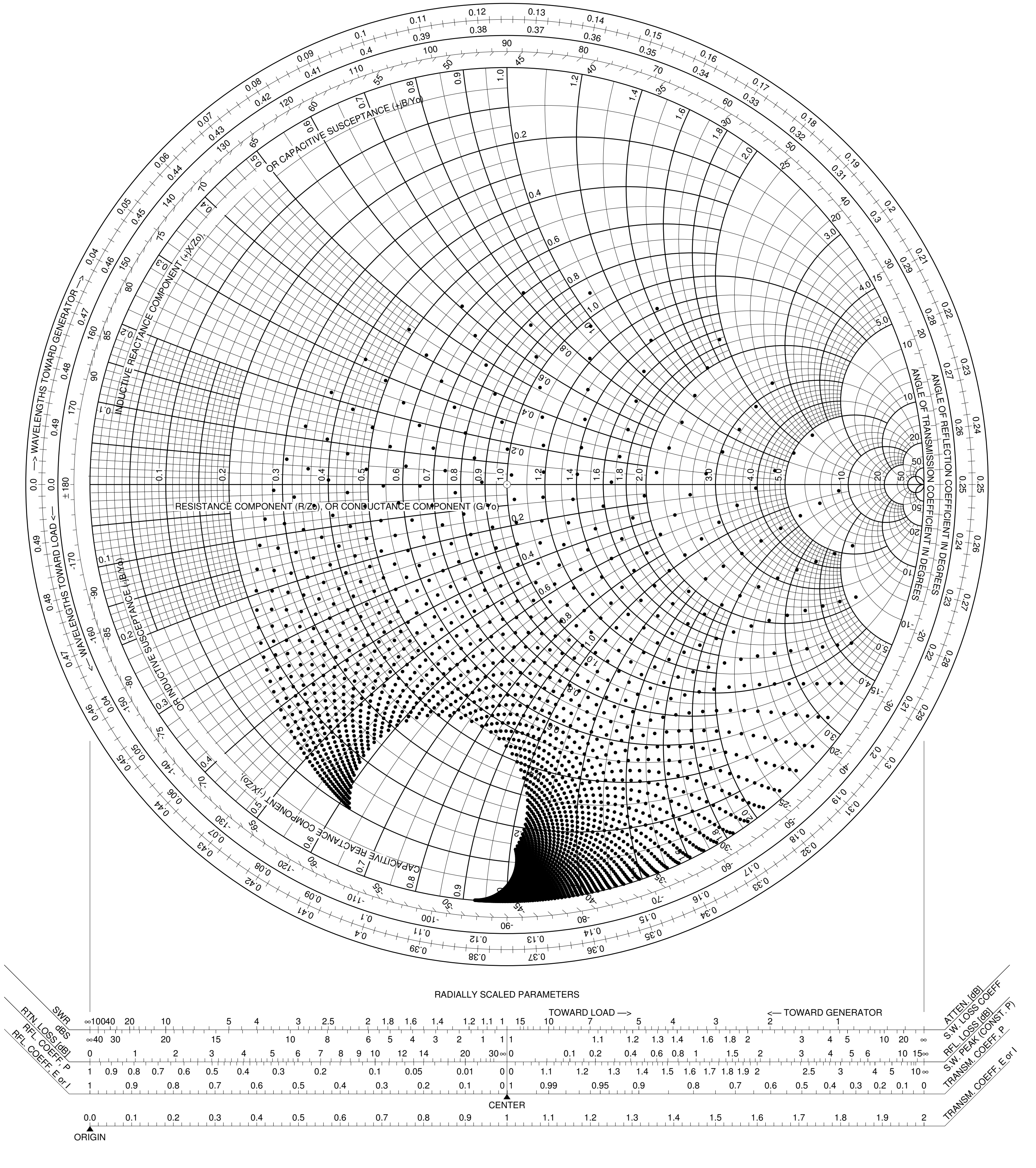

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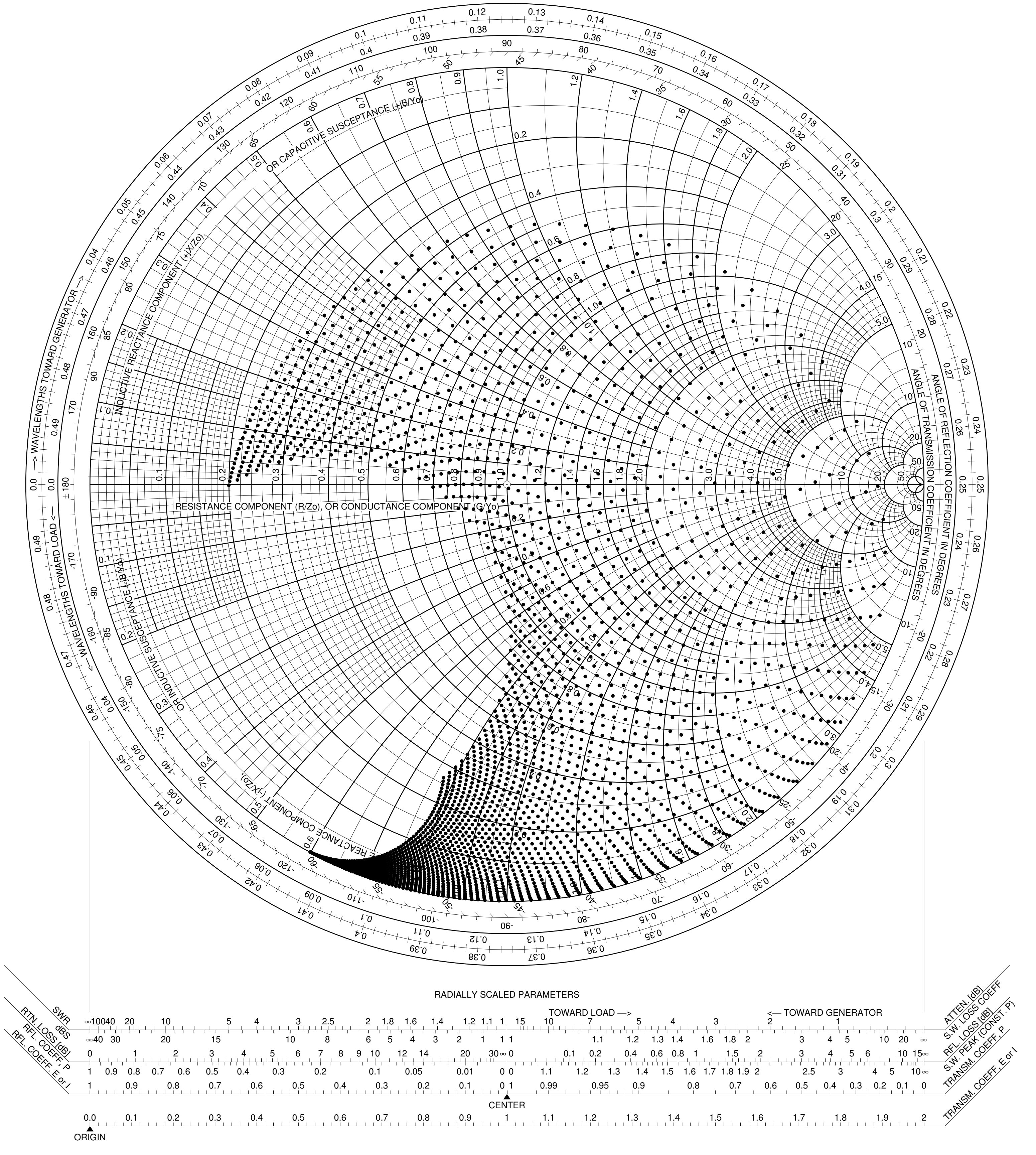

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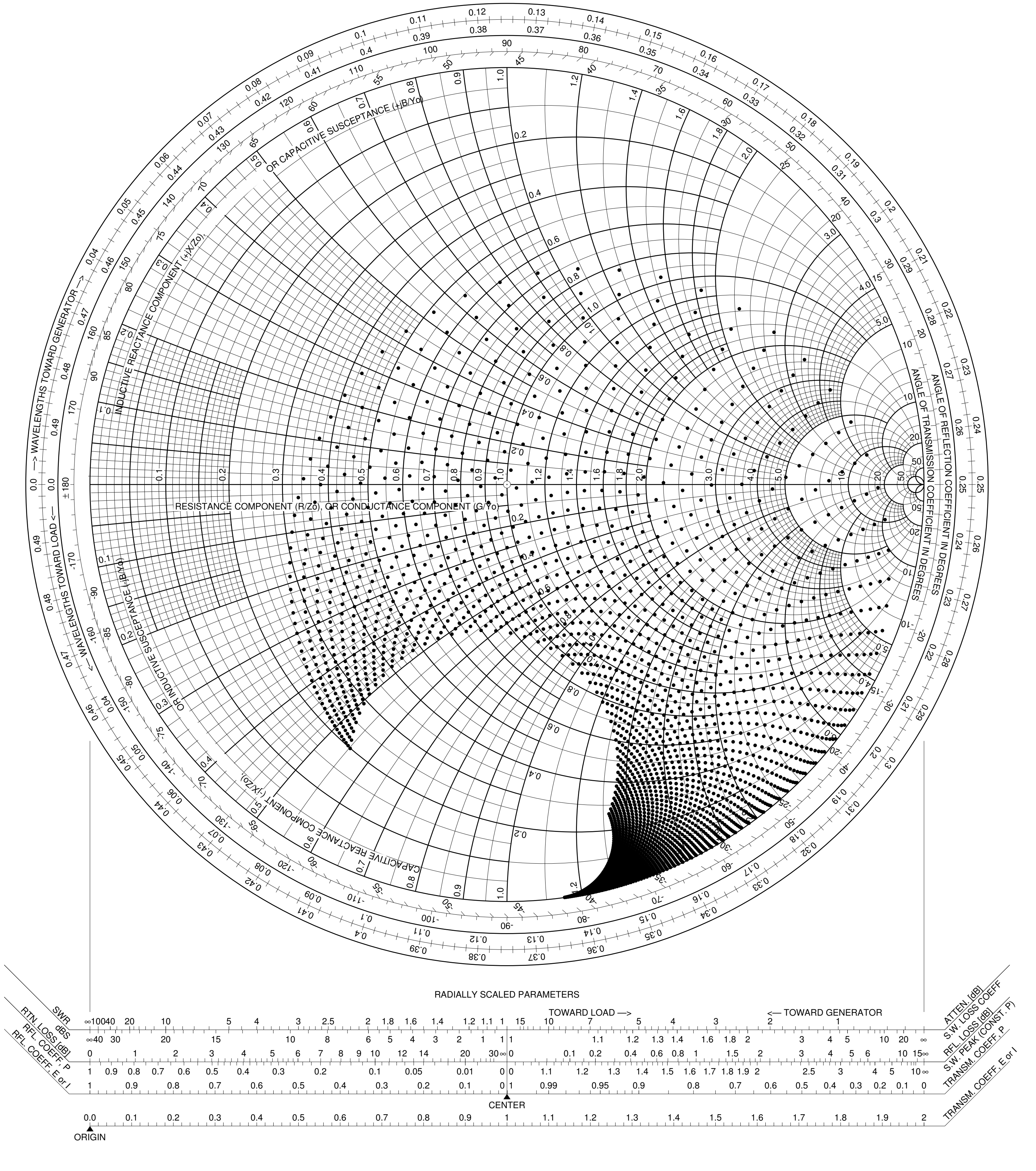

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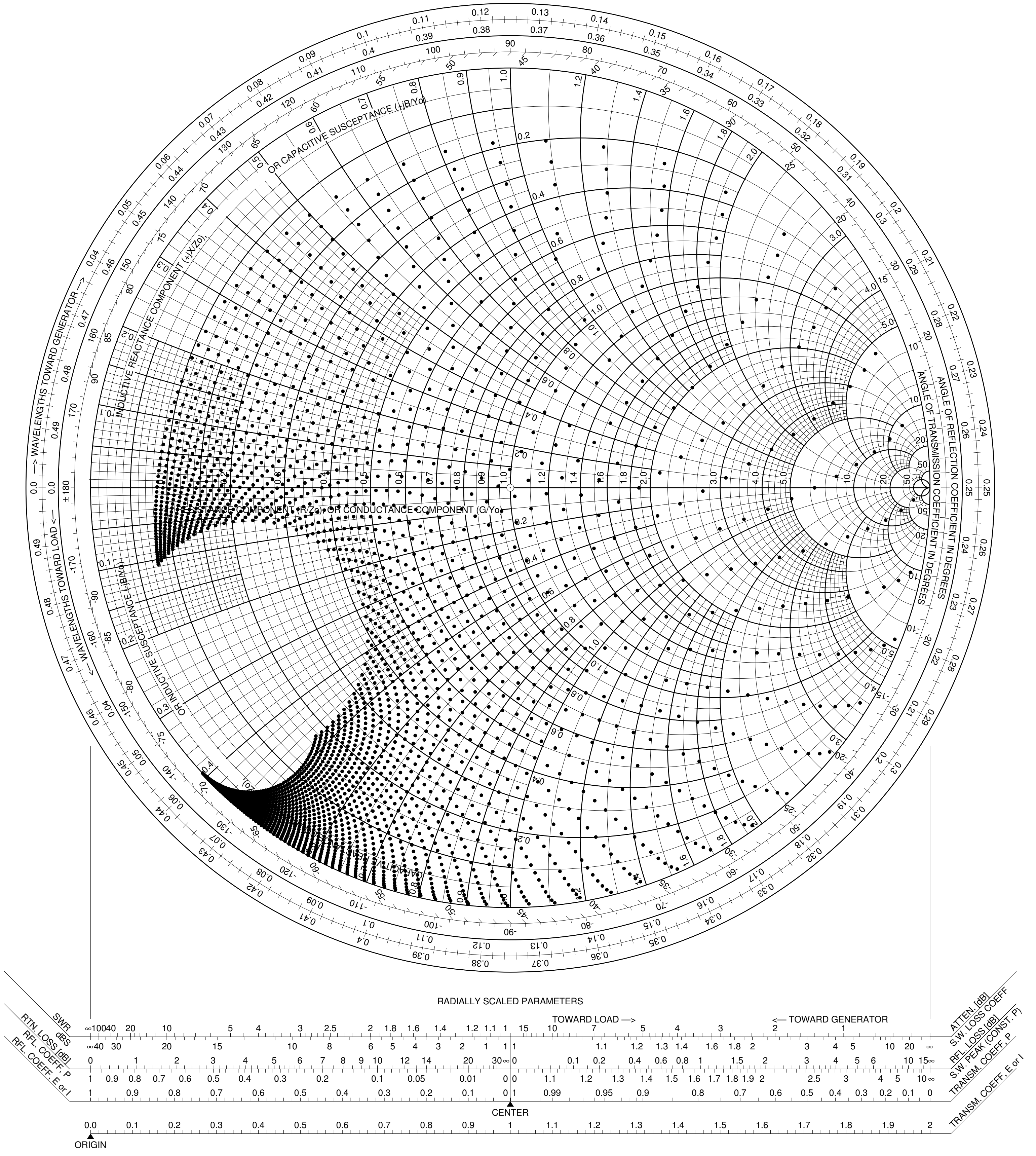

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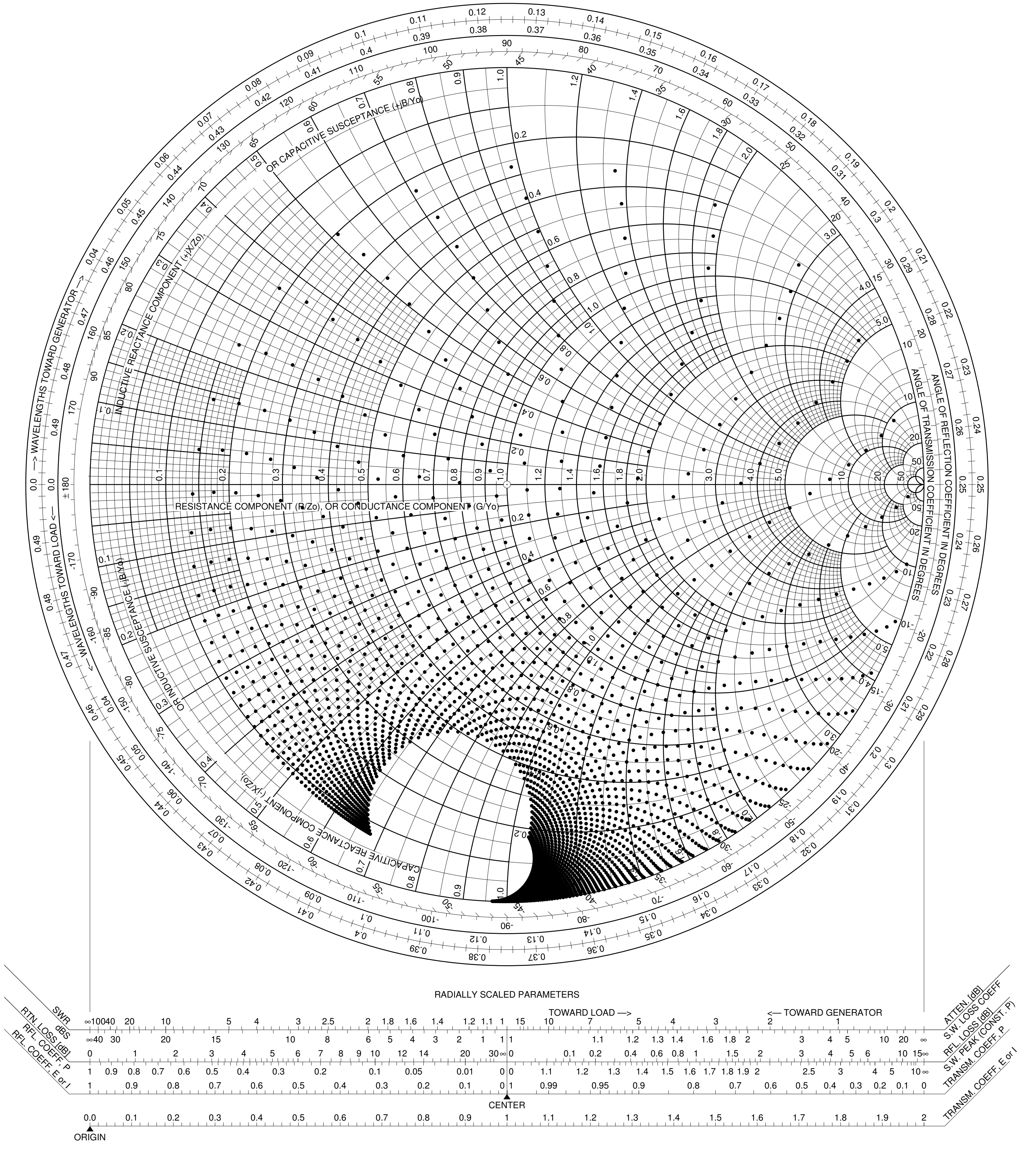

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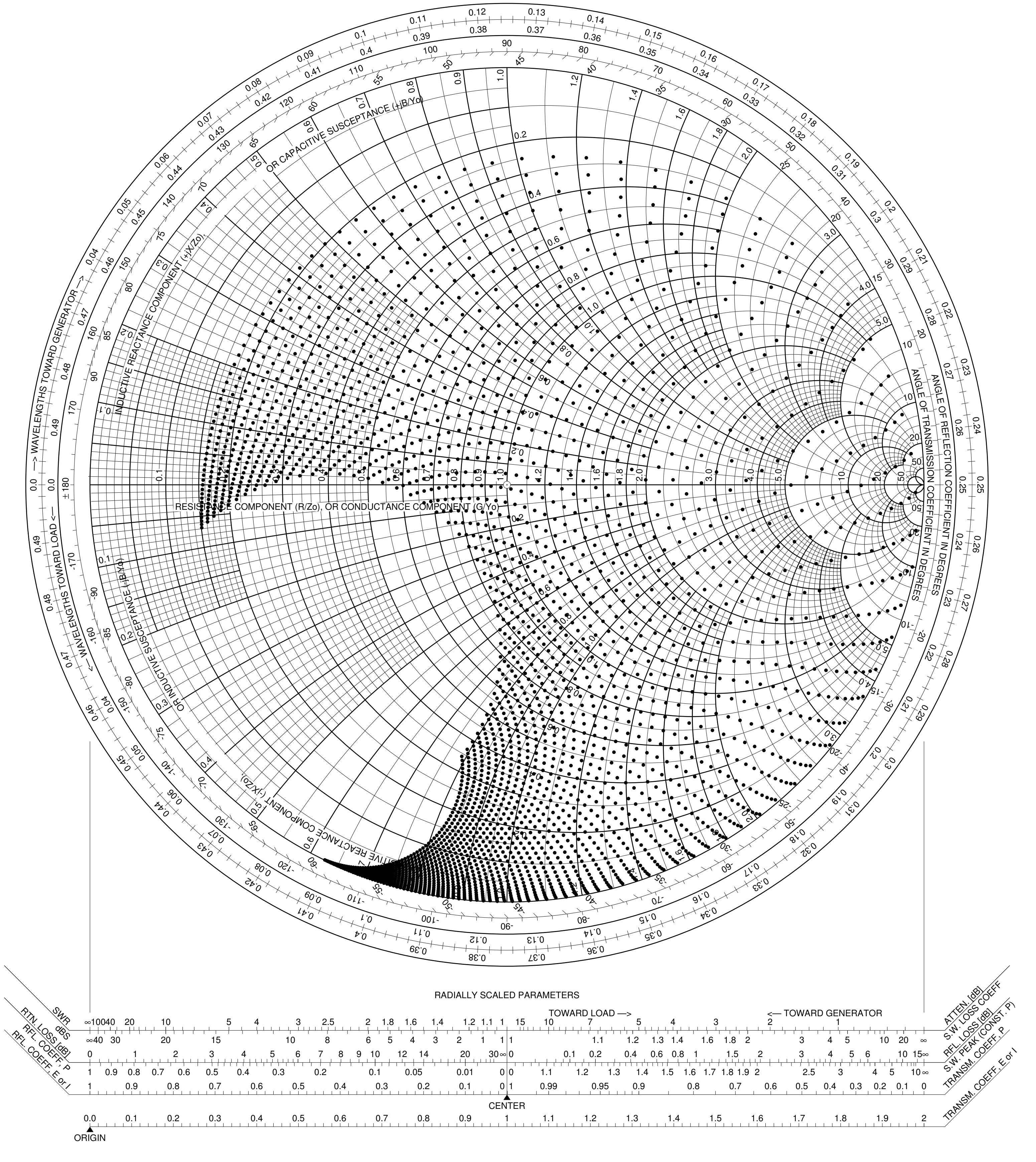

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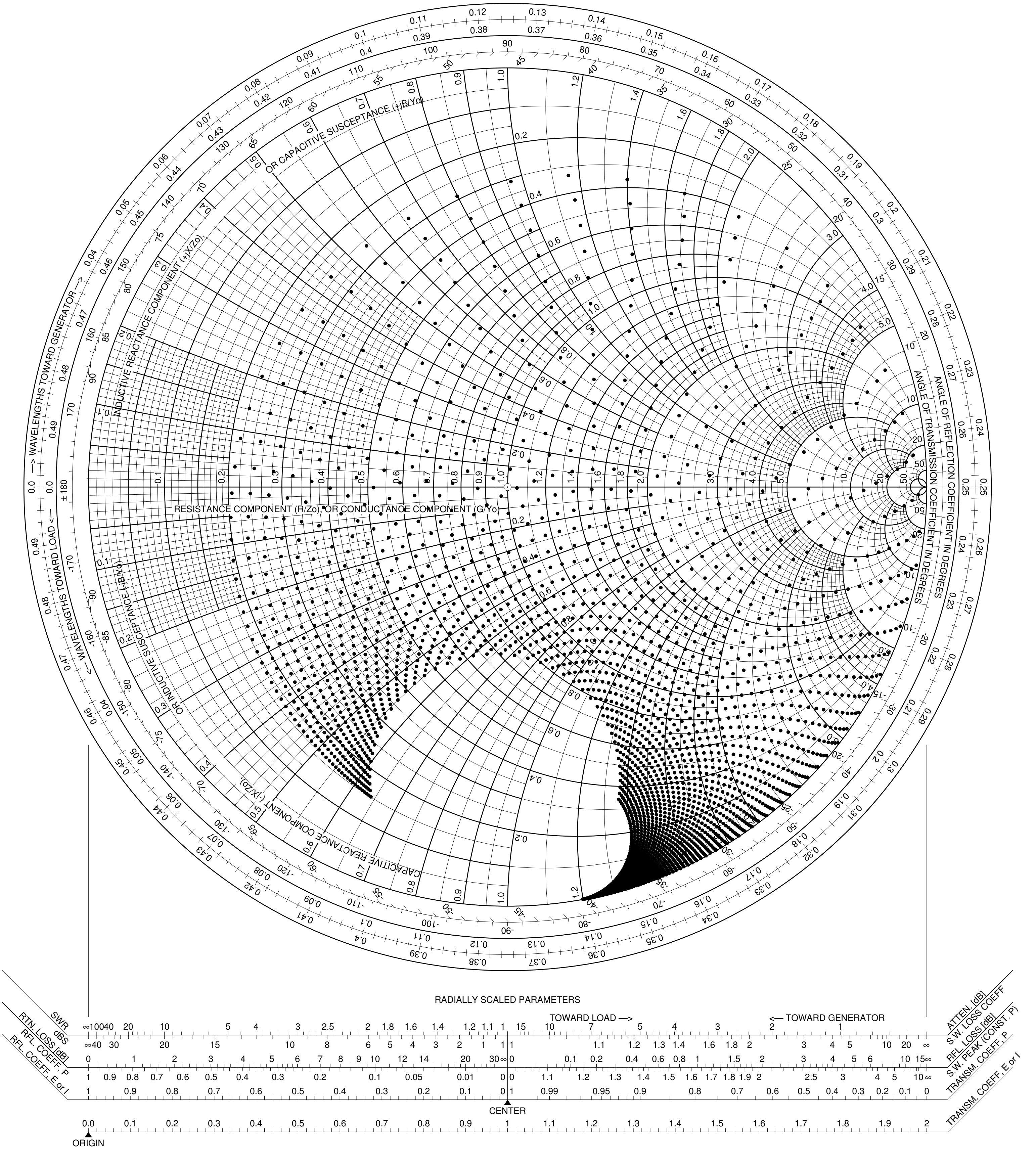

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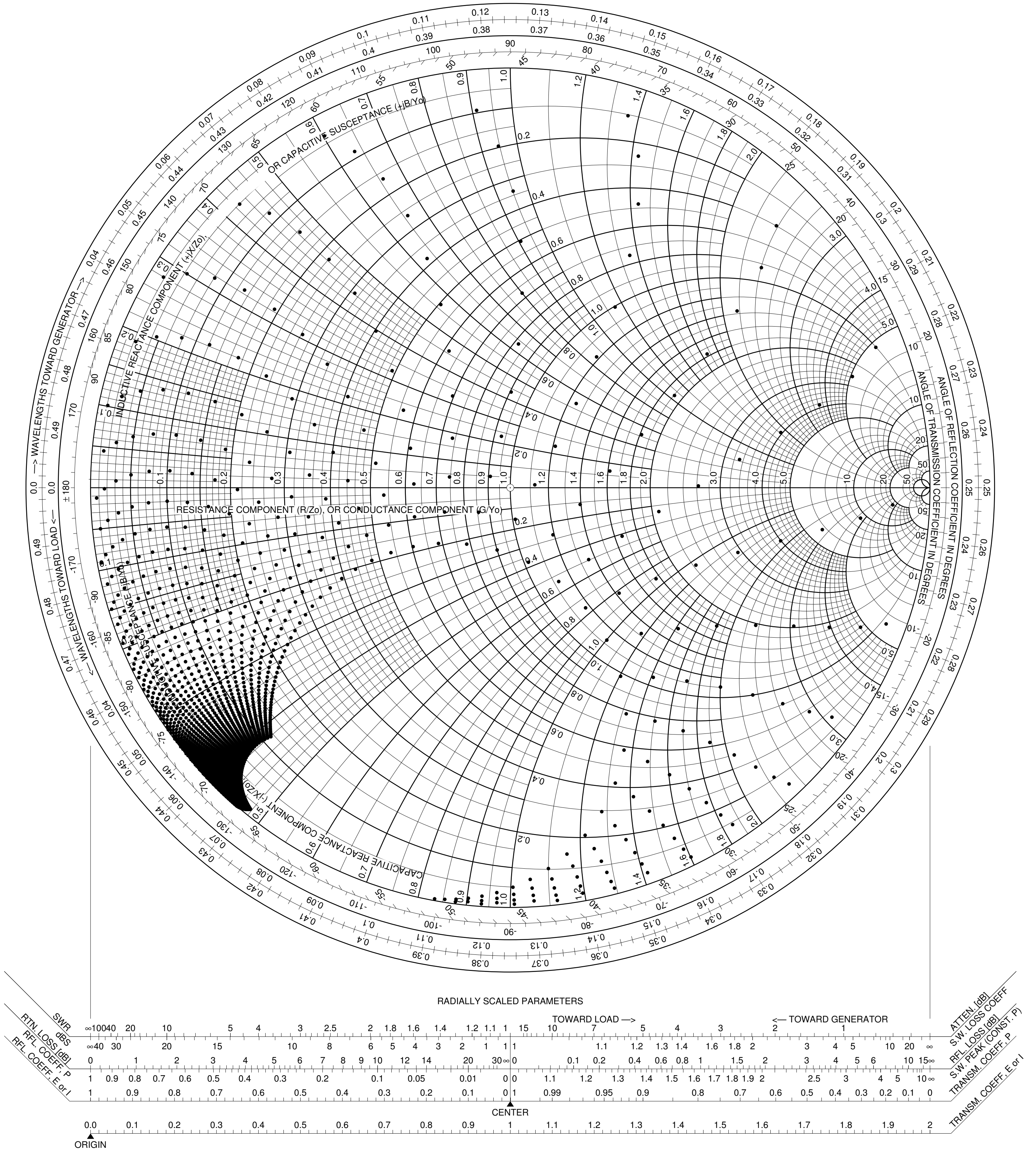

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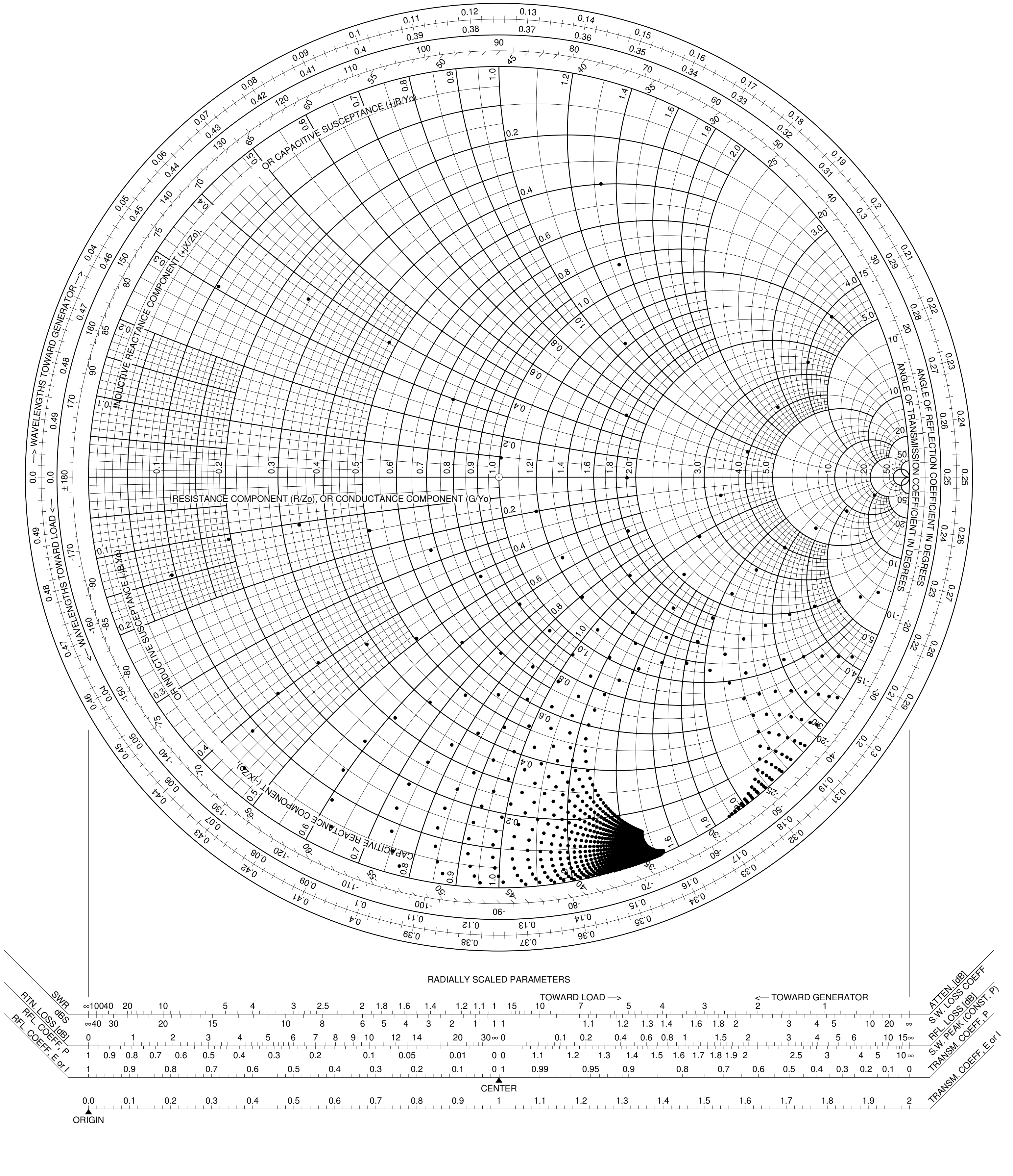

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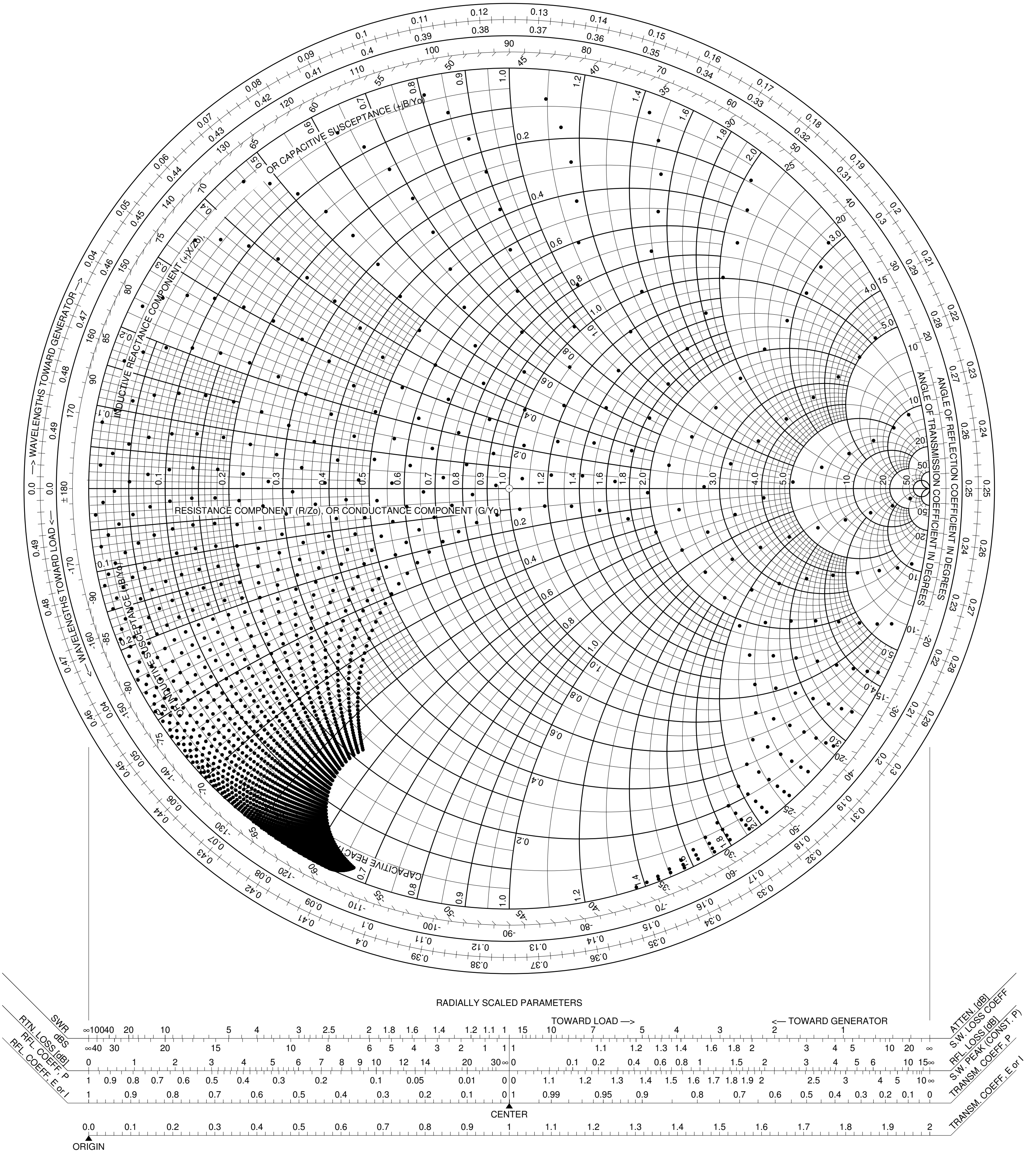

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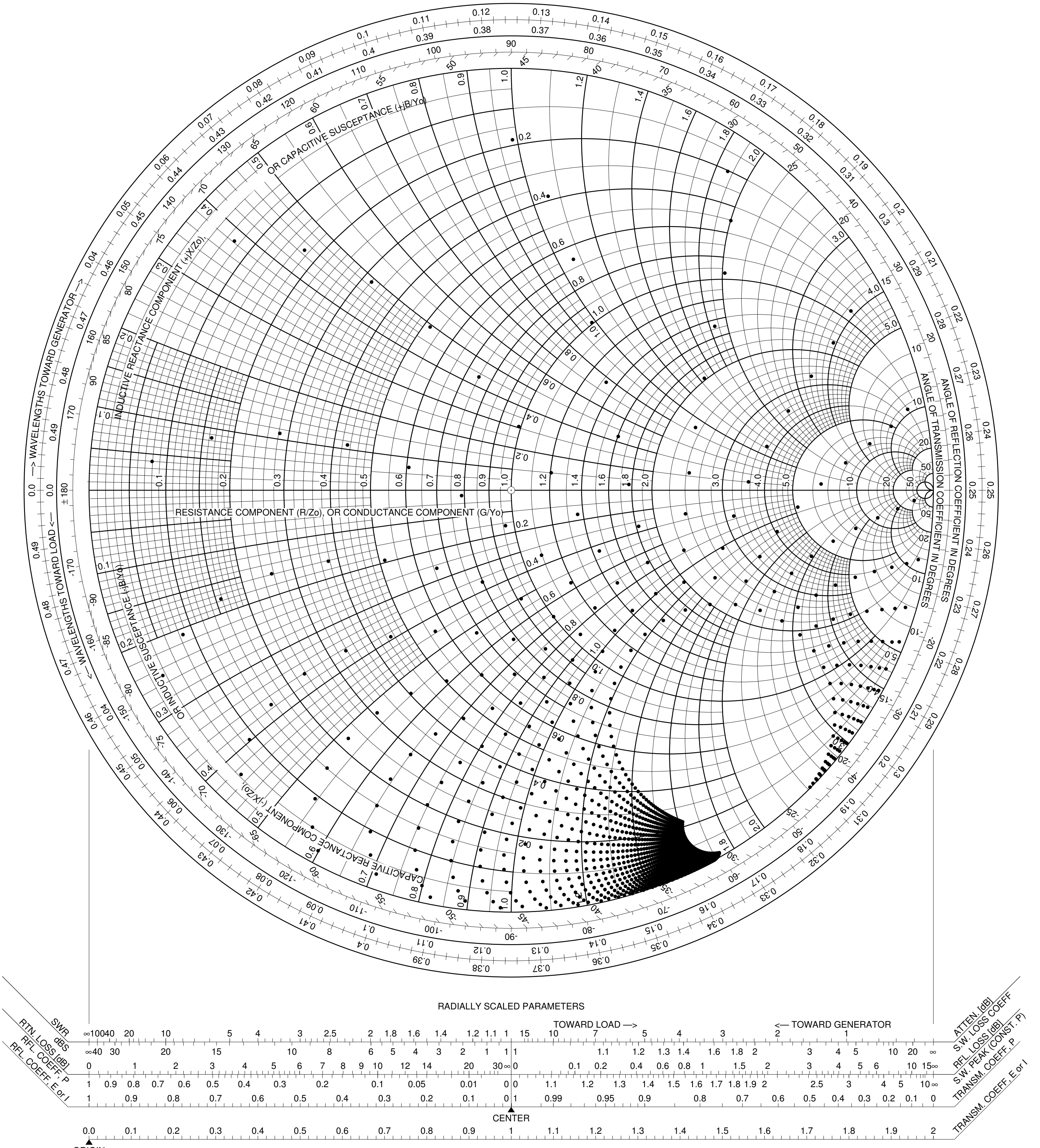

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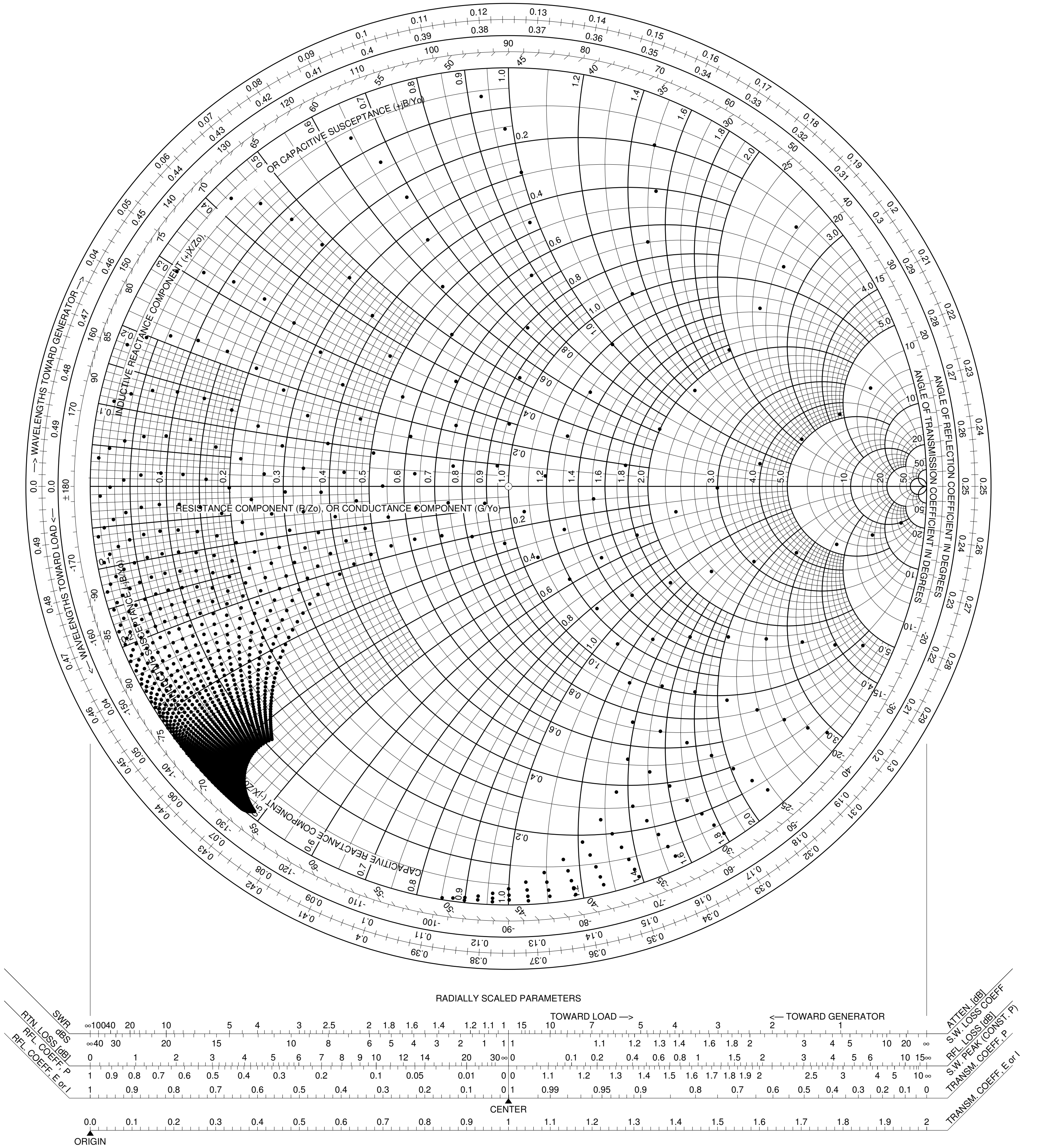

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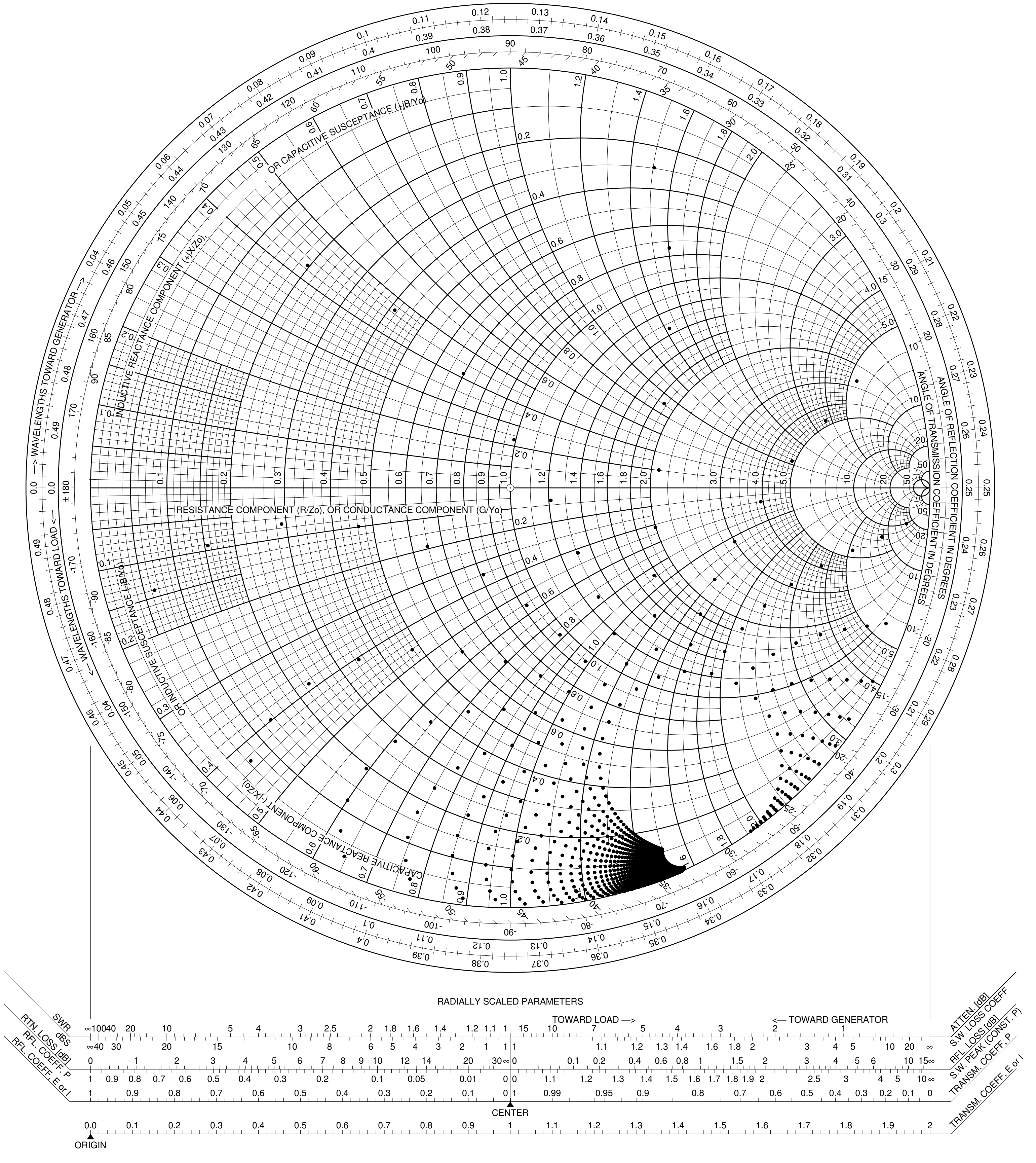

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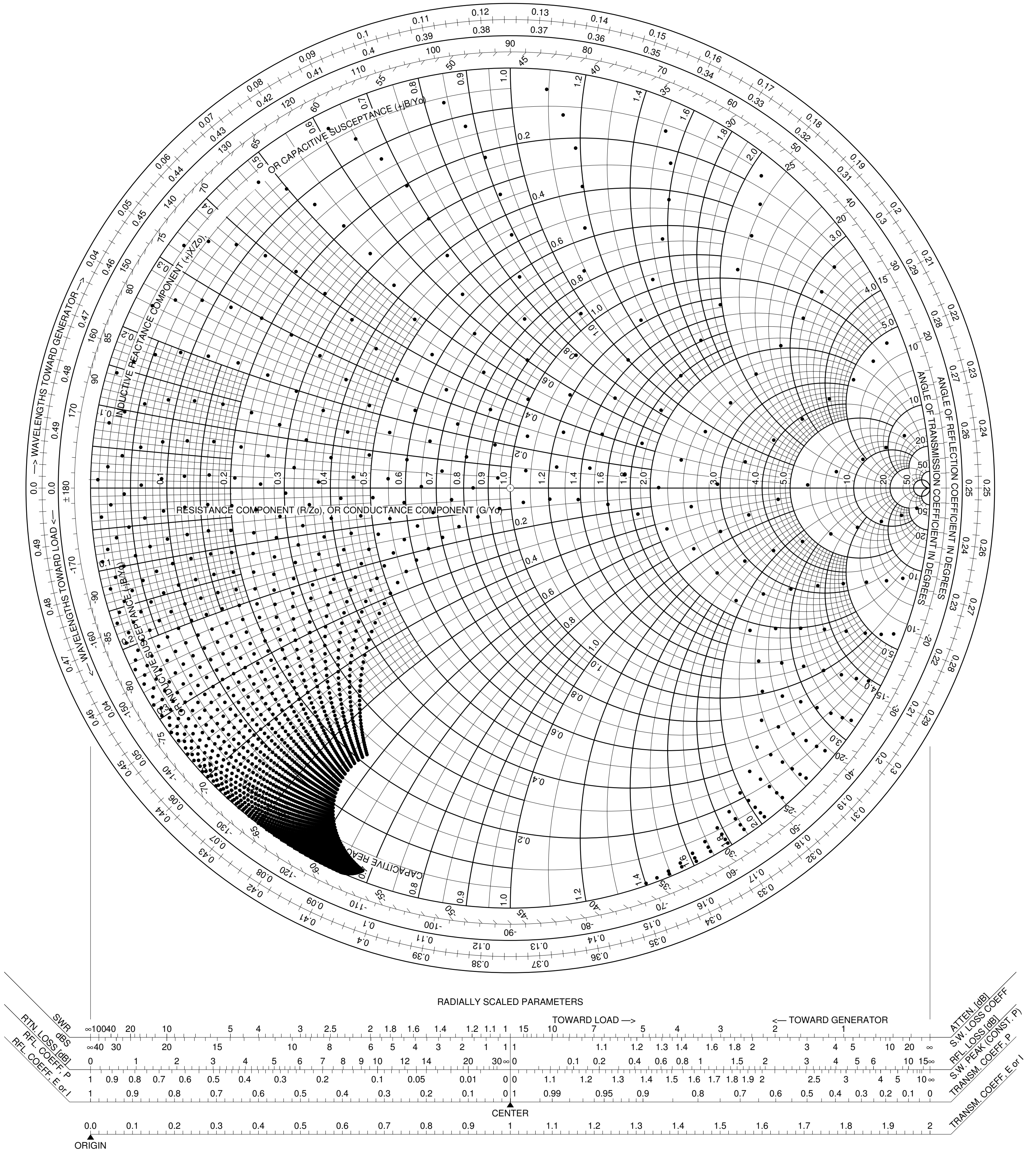

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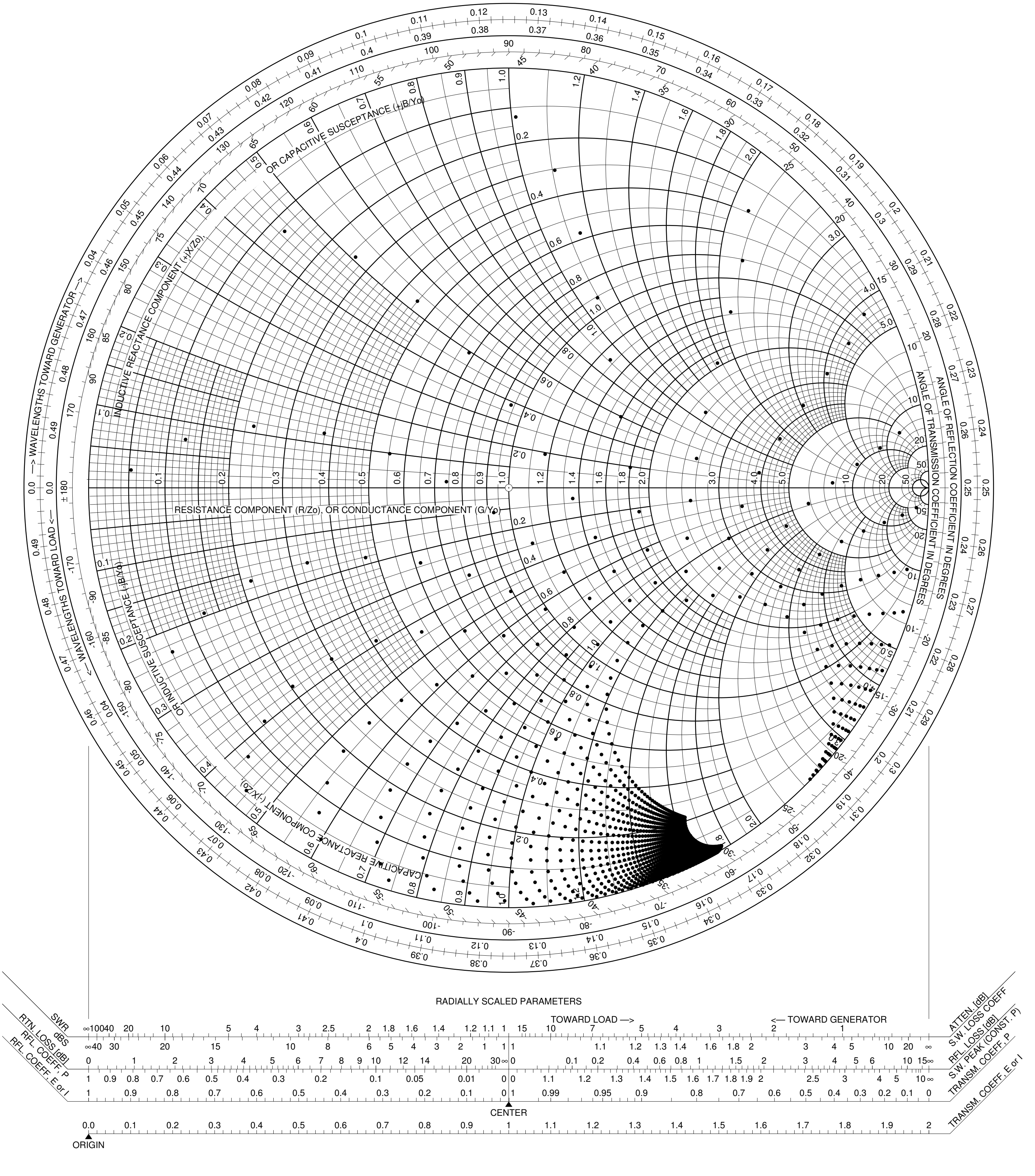

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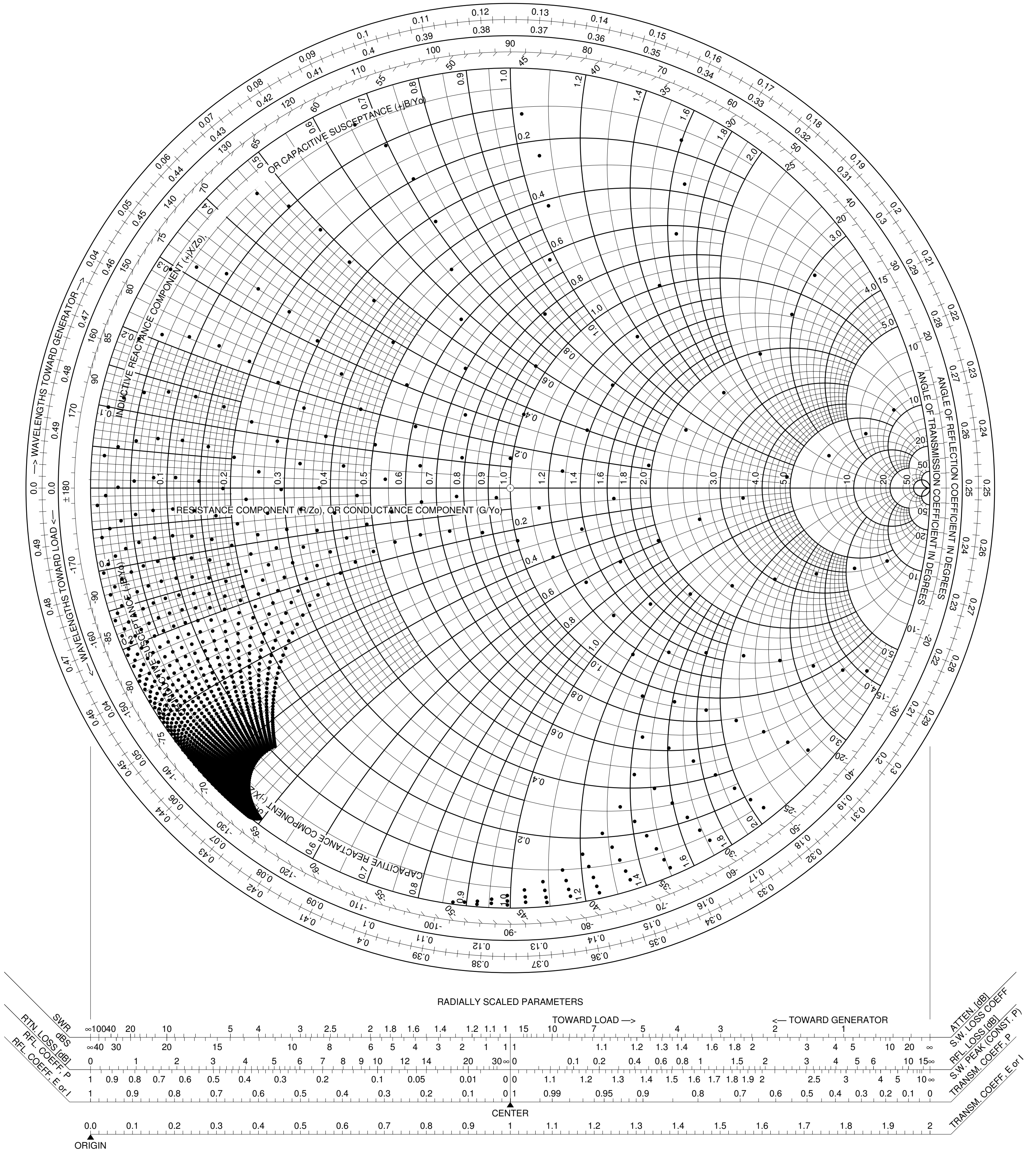

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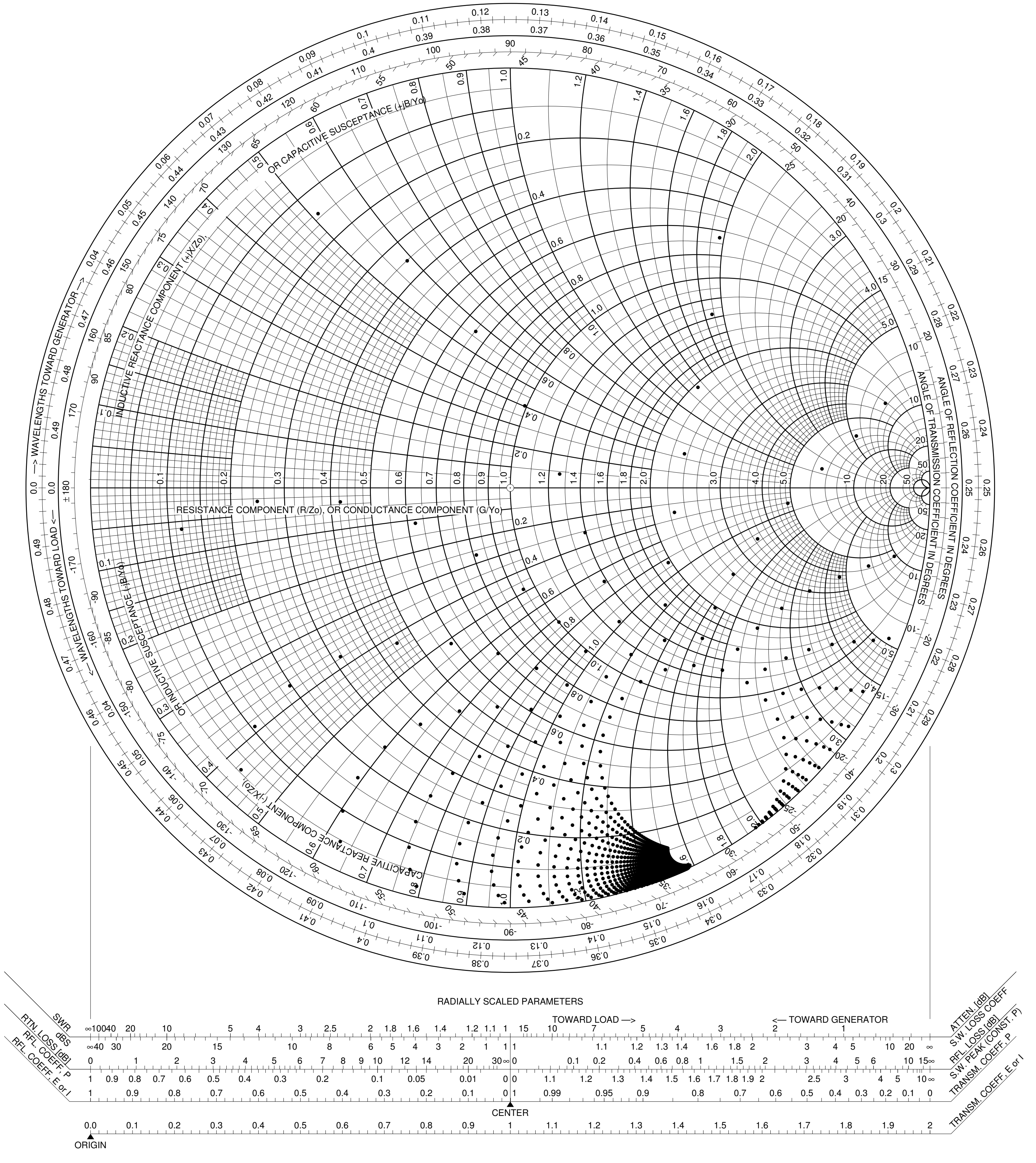

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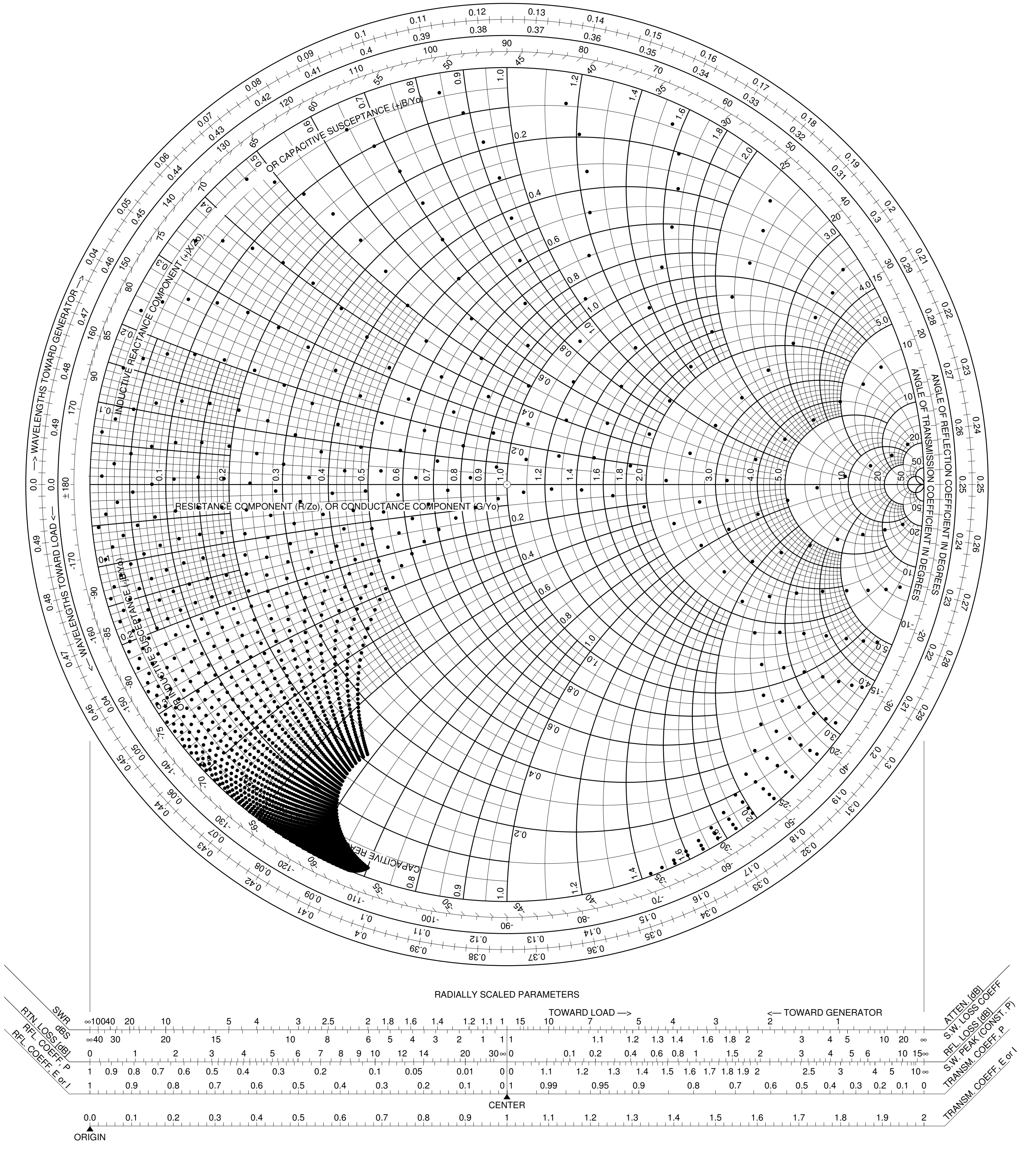

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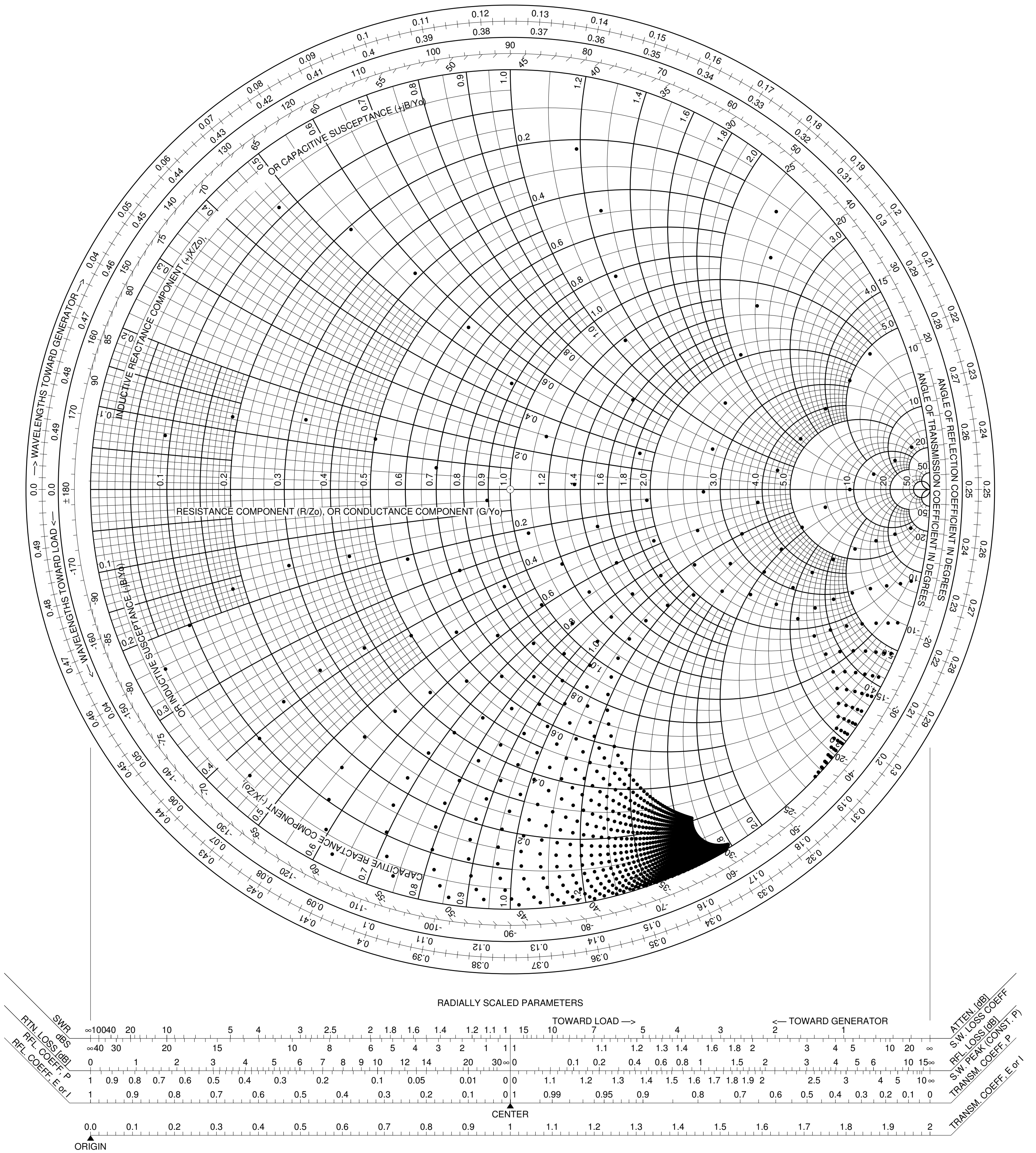

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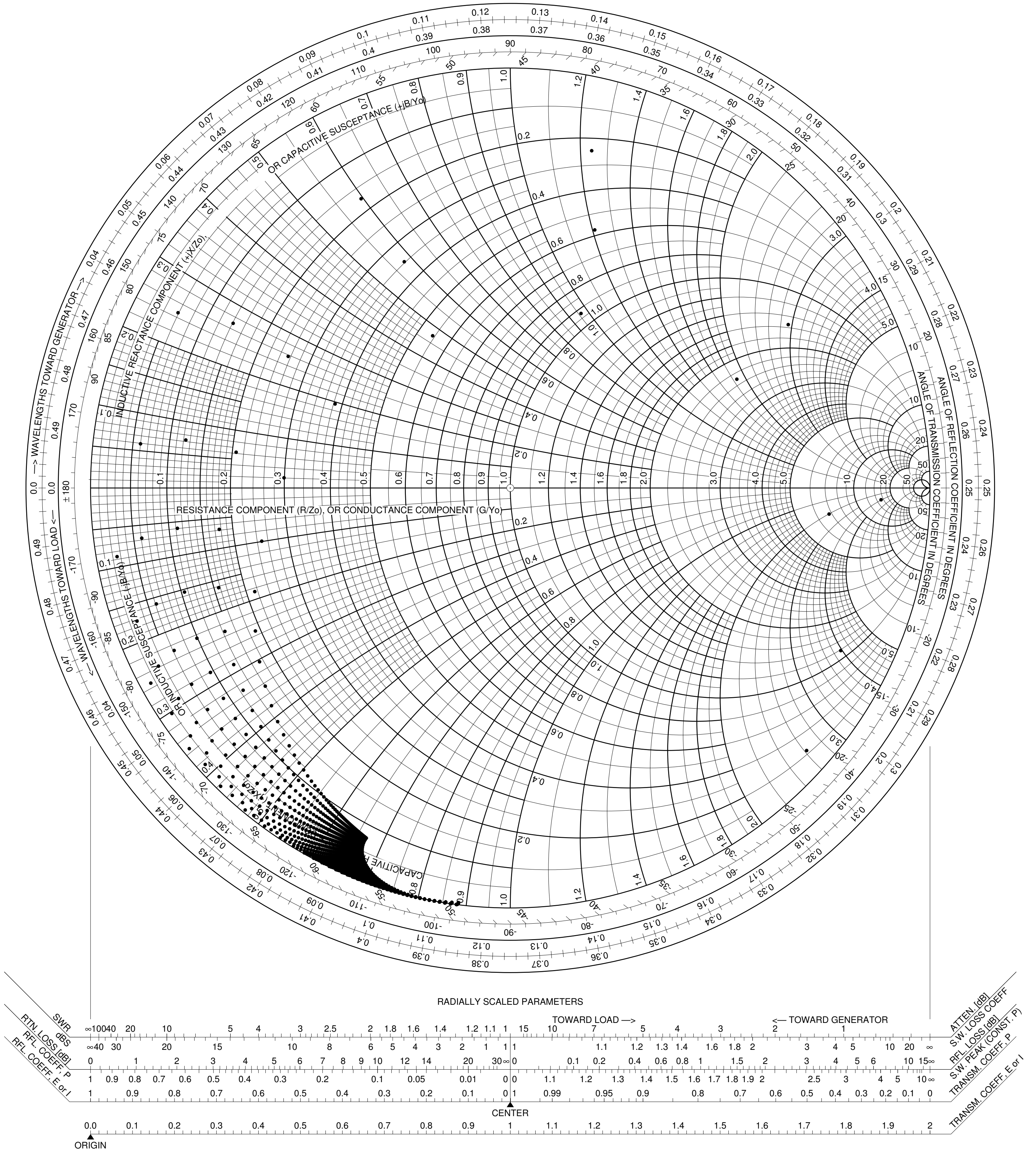

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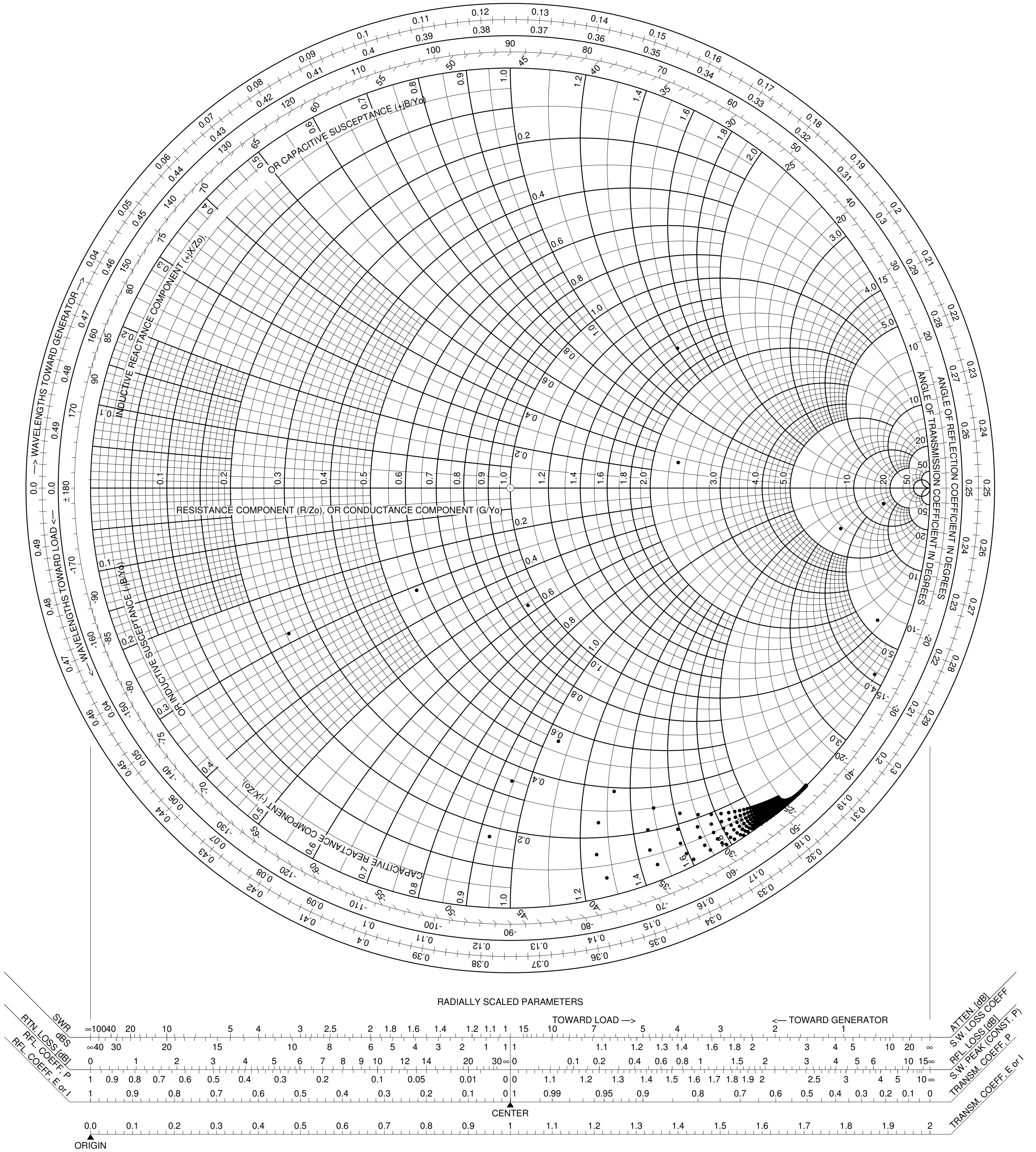

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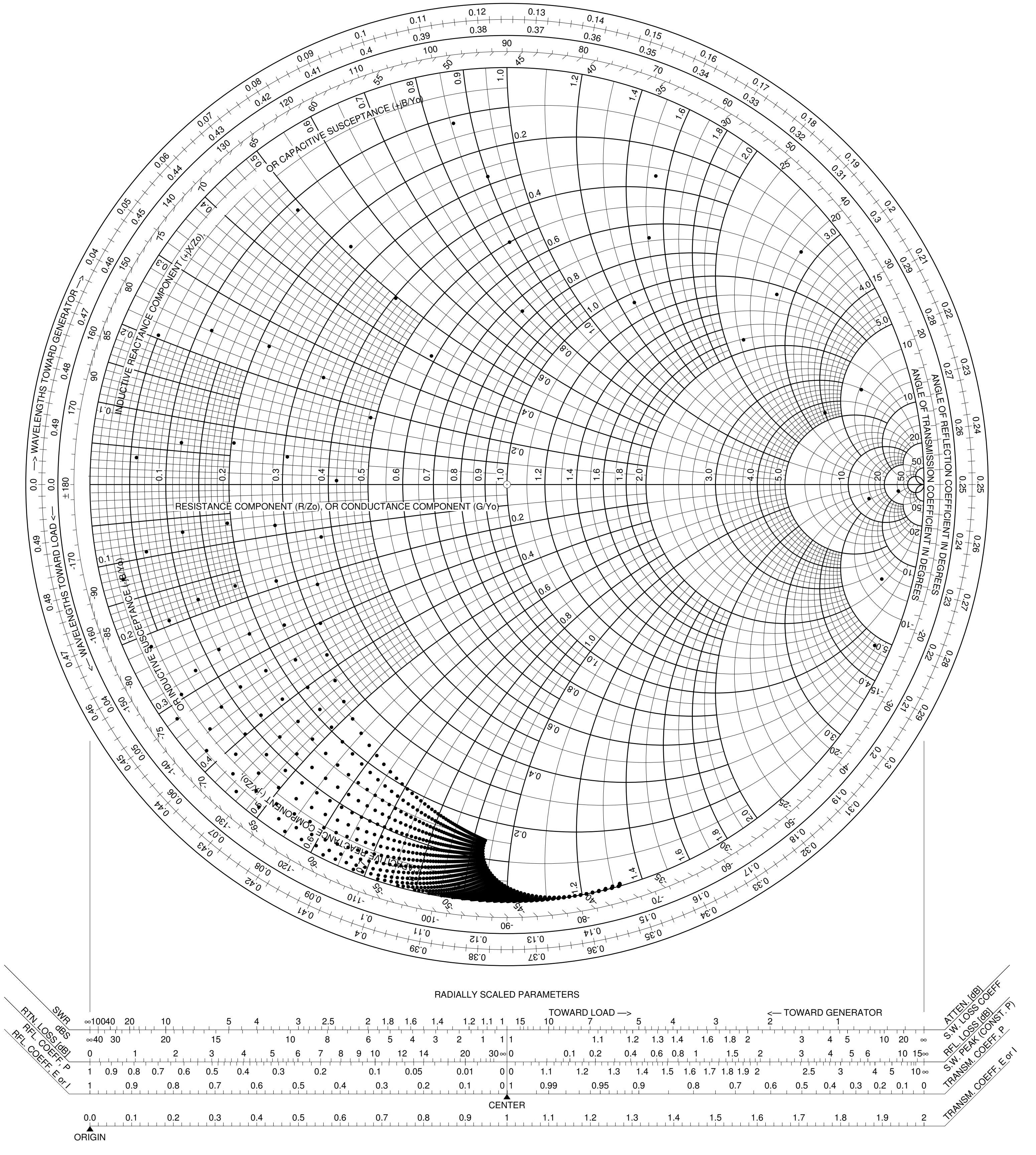

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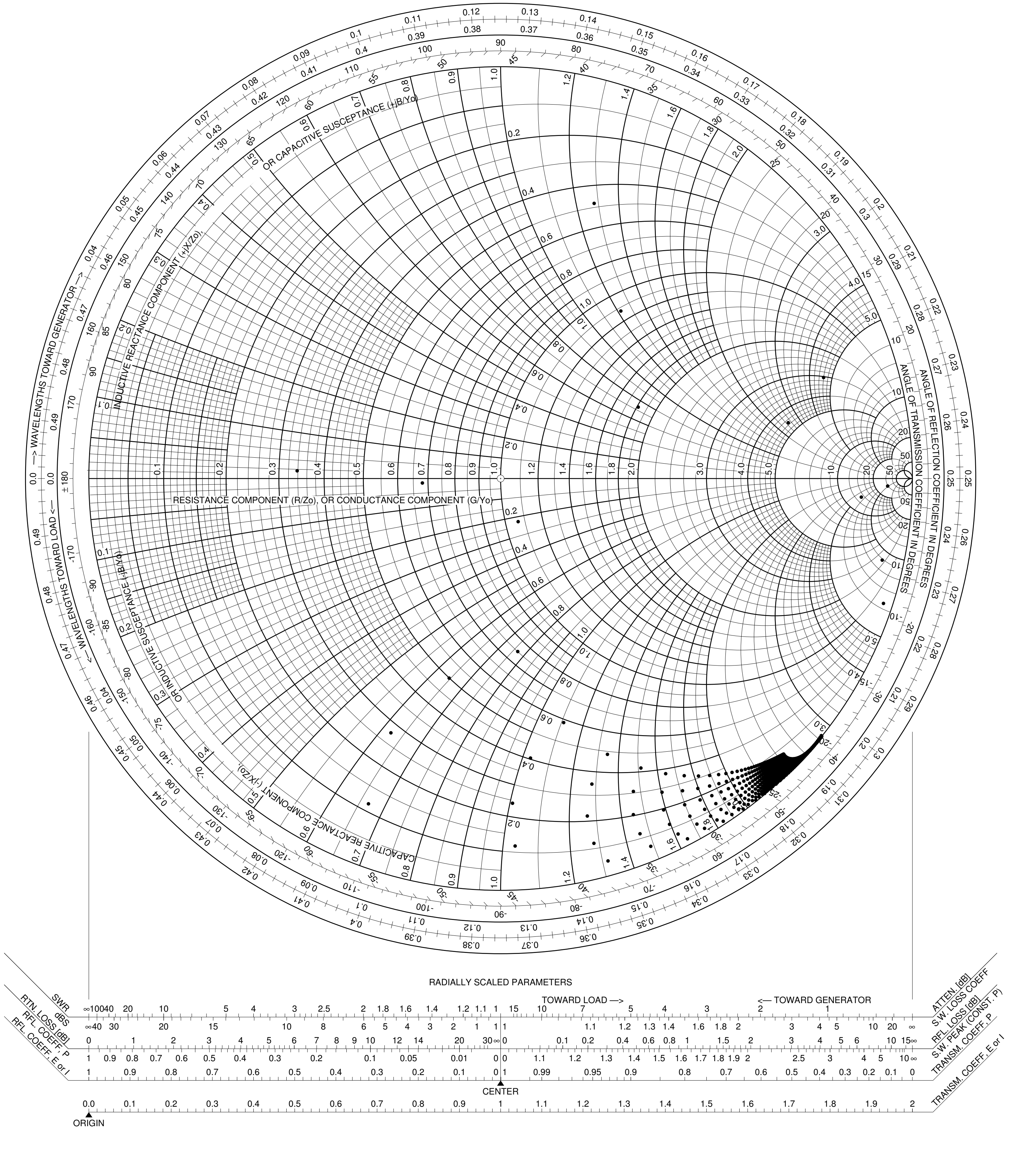

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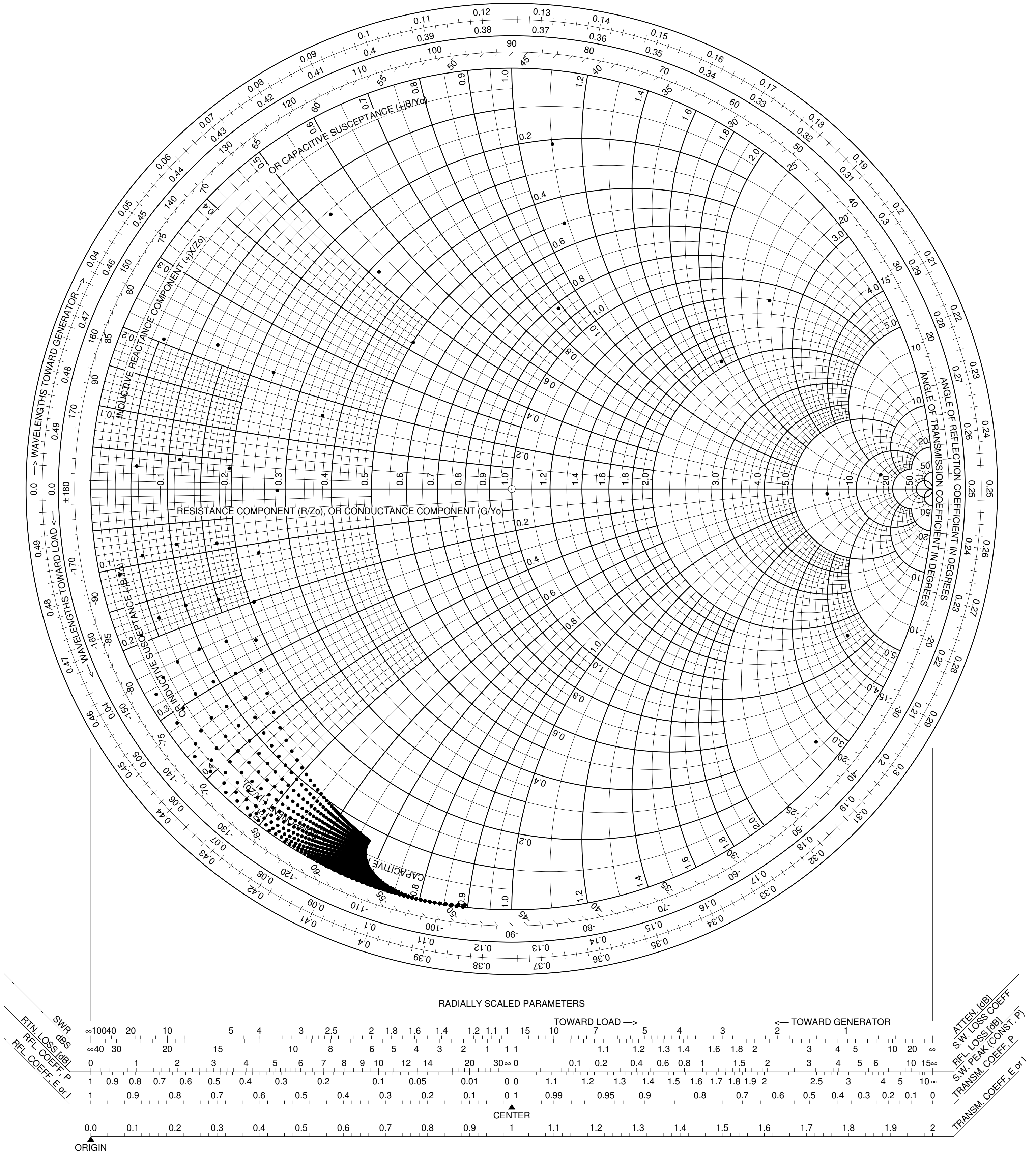

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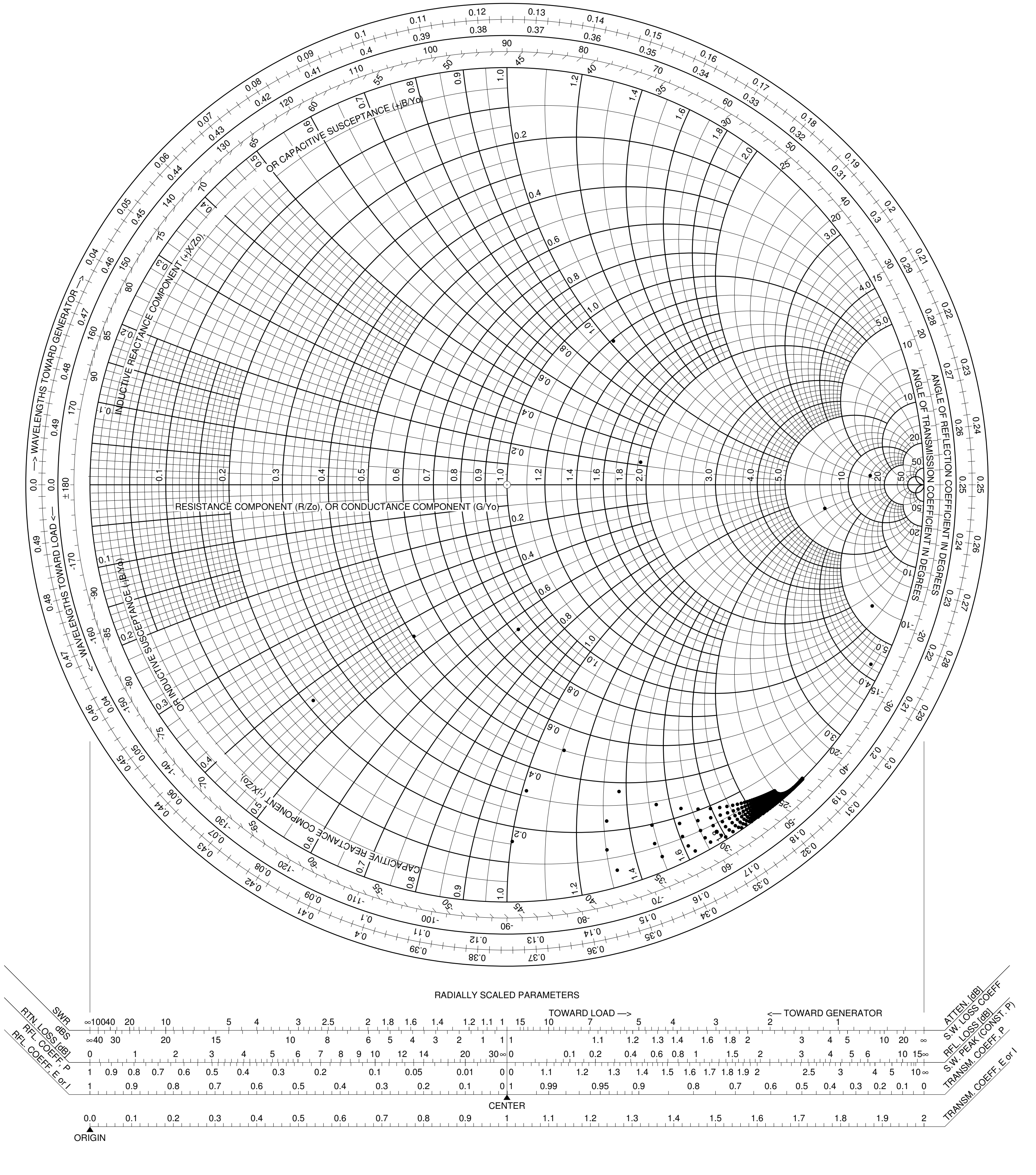
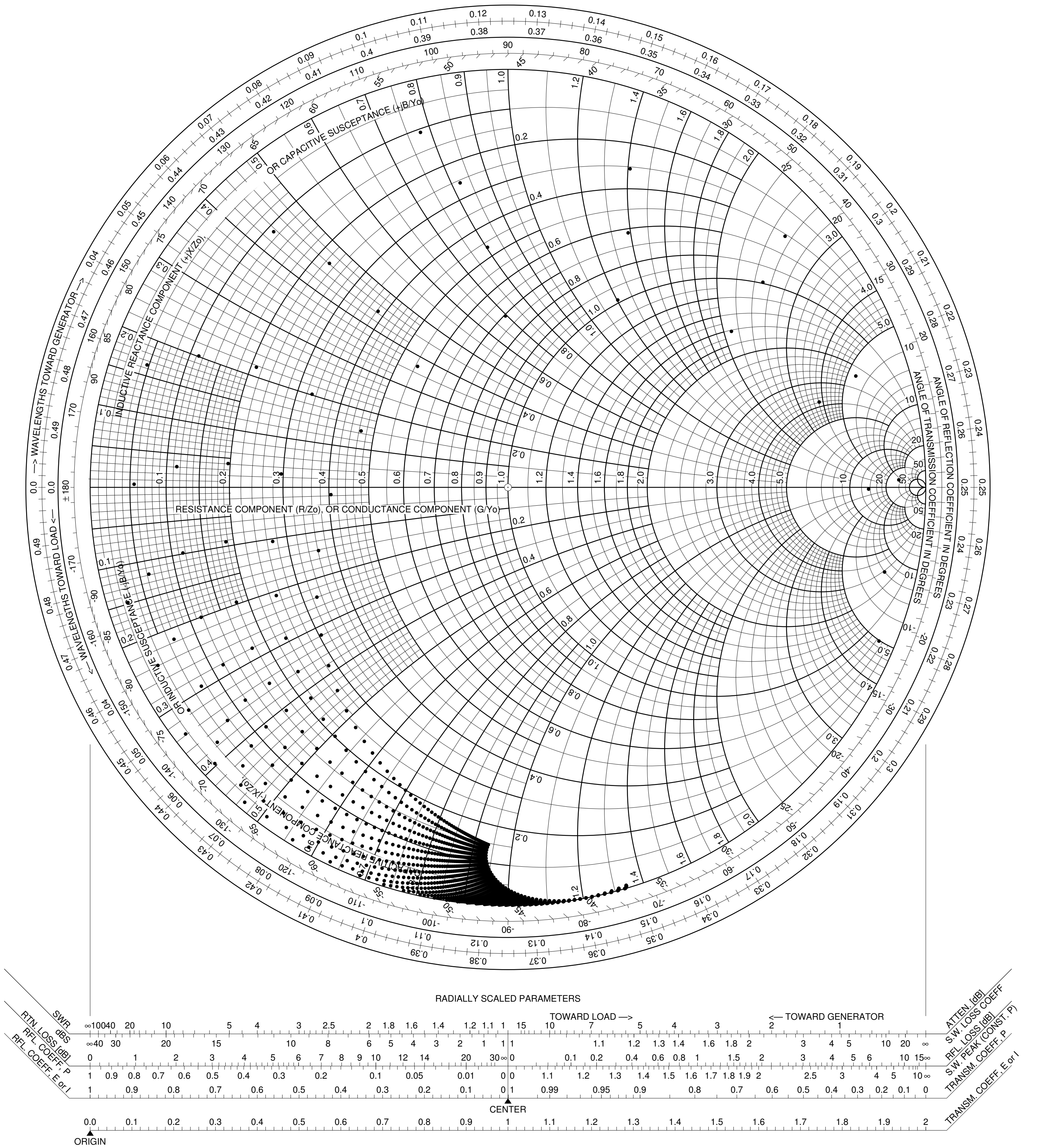
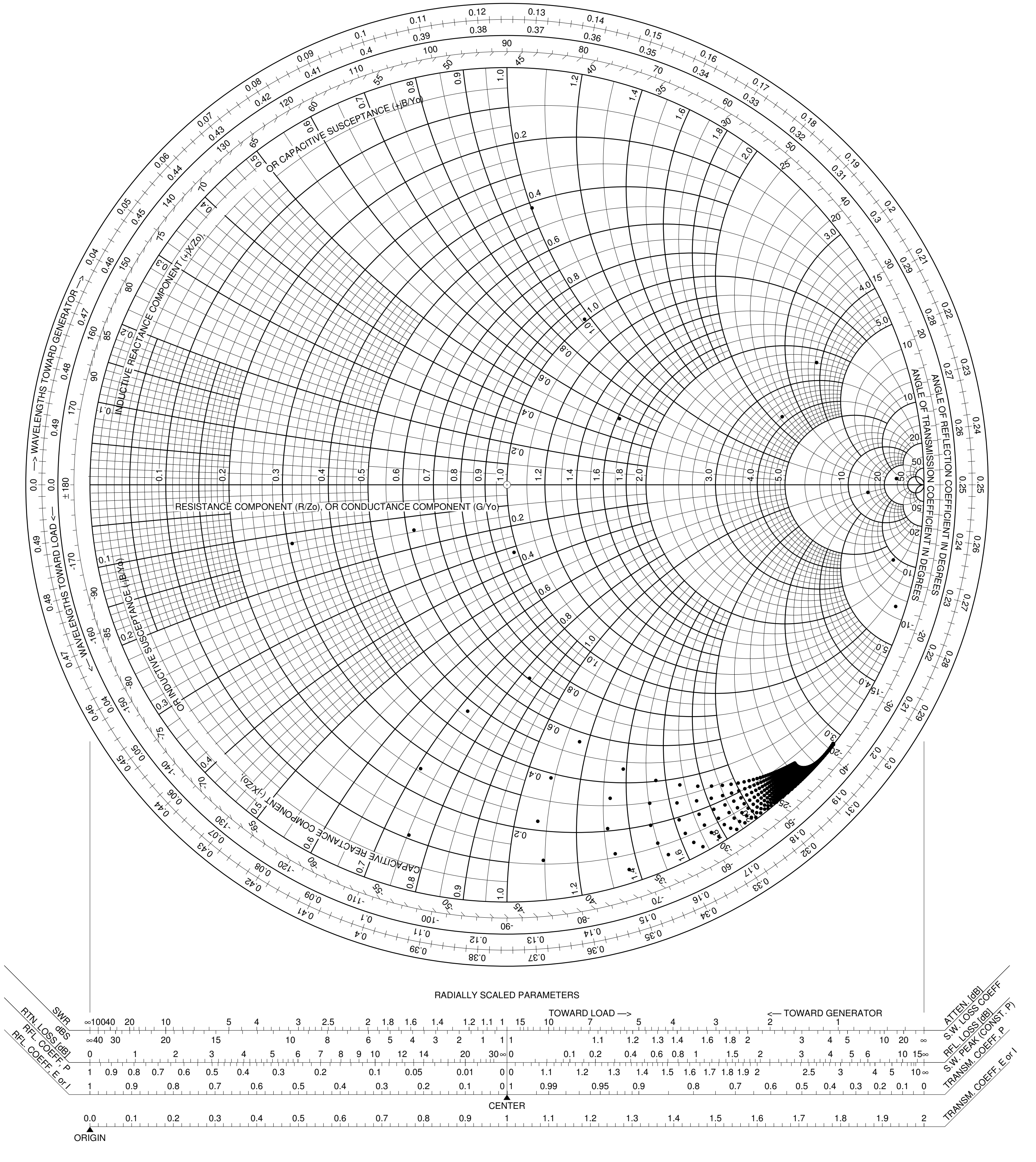


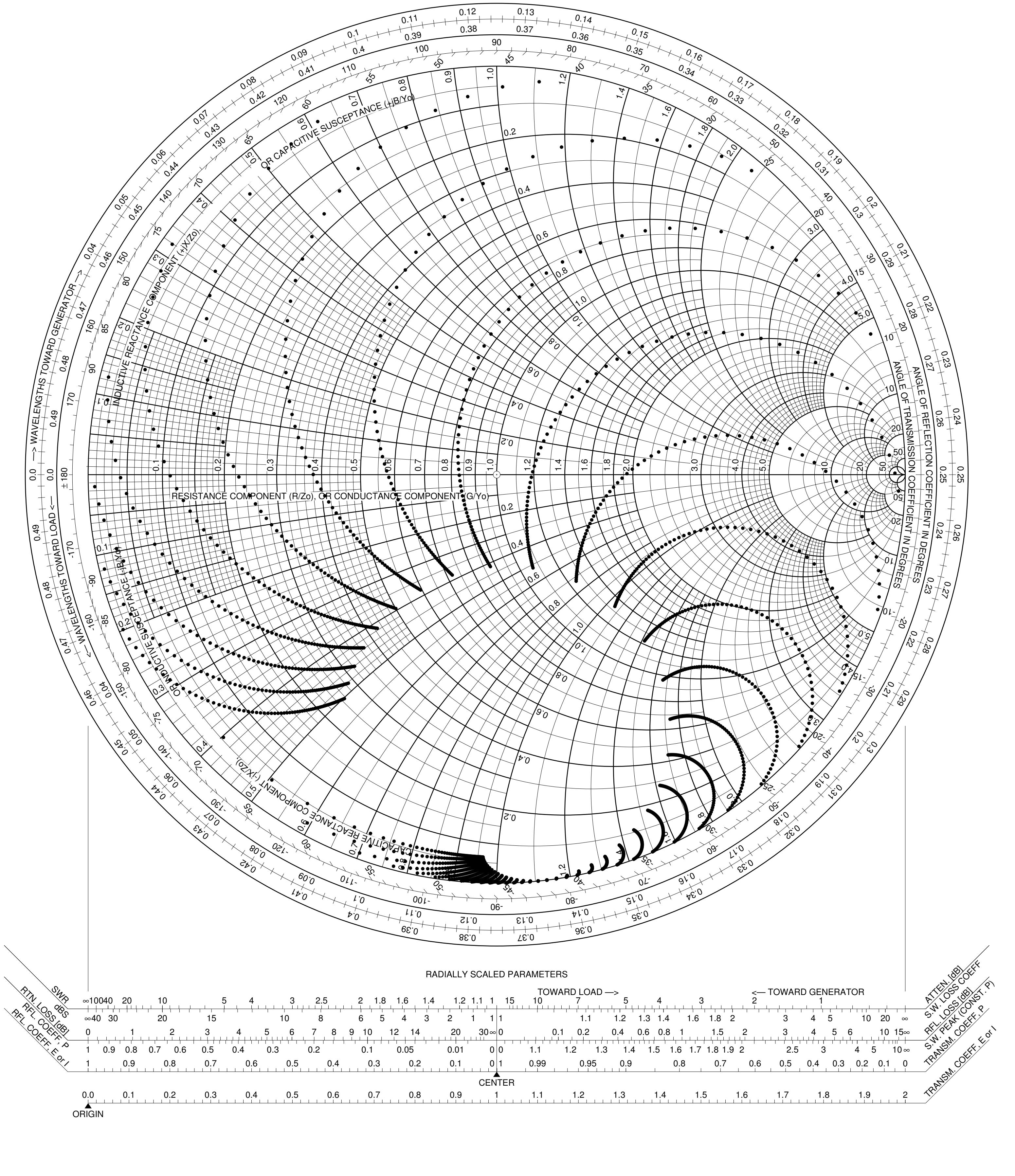
at 10.150 MHz, 4 turn secondary



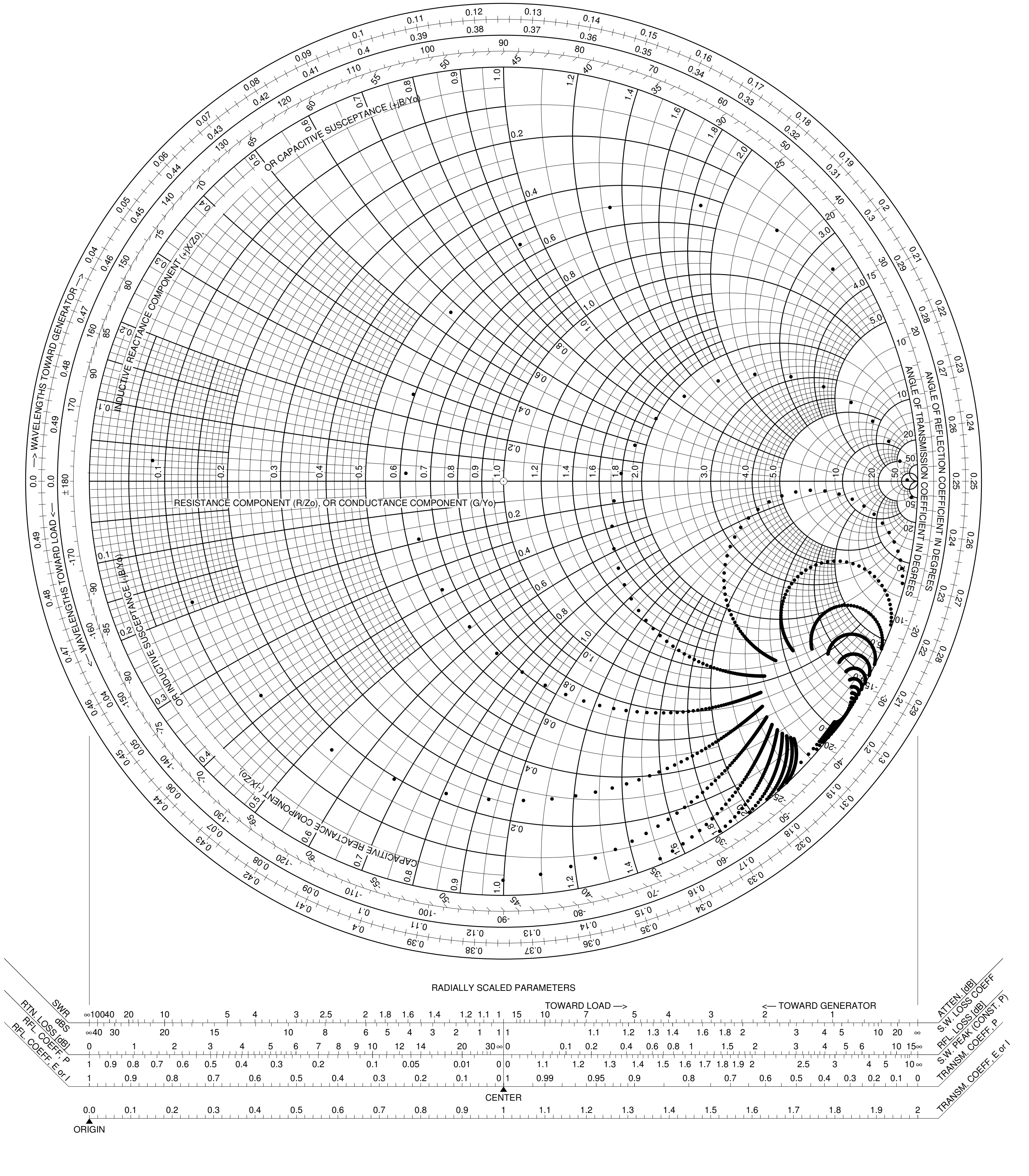
at 10.150 MHz, 4 turn secondary with L3



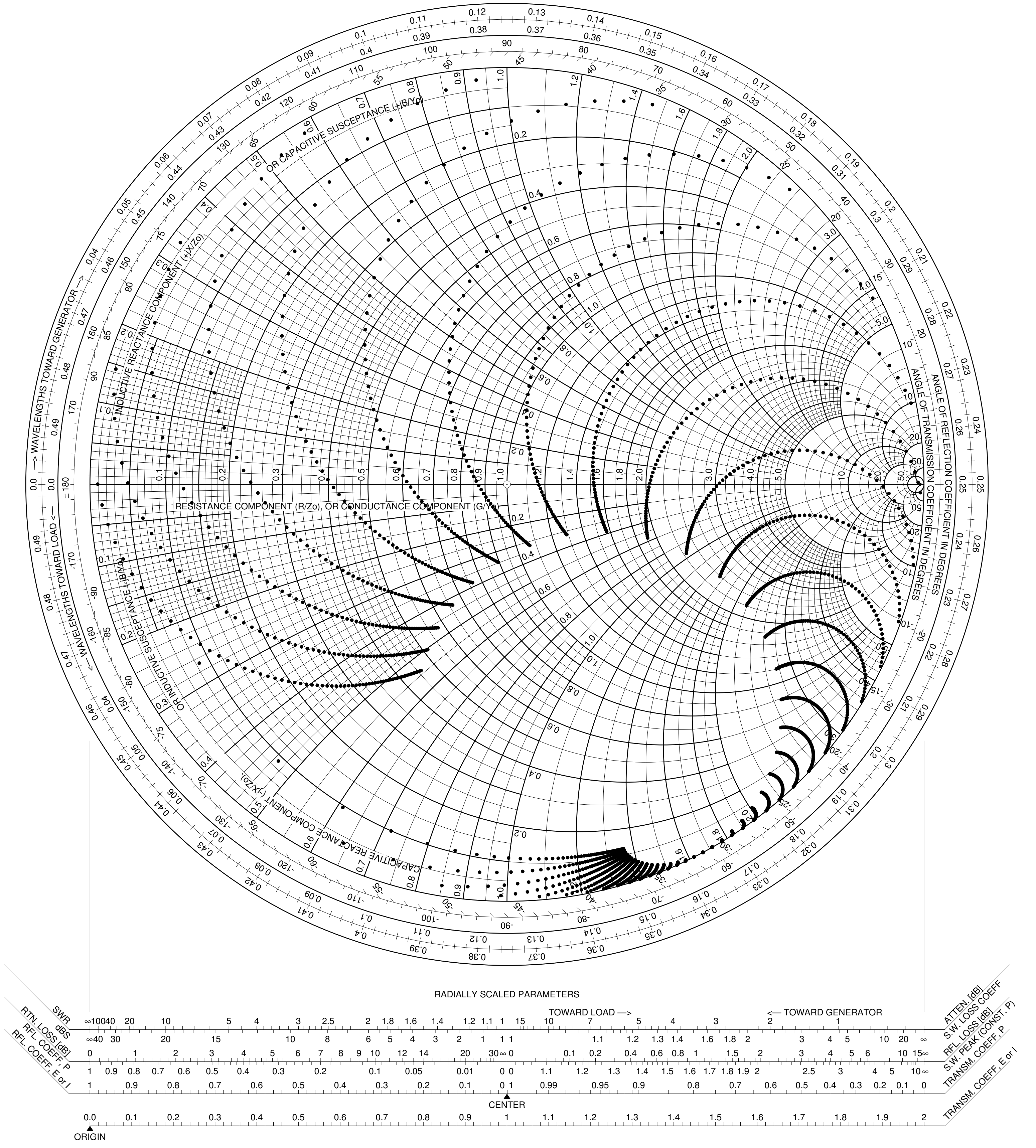
at 14.000 MHz, 3 turn secondary



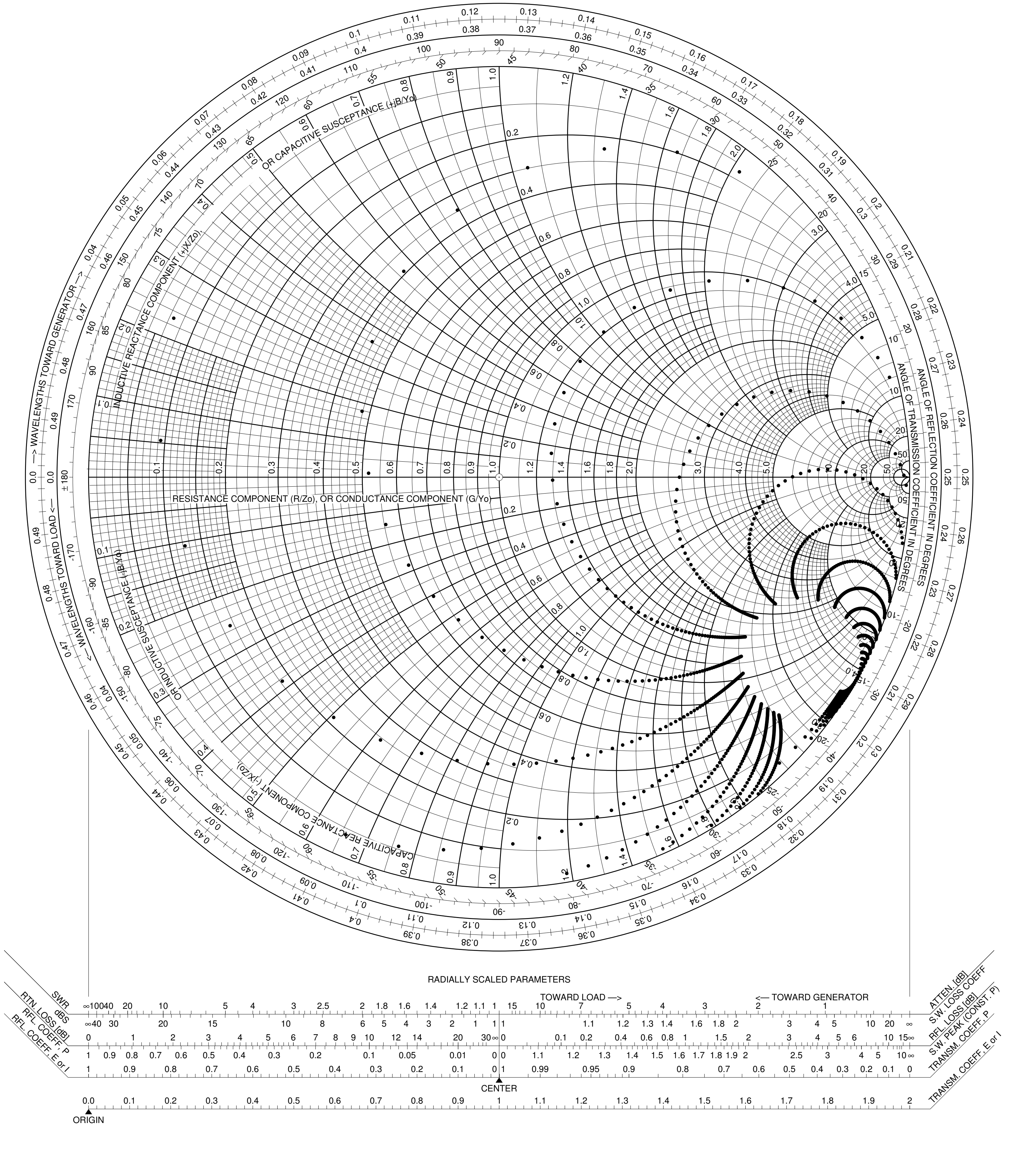
at 14.000 MHz, 3 turn secondary with L3



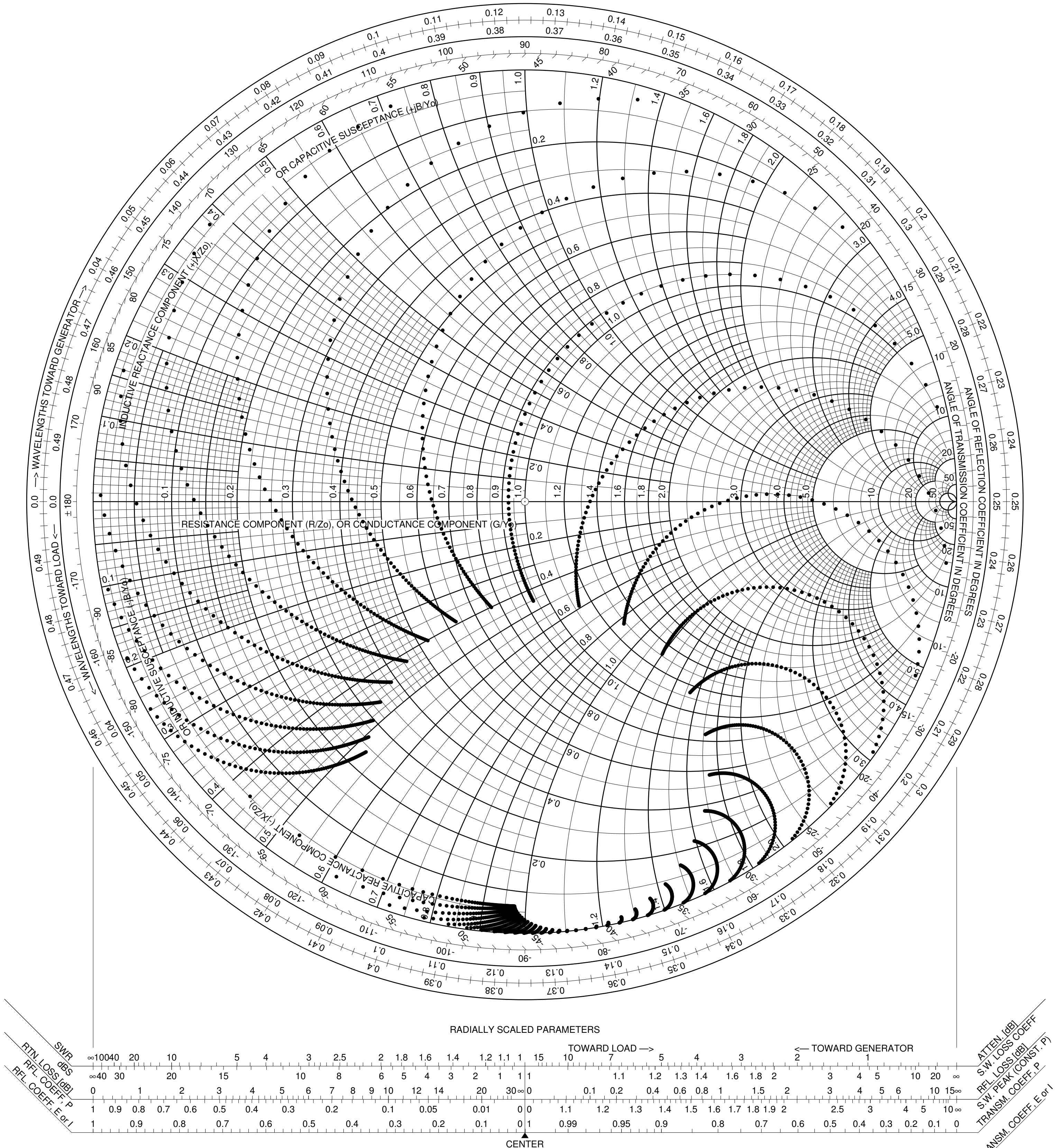
at 14.000 MHz, 4 turn secondary



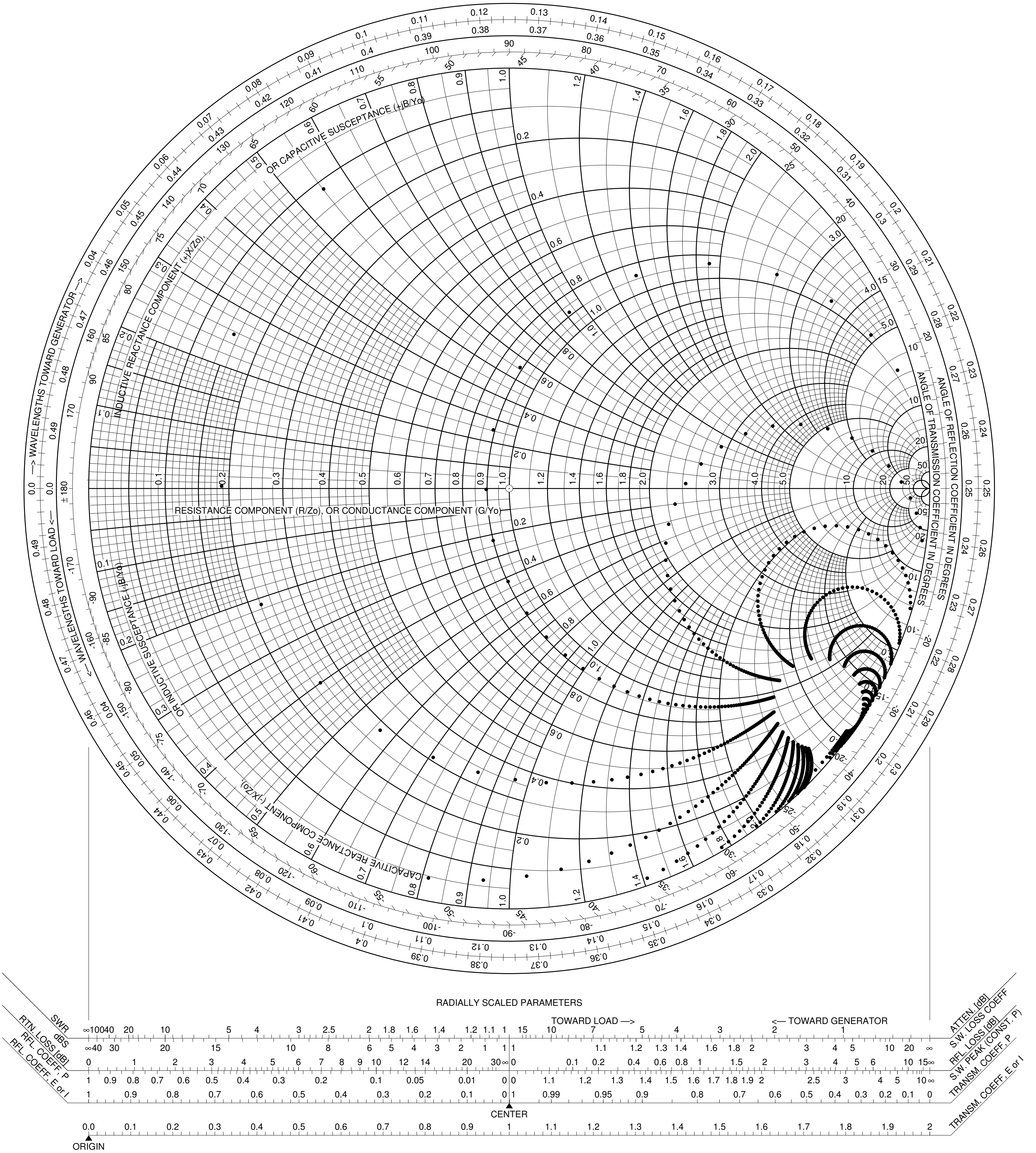
at 14.000 MHz, 4 turn secondary with L3



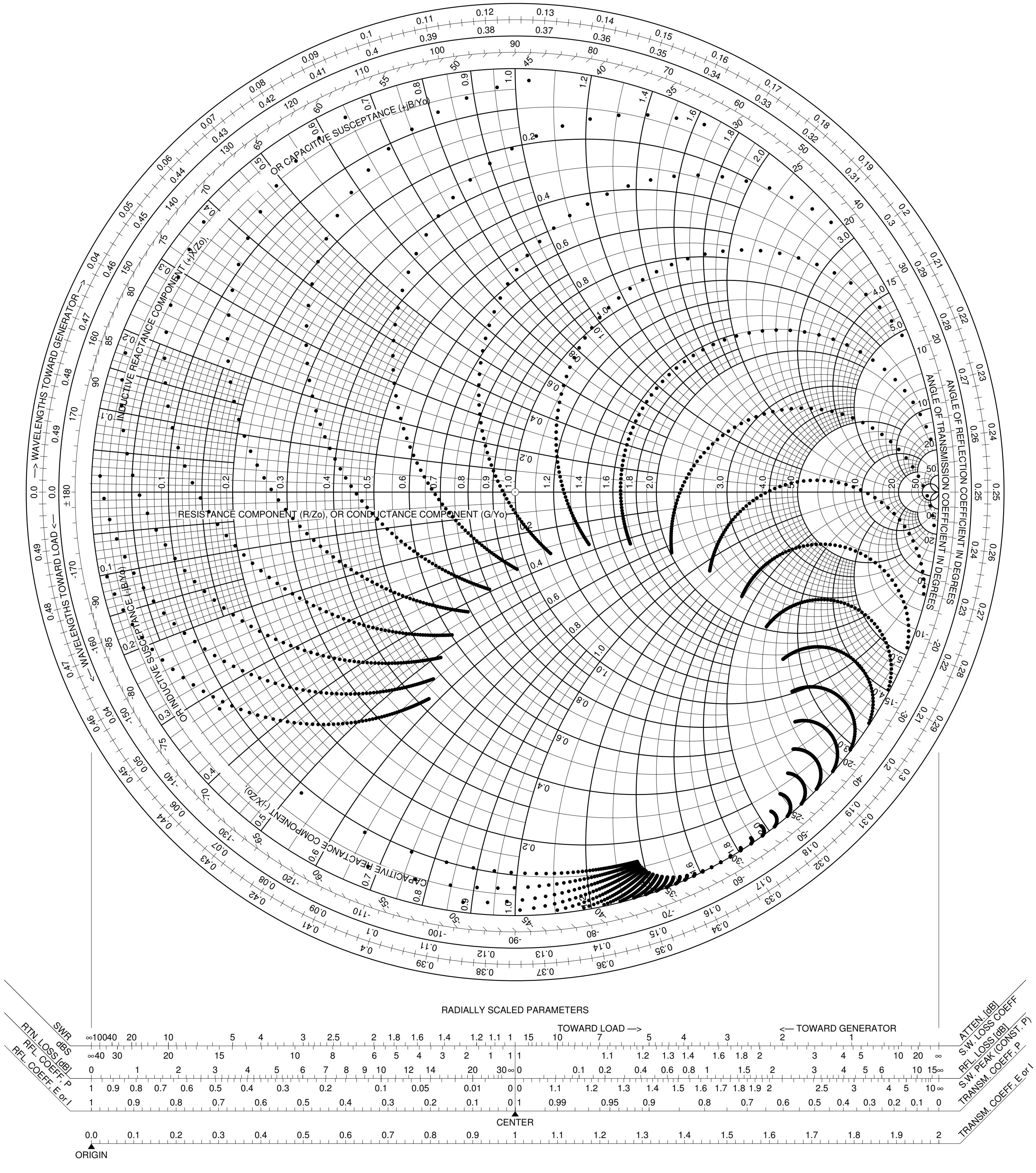
at 14.130 MHz, 3 turn secondary



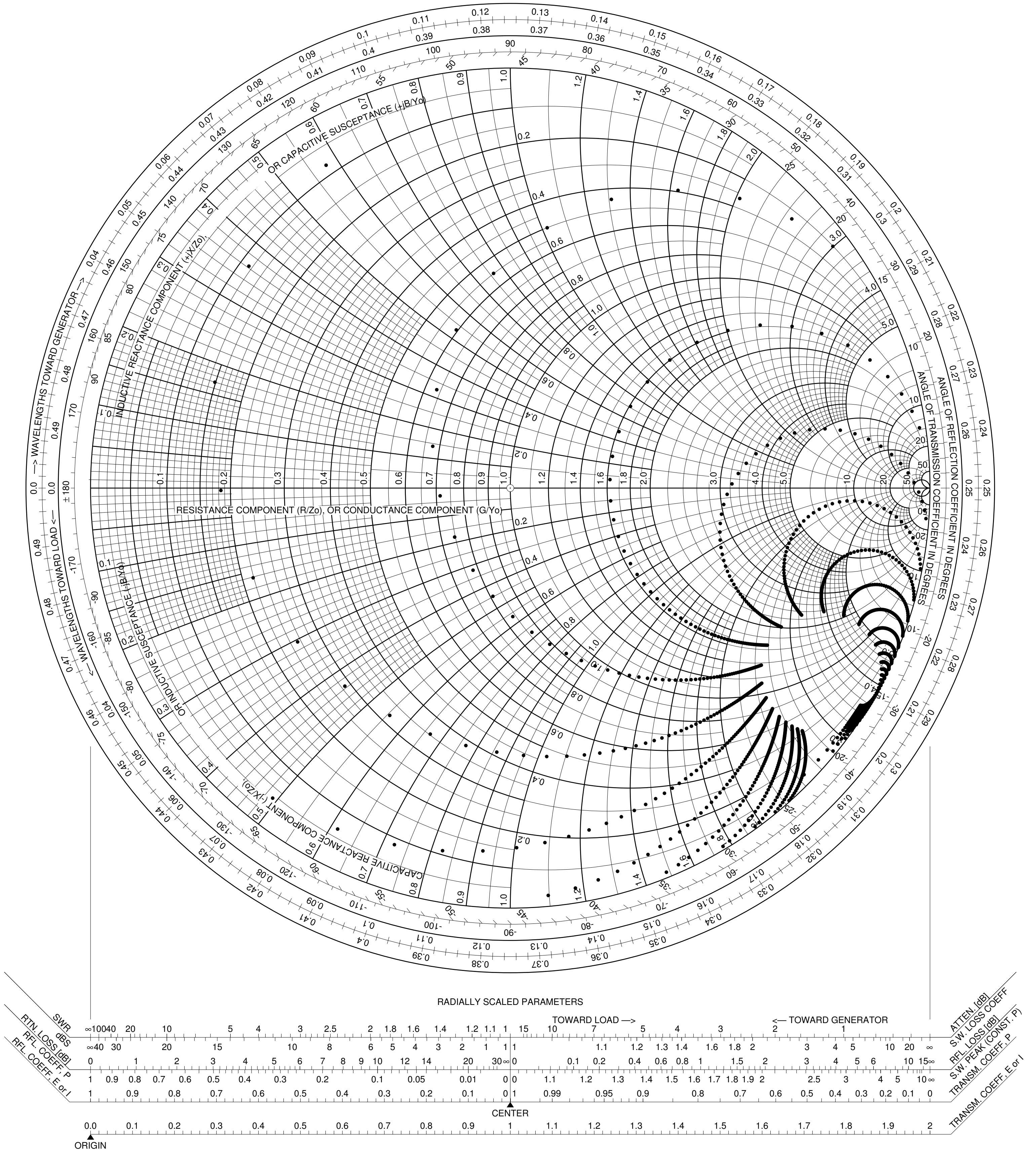
at 14.130 MHz, 3 turn secondary with L3



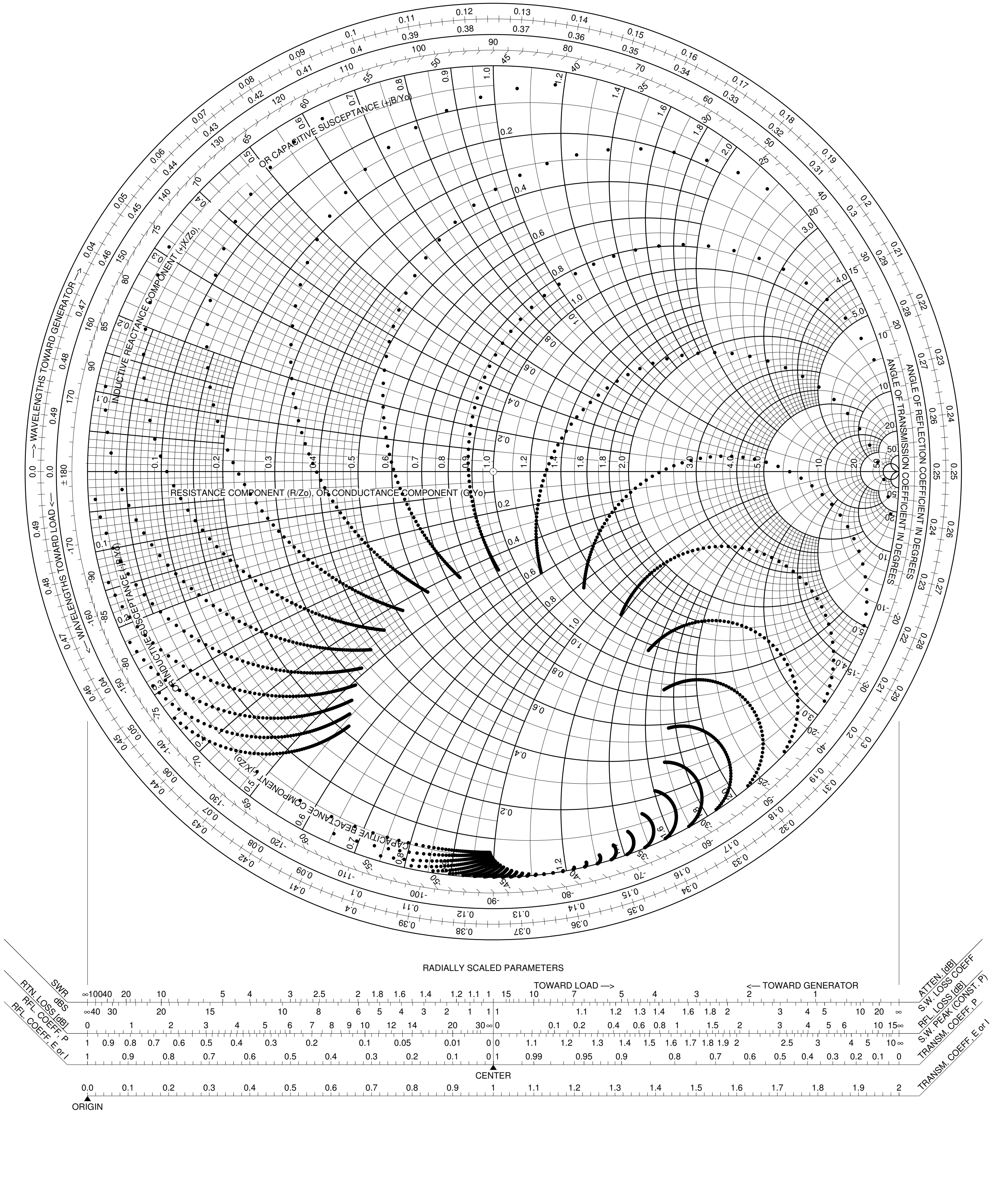
at 14.130 MHz, 4 turn secondary



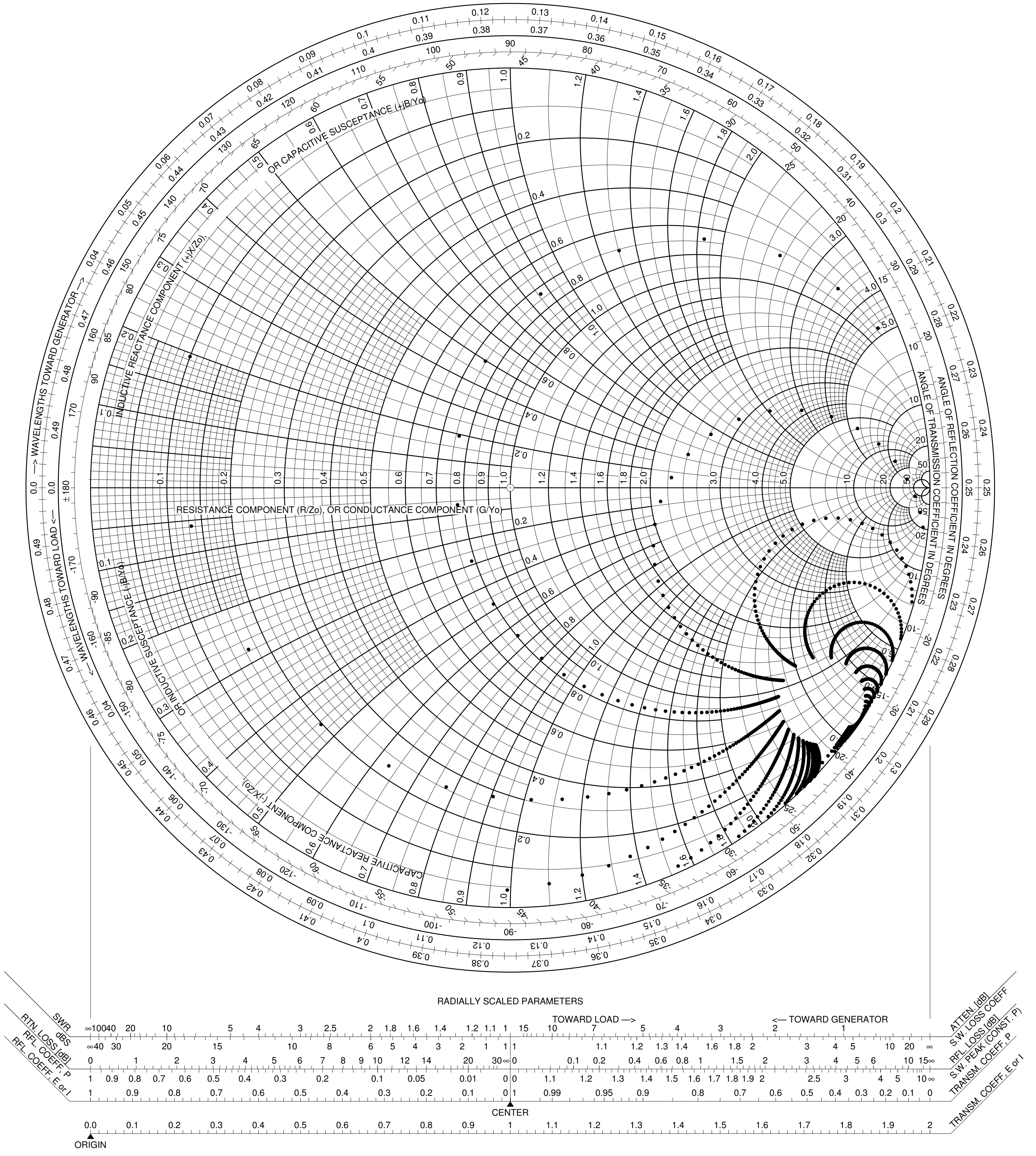
at 14.130 MHz, 4 turn secondary with L3



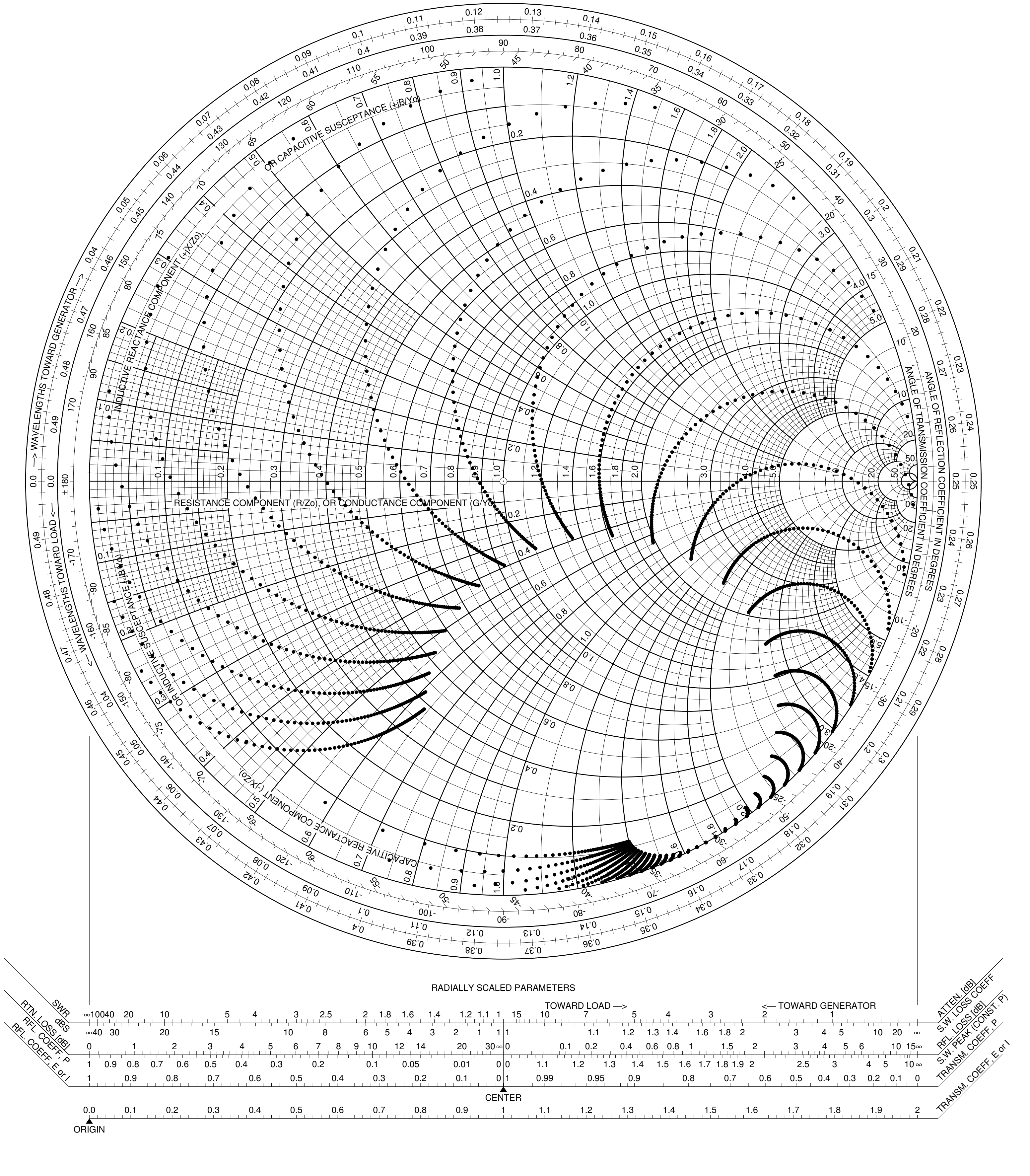
at 14.350 MHz, 3 turn secondary



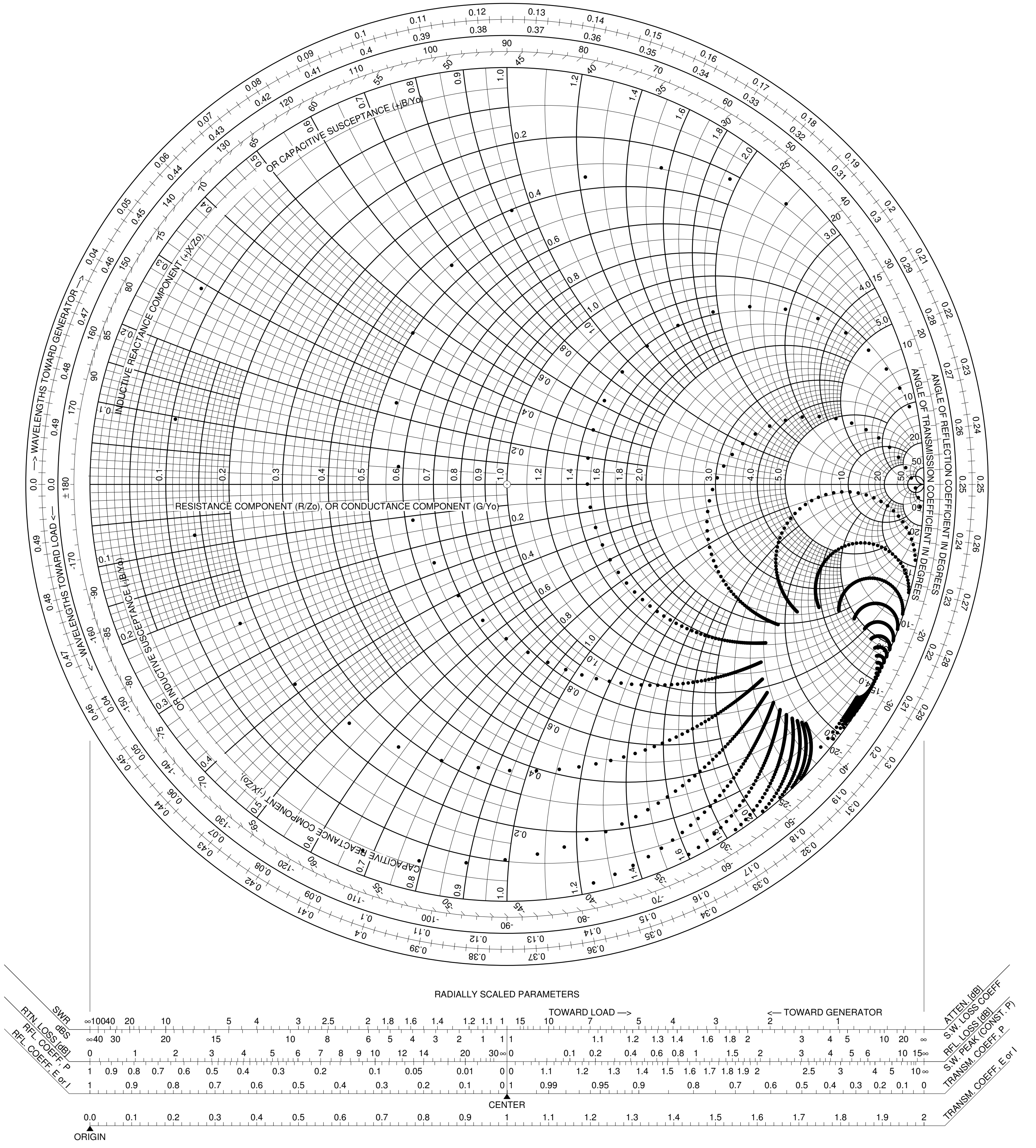
at 14.350 MHz, 3 turn secondary with L3



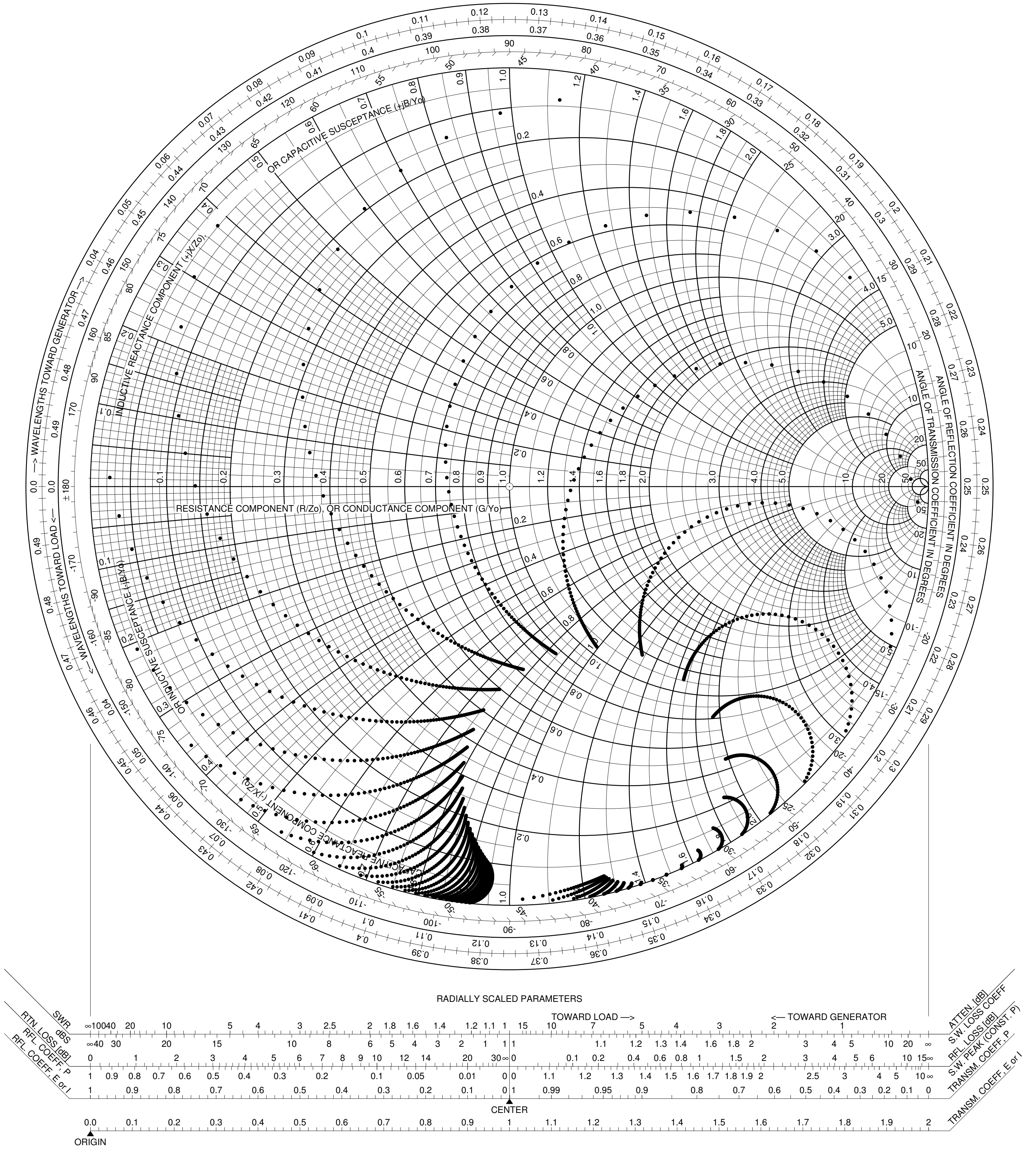
at 14.350 MHz, 4 turn secondary



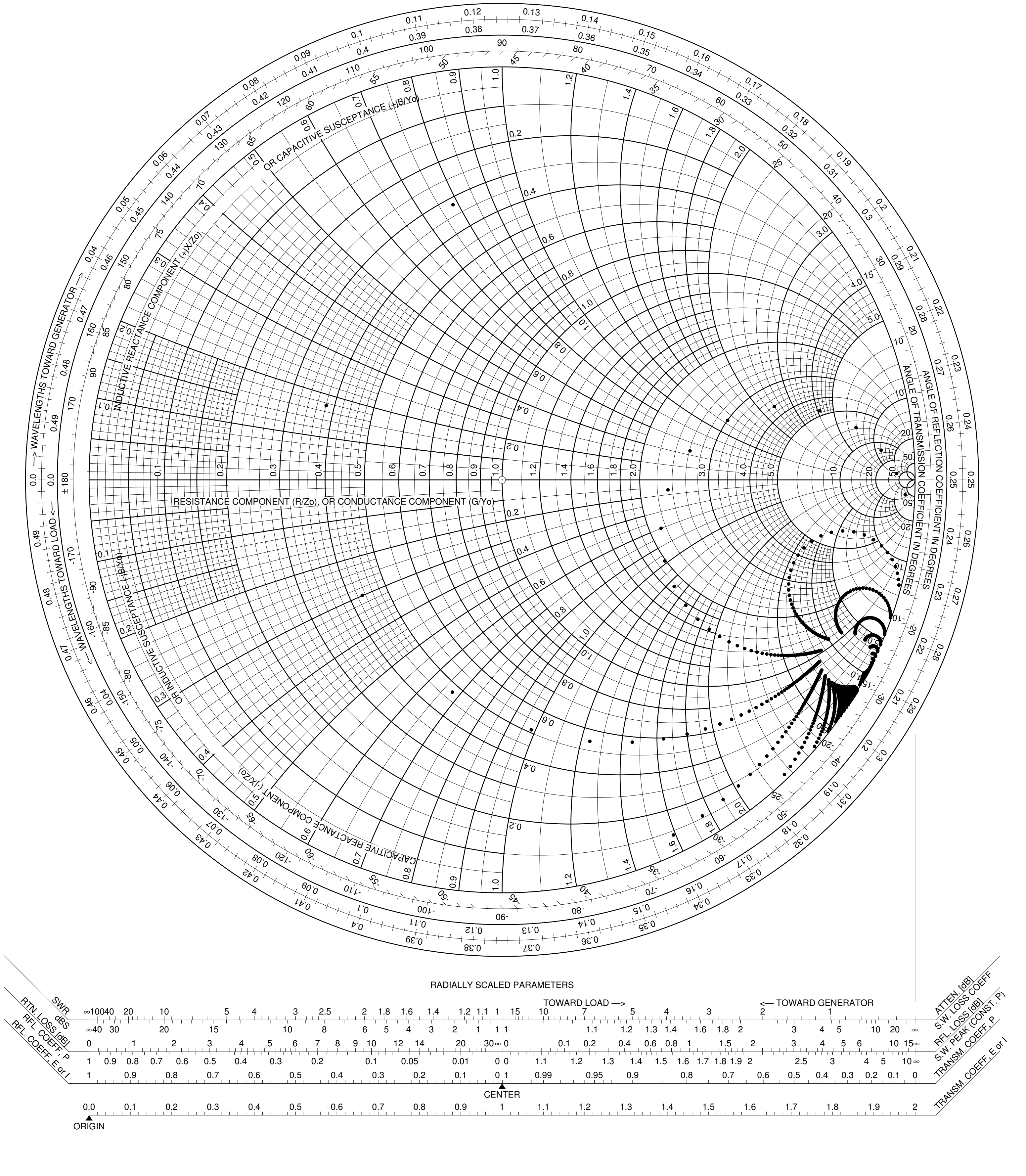
at 14.350 MHz, 4 turn secondary with L3



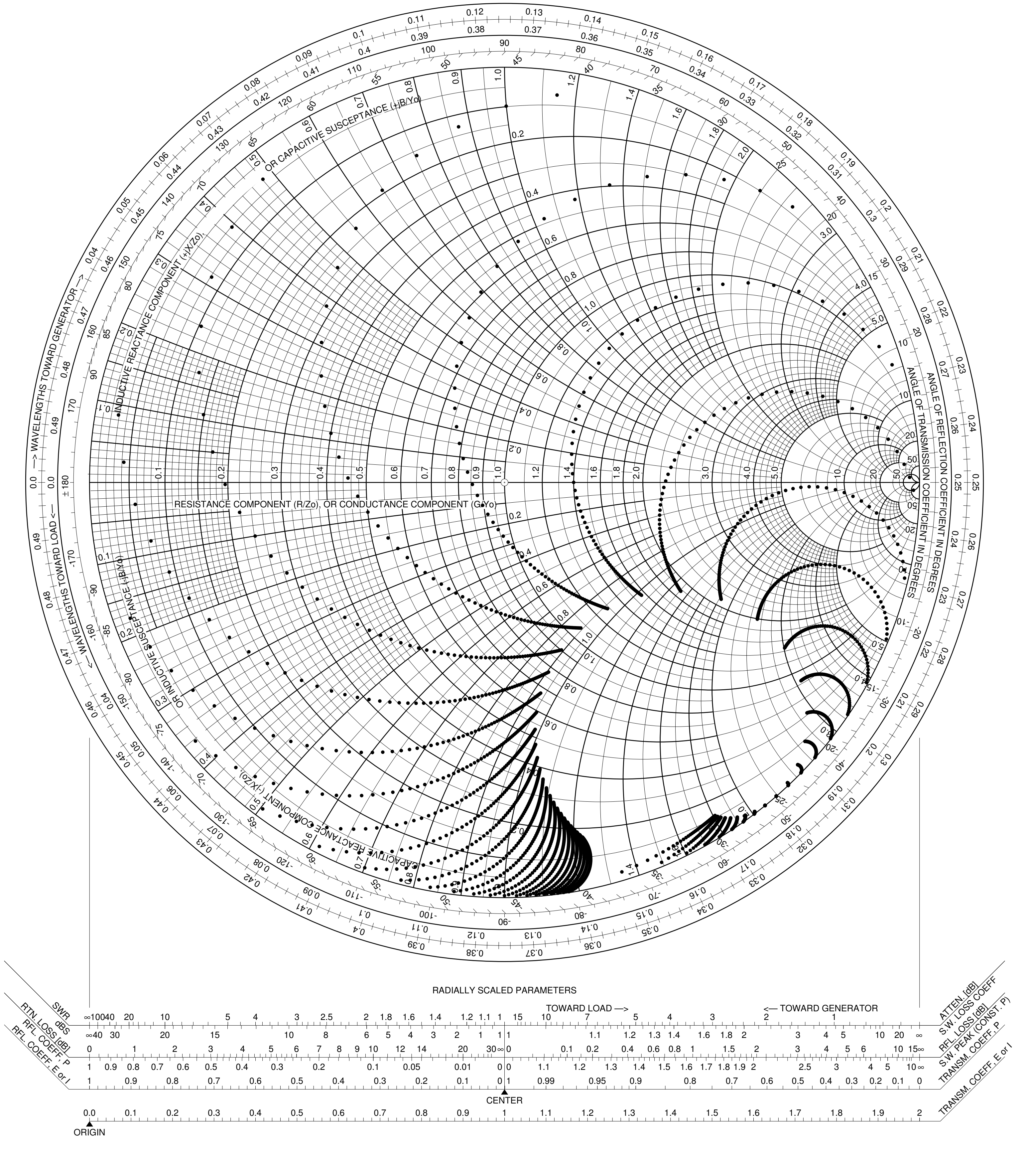
at 18.068 MHz, 3 turn secondary



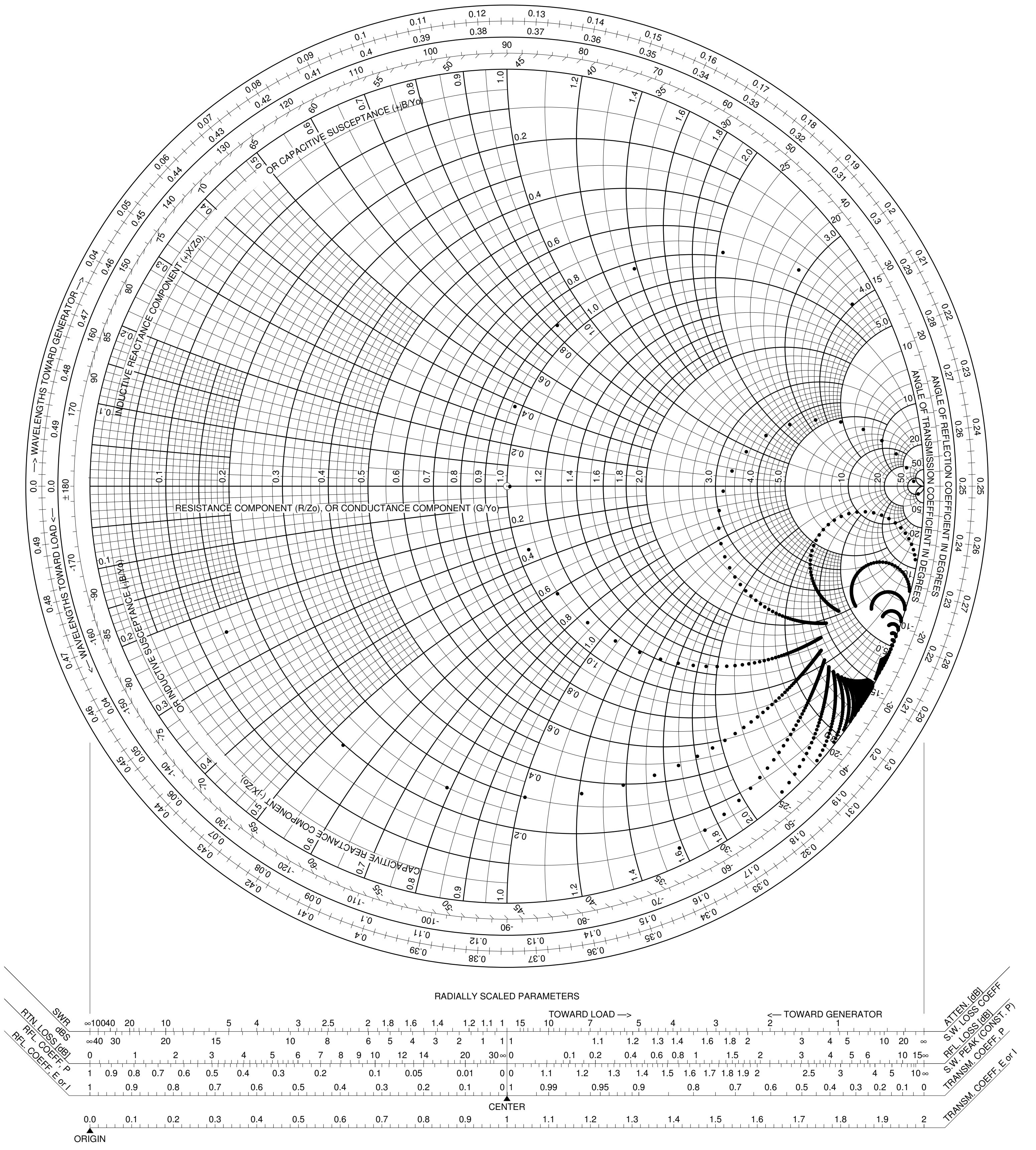
at 18.068 MHz, 3 turn secondary with L3



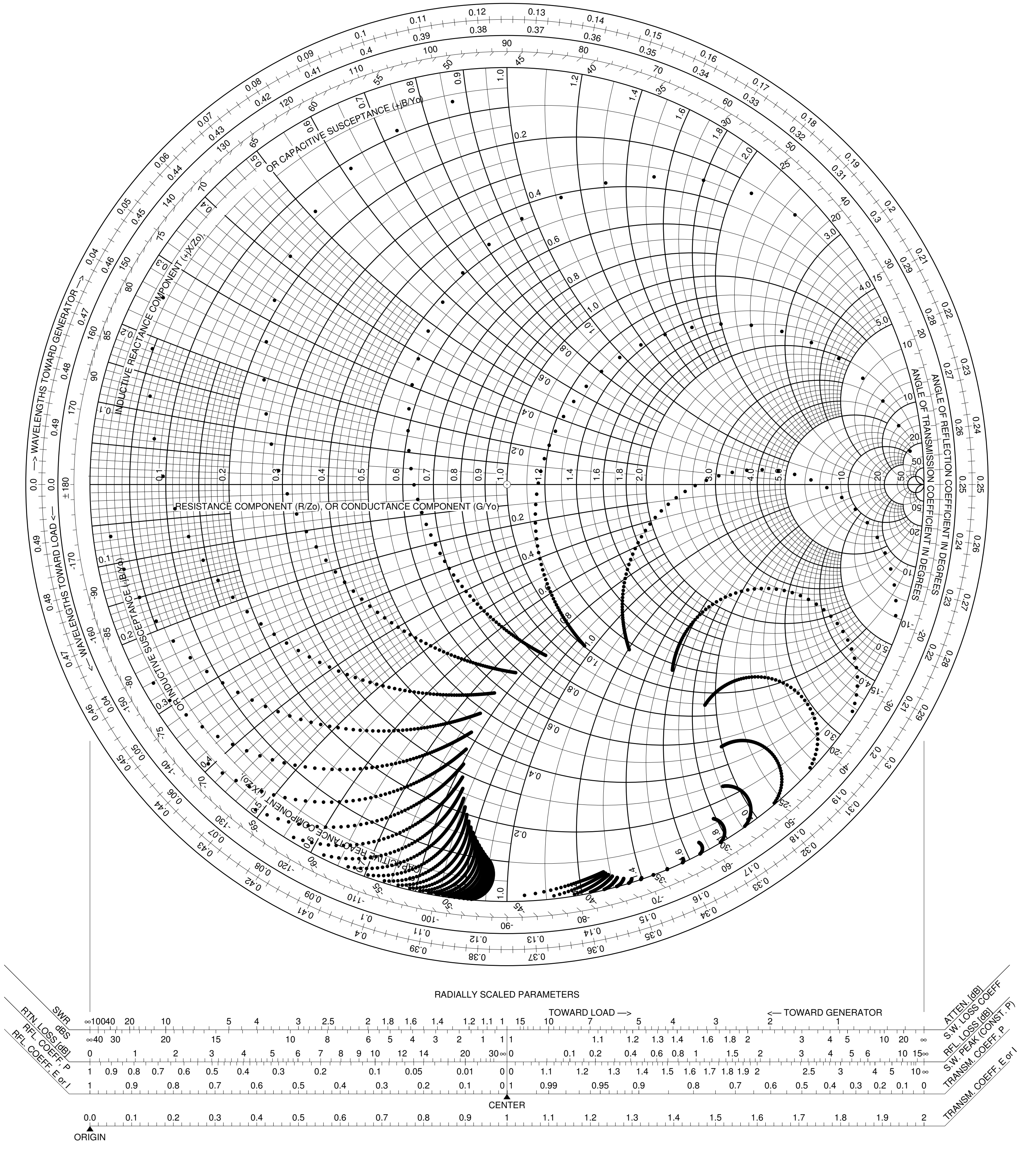
at 18.068 MHz, 4 turn secondary



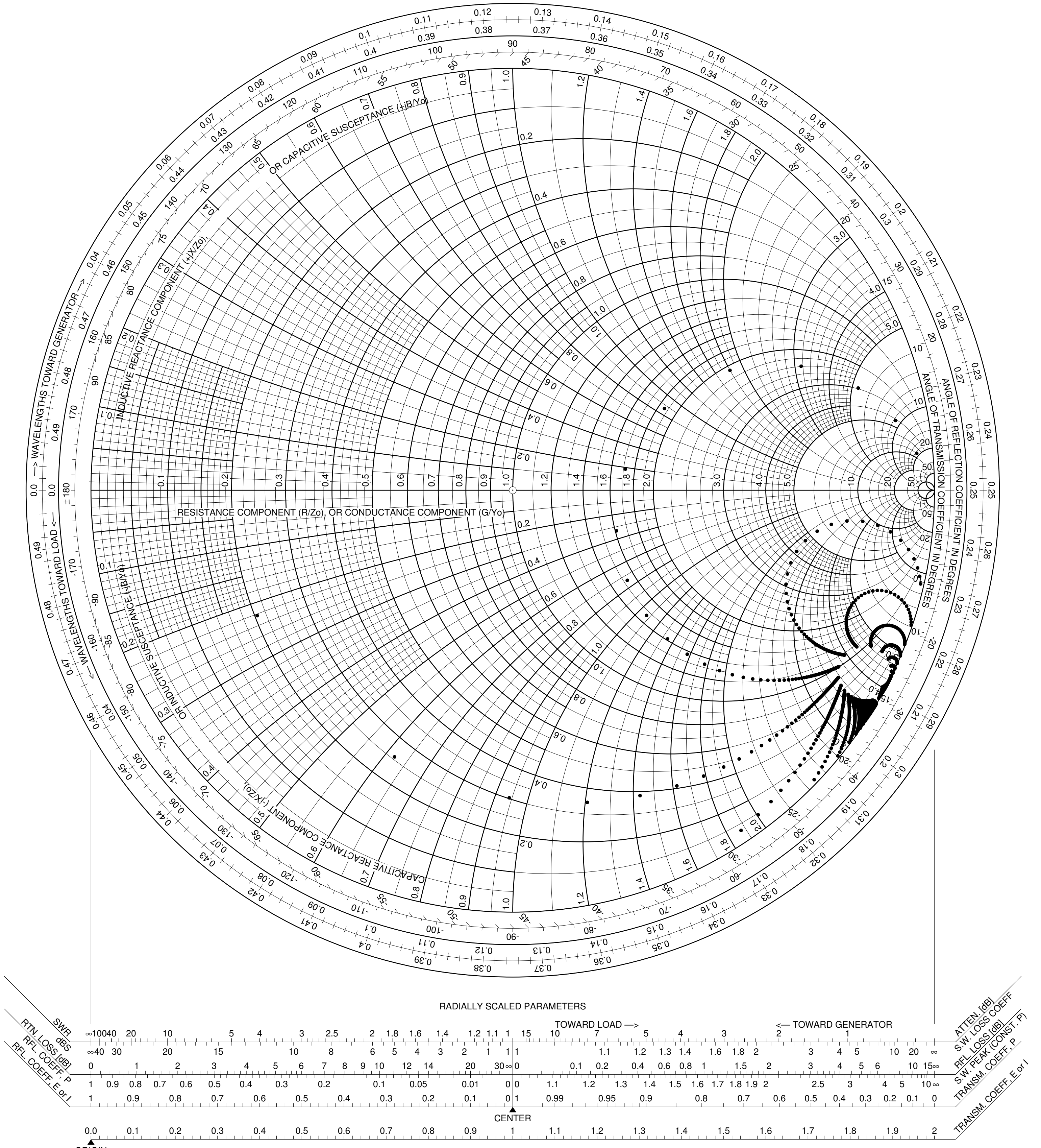
at 18.068 MHz, 4 turn secondary with L3



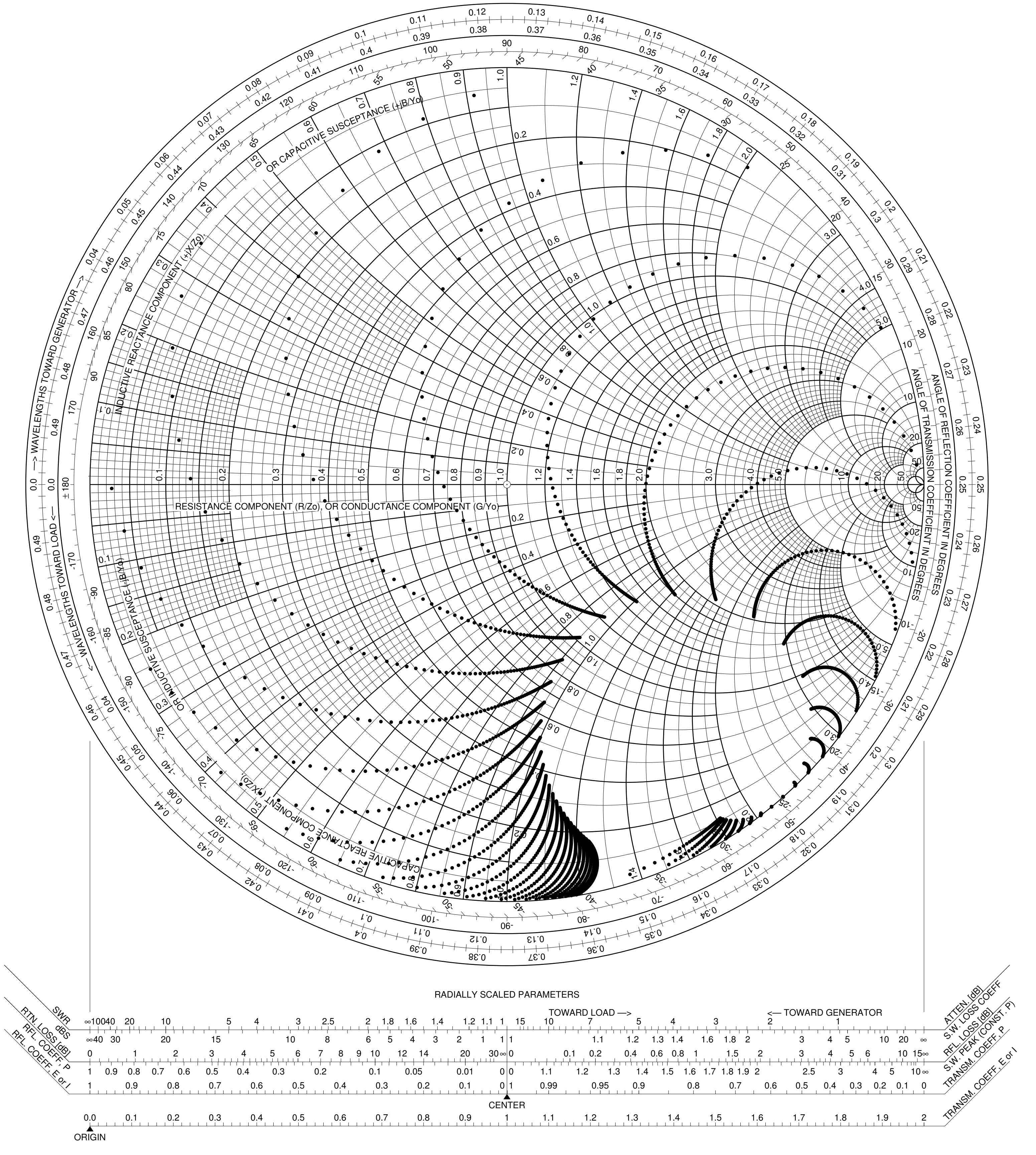
at 18.168 MHz, 3 turn secondary



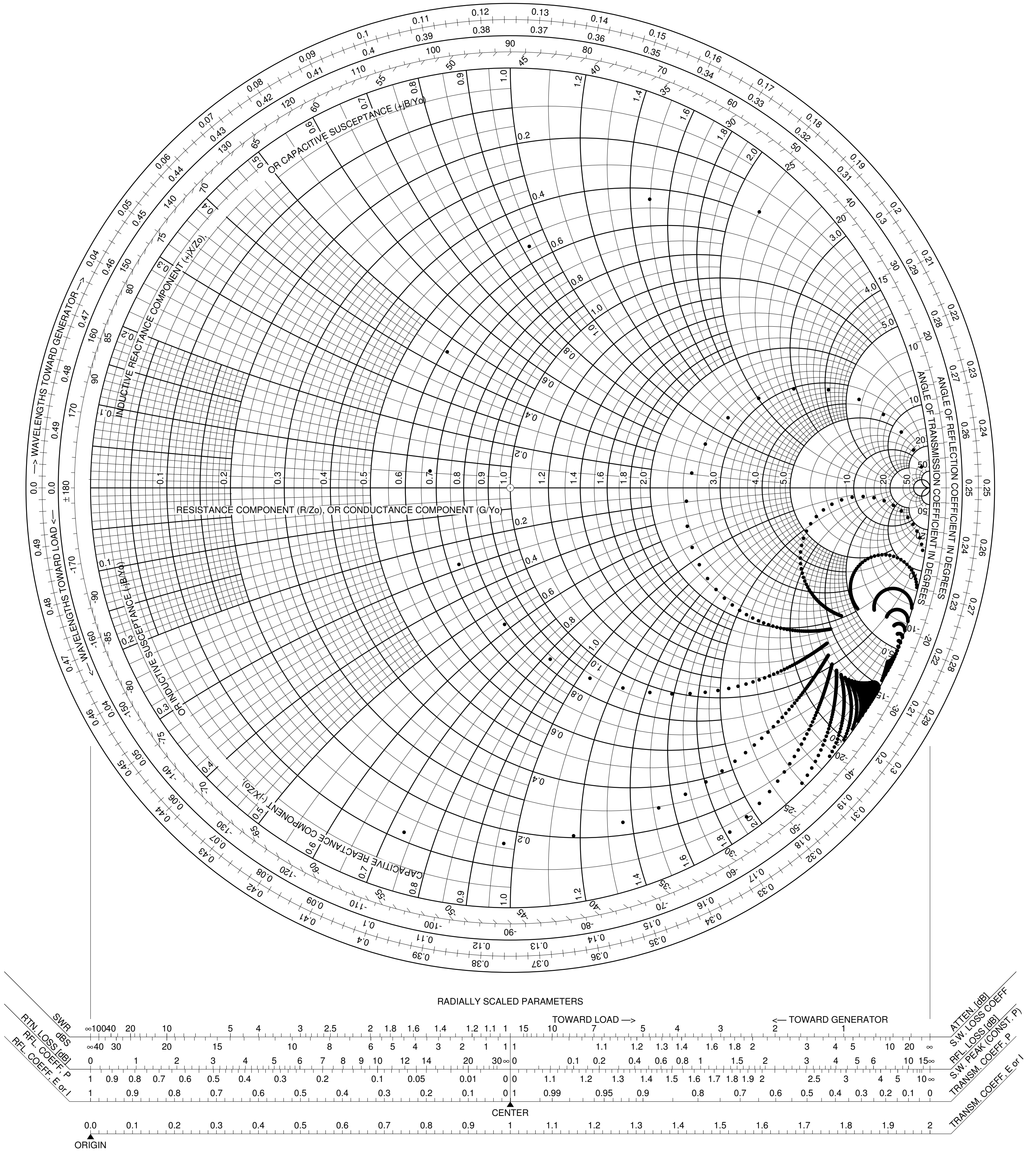
at 18.168 MHz, 3 turn secondary with L3



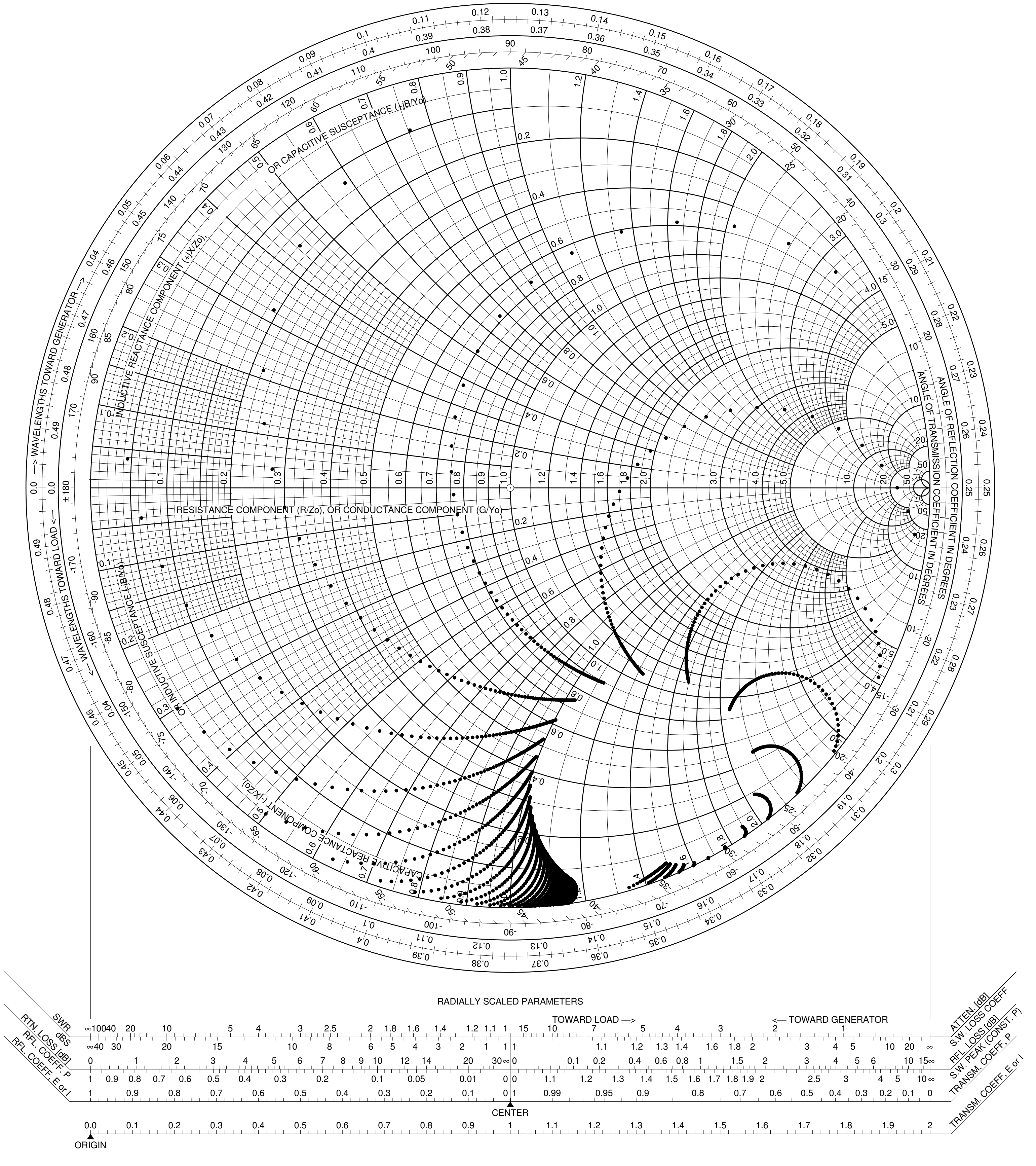
at 18.168 MHz, 4 turn secondary



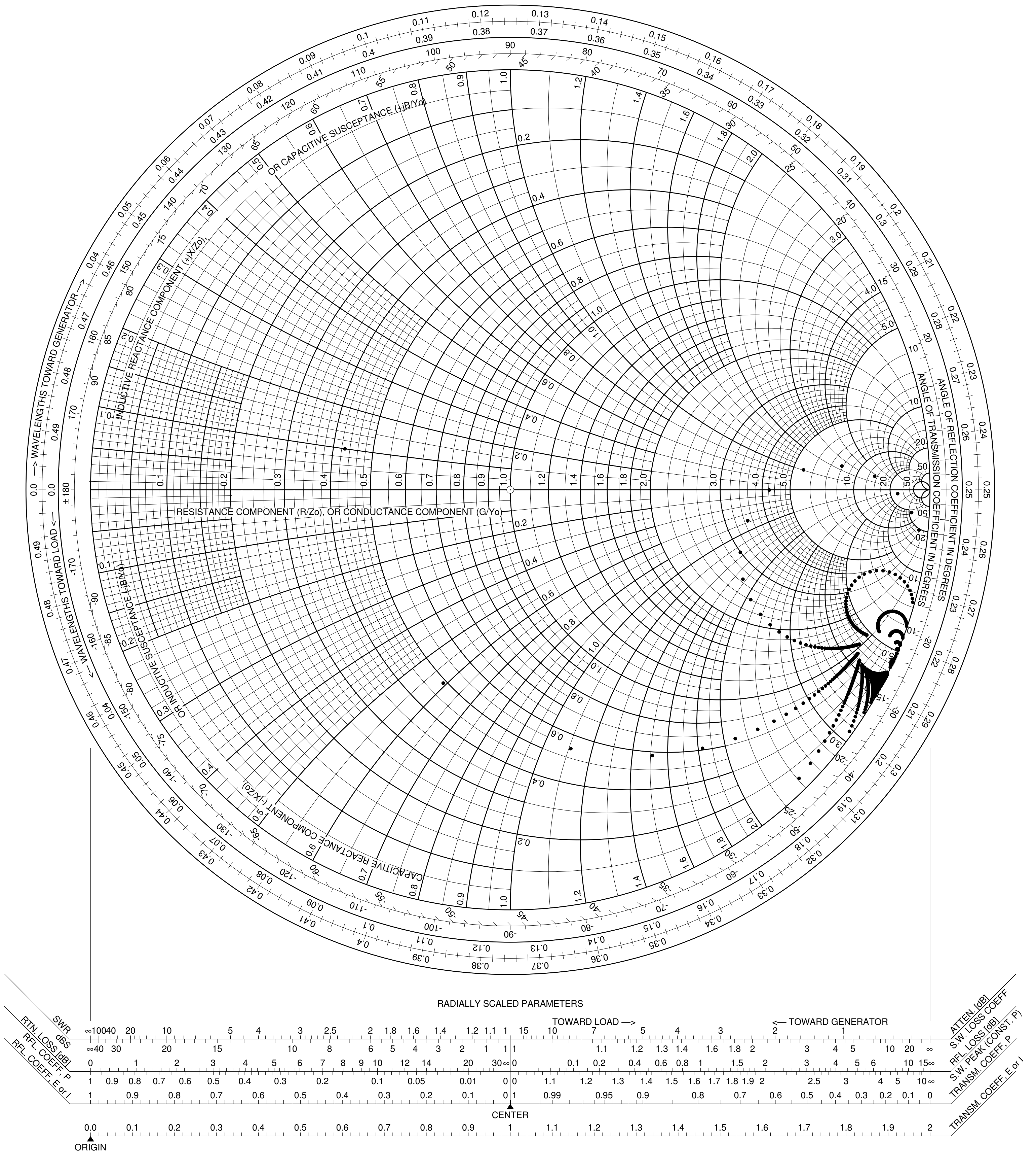
at 18.168 MHz, 4 turn secondary with L3



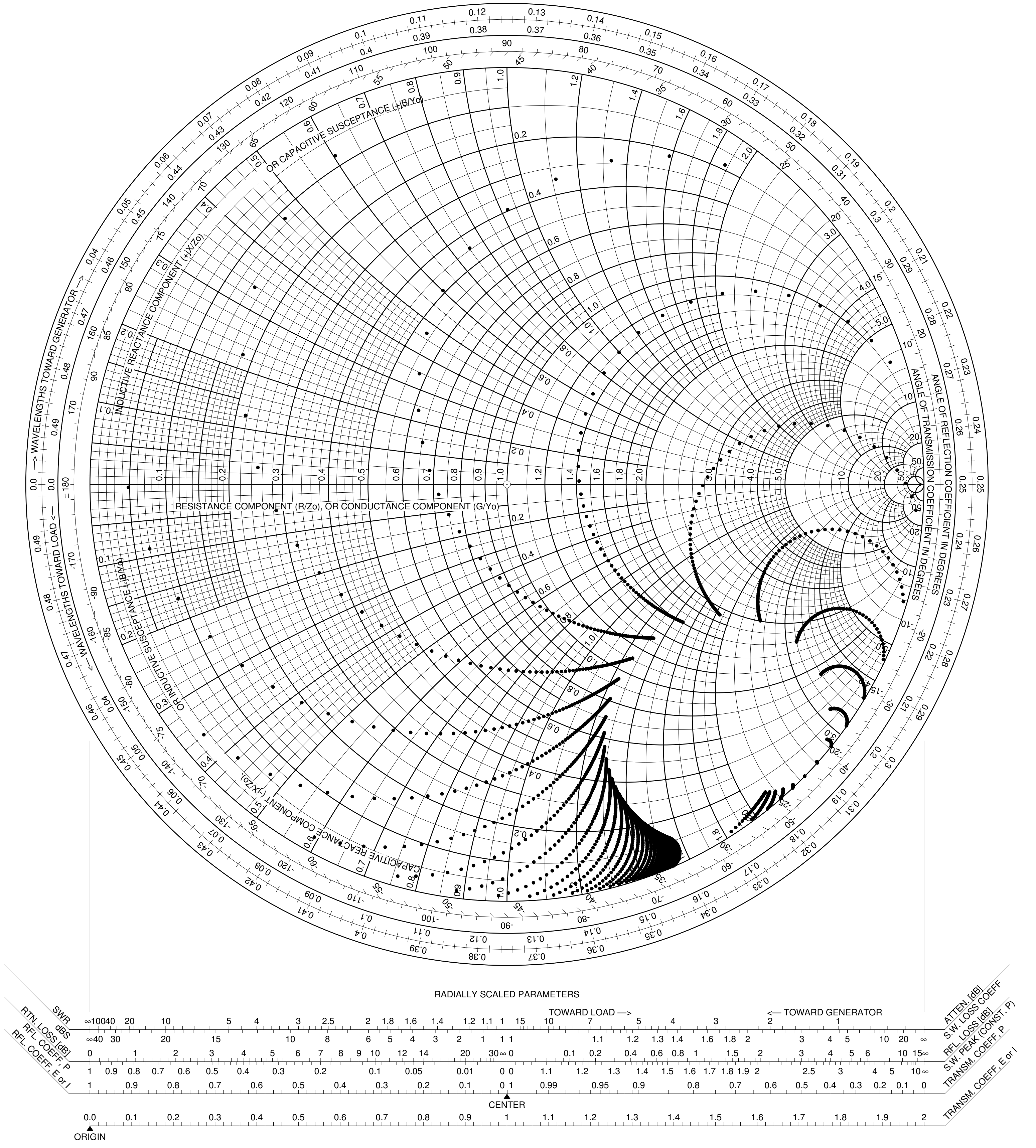
at 21.000 MHz, 3 turn secondary



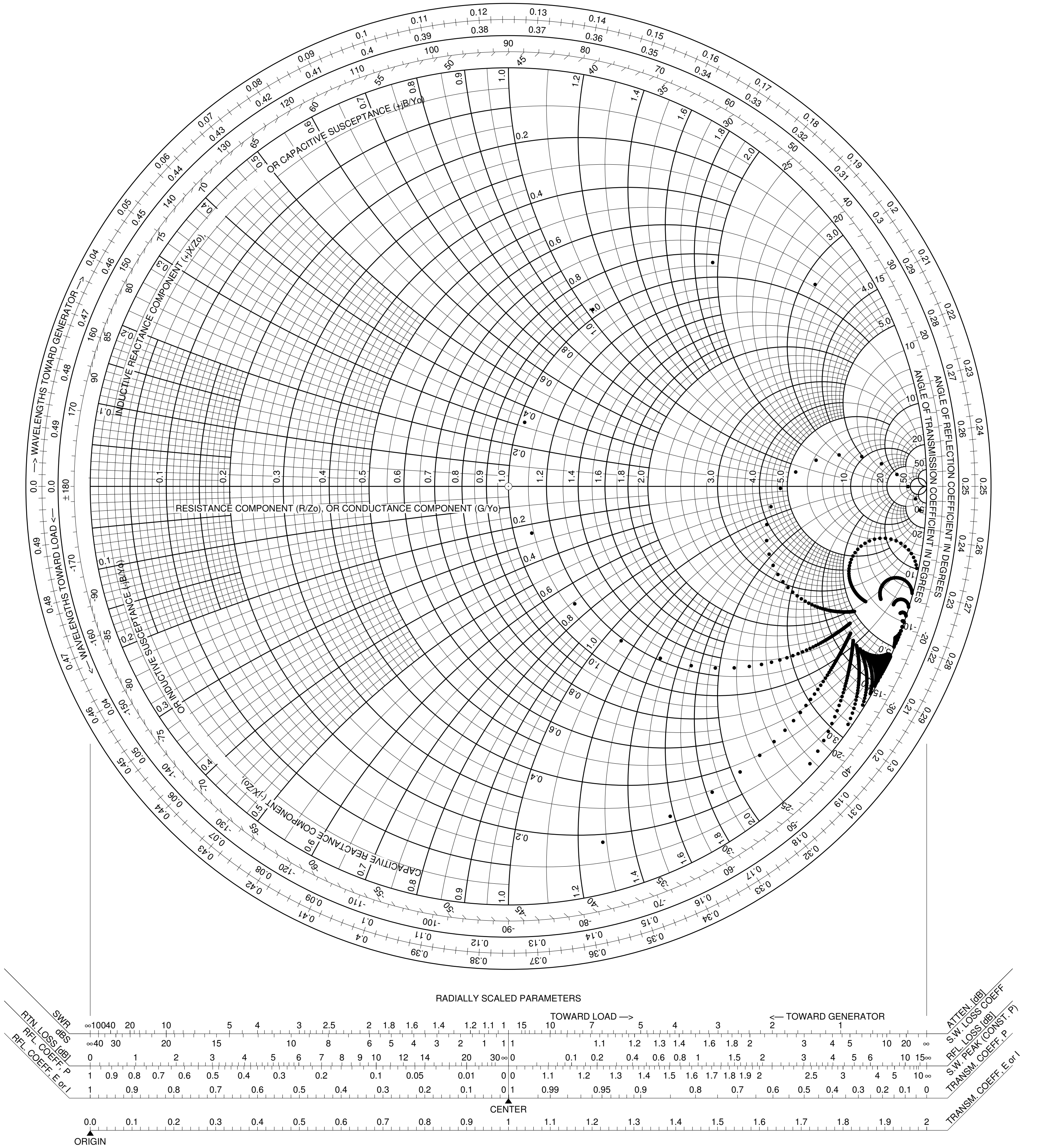
at 21.000 MHz, 3 turn secondary with L3



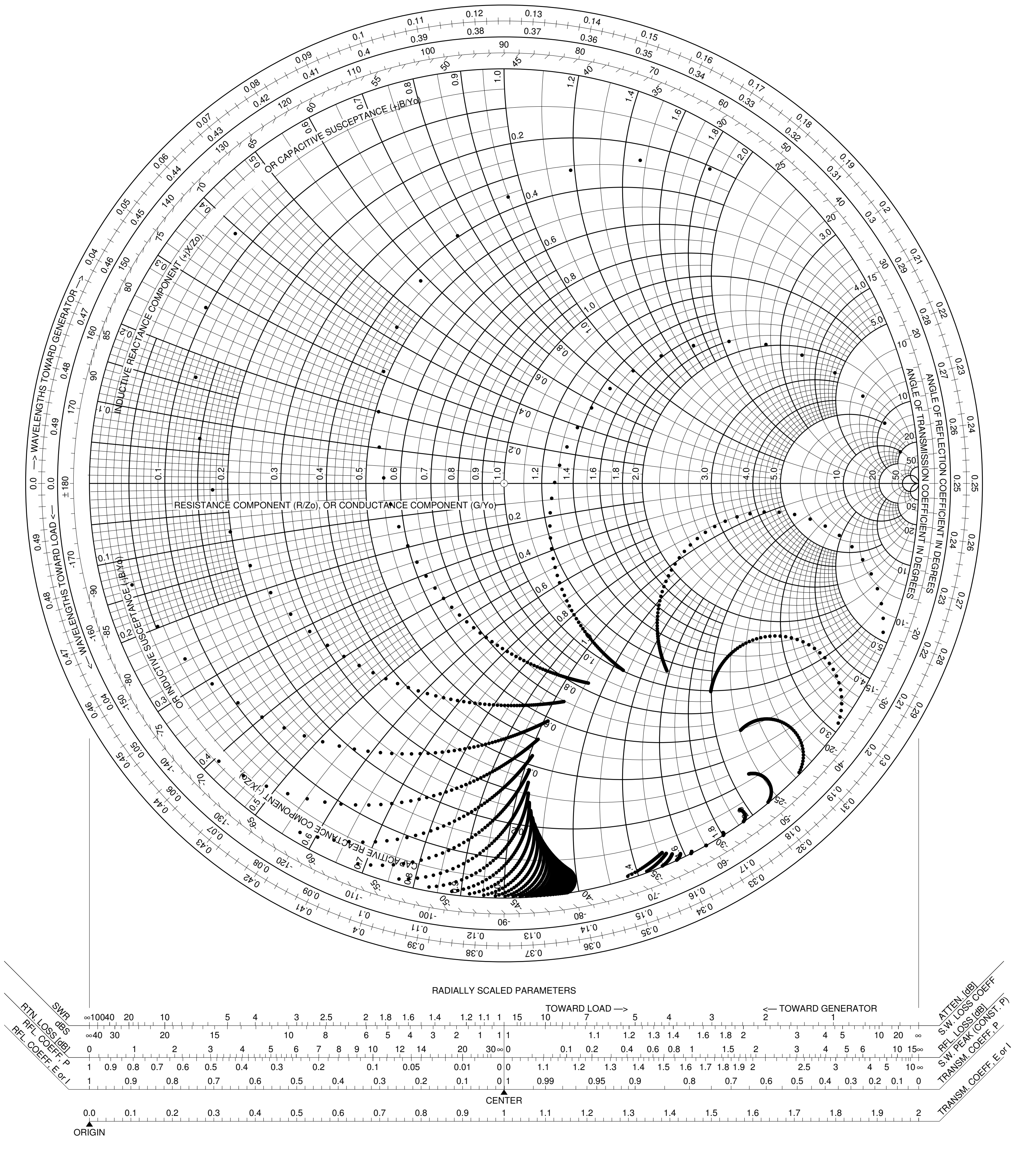
at 21.000 MHz, 4 turn secondary



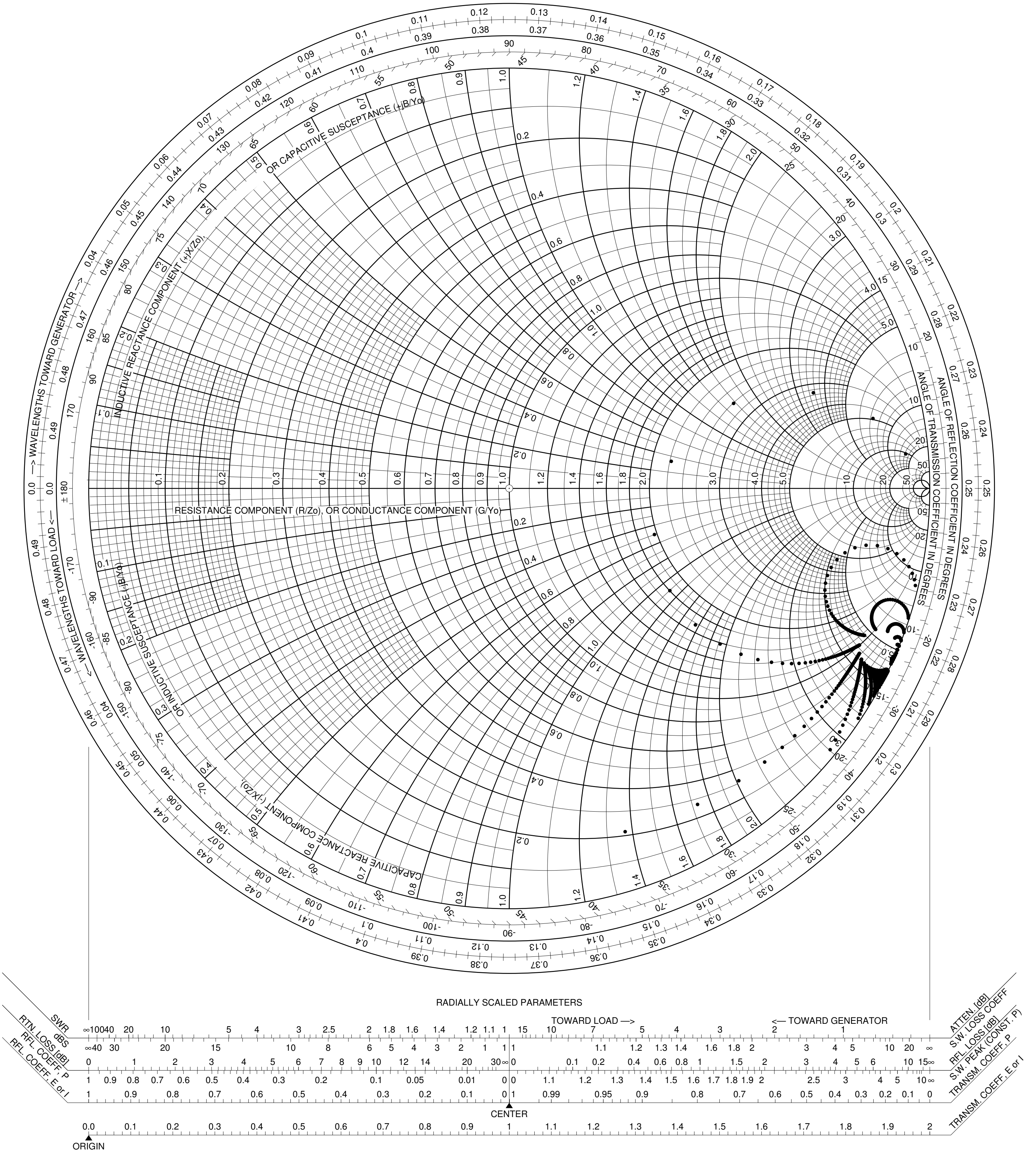
at 21.000 MHz, 4 turn secondary with L3



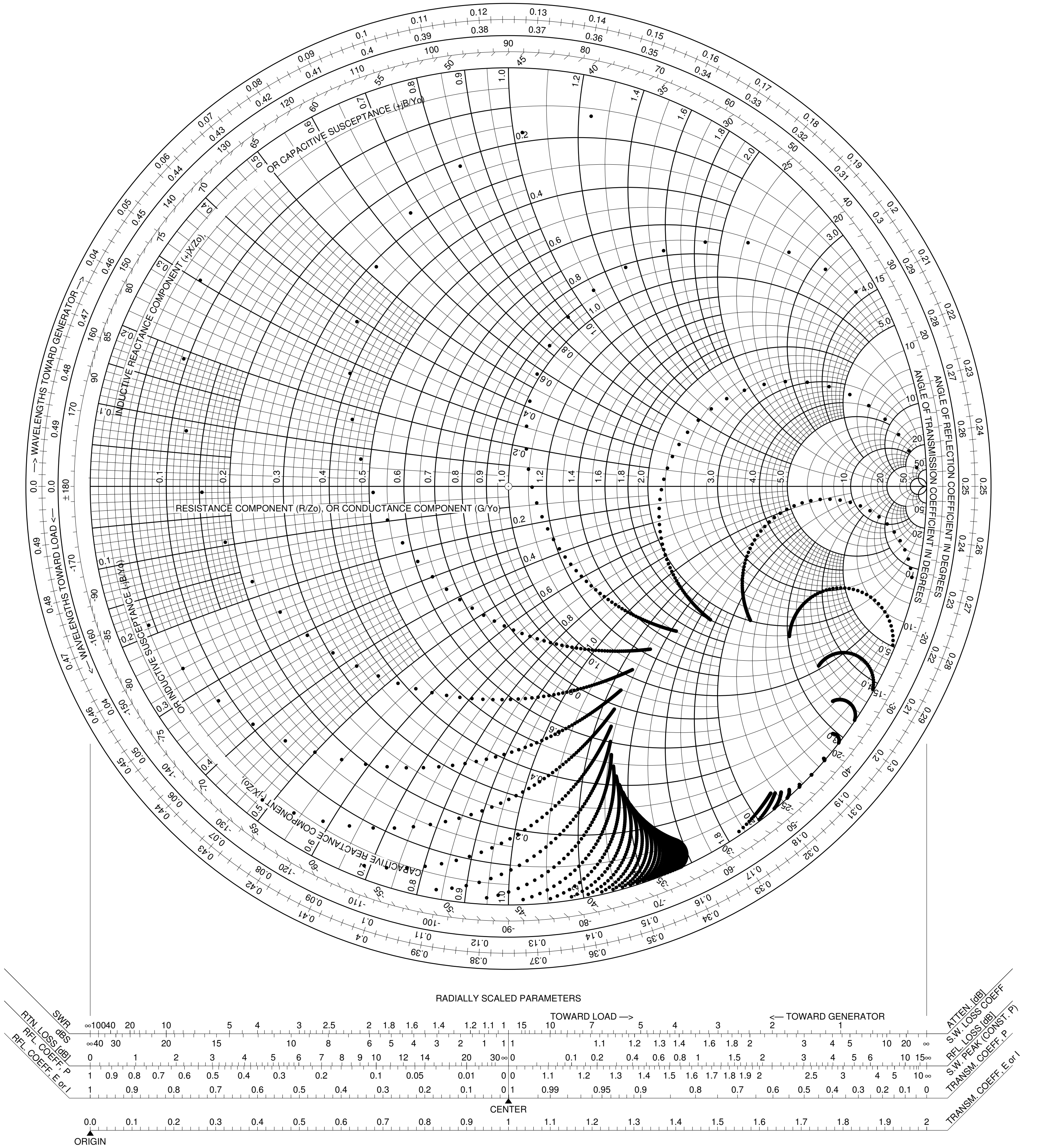
at 21.225 MHz, 3 turn secondary



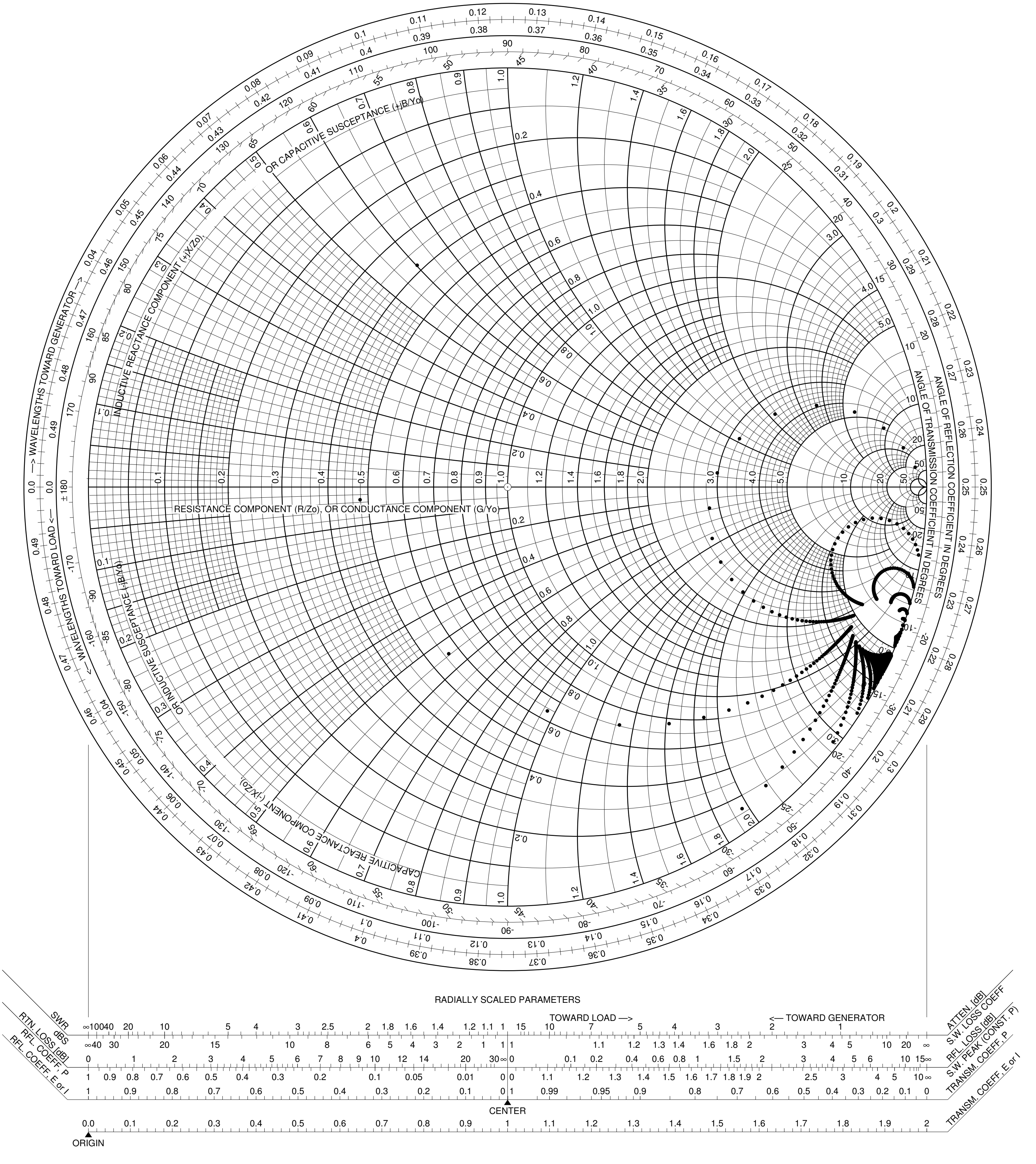
at 21.225 MHz, 3 turn secondary with L3



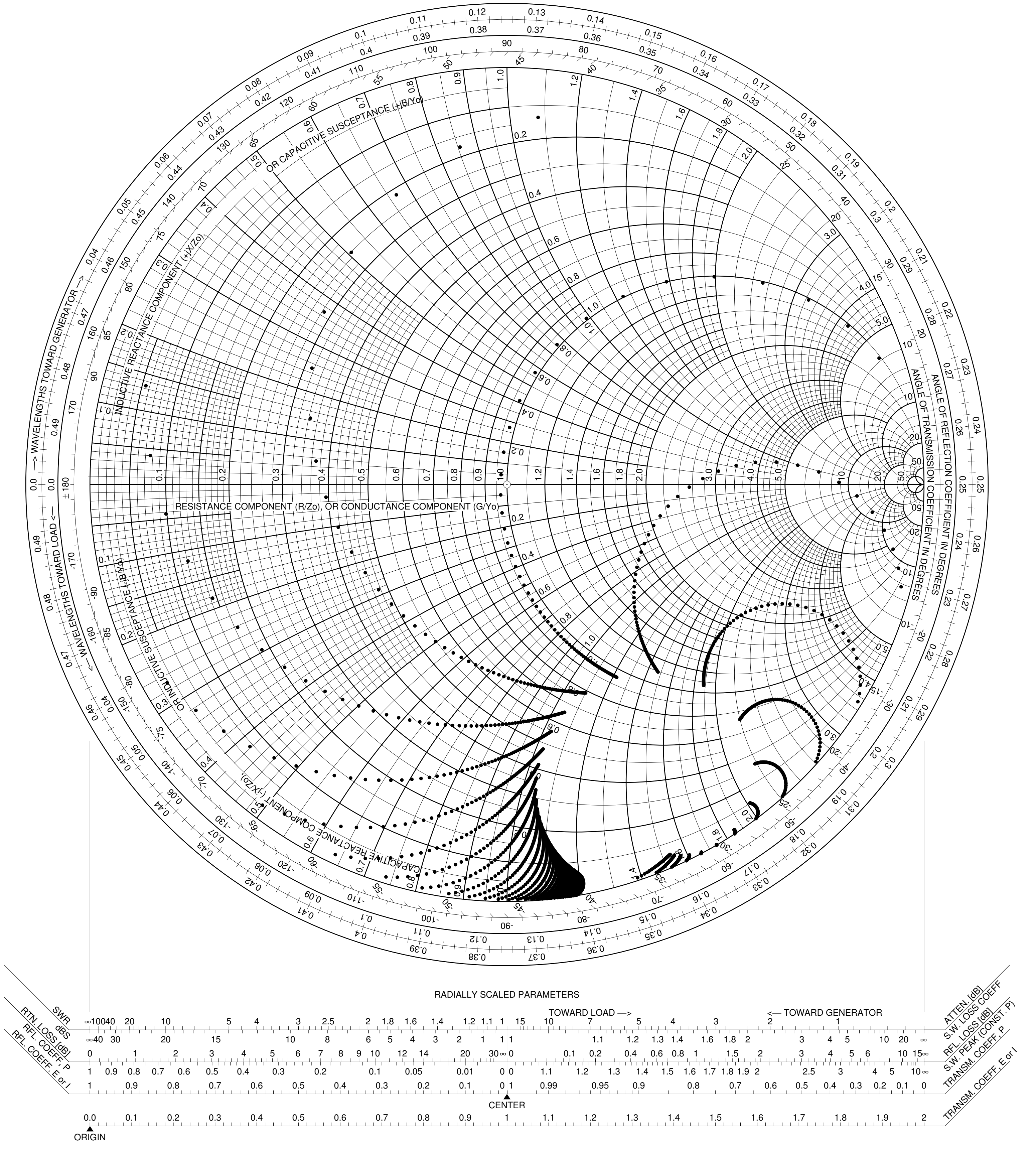
at 21.225 MHz, 4 turn secondary



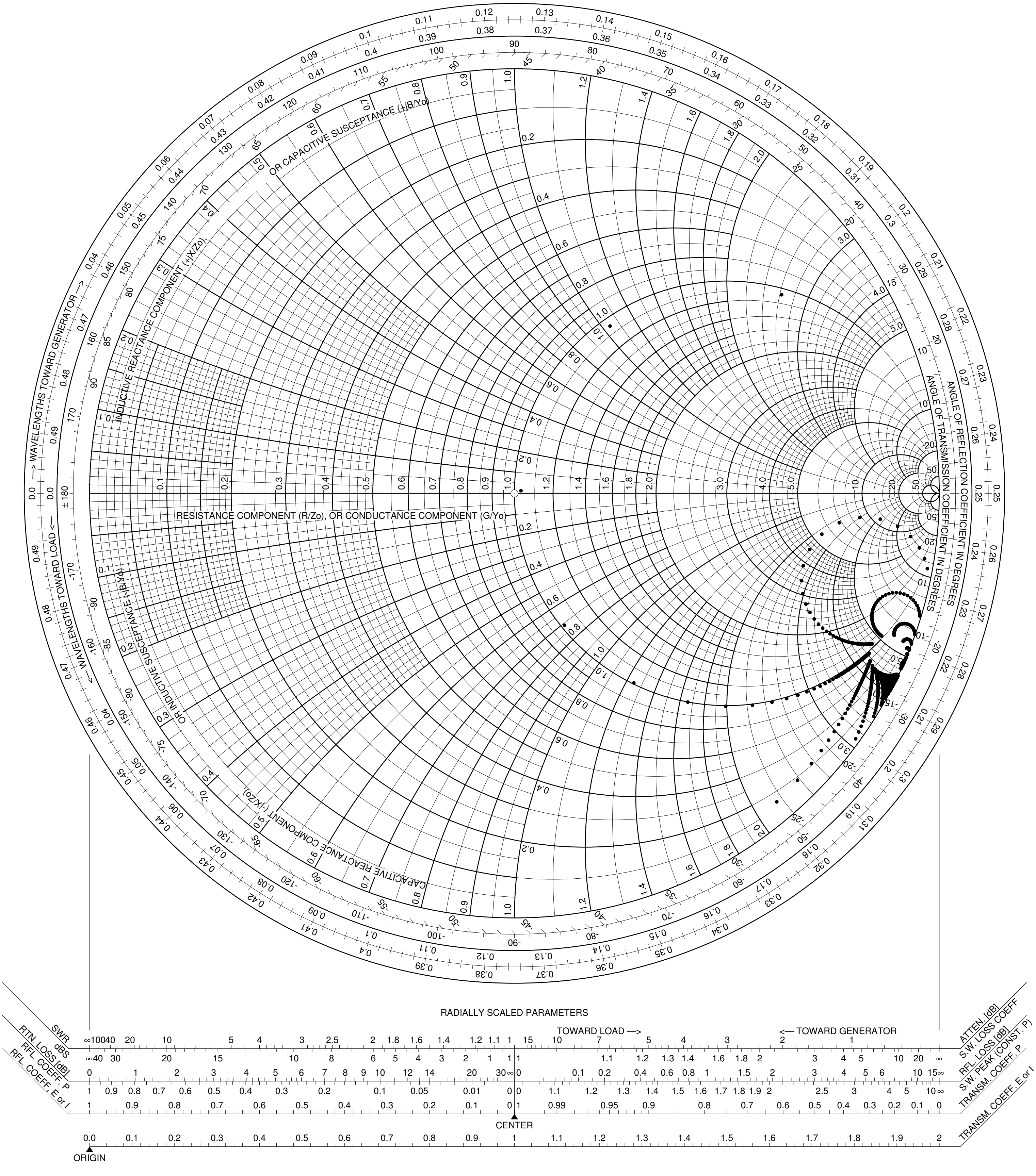
at 21.225 MHz, 4 turn secondary with L3



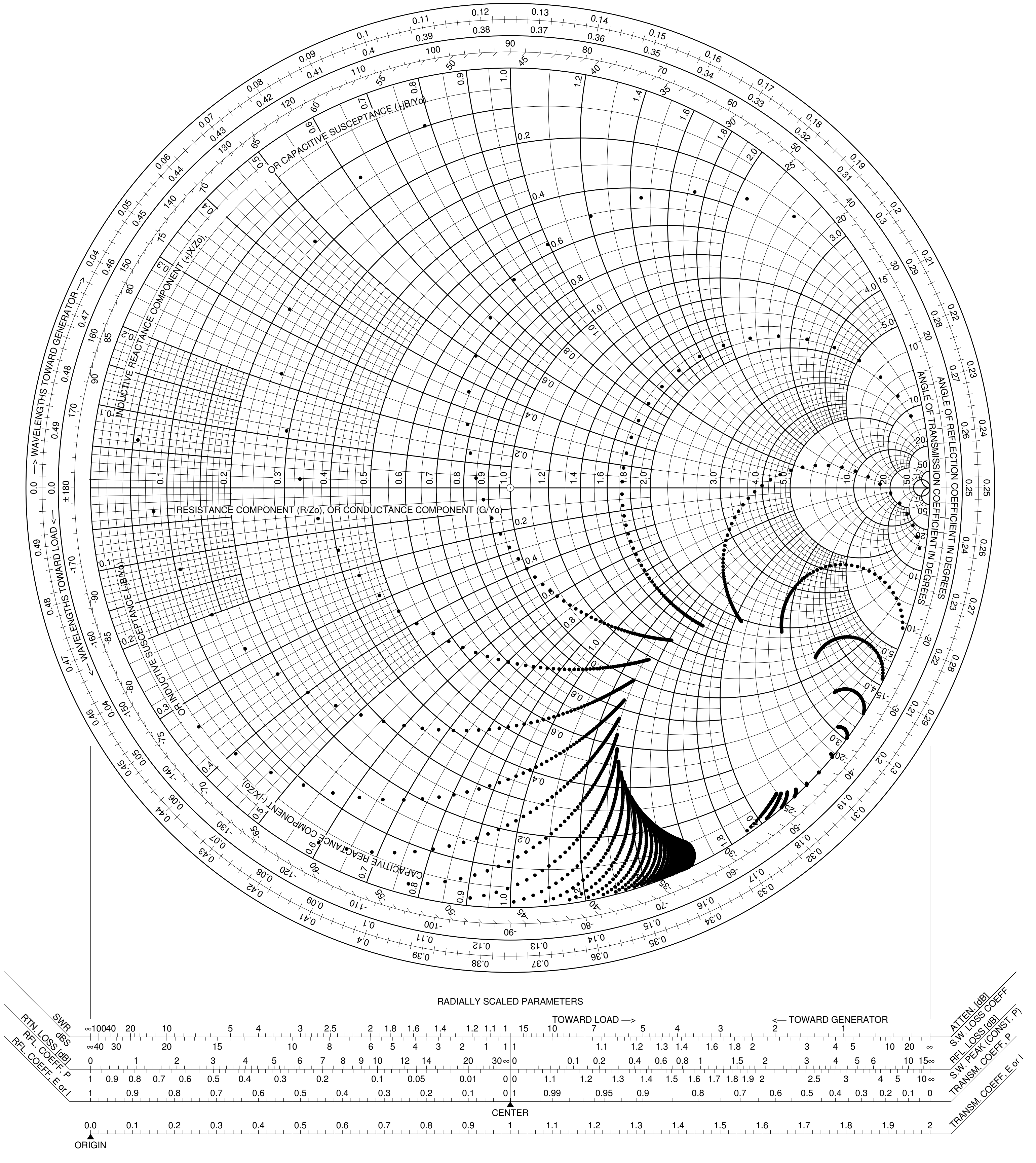
at 21.450 MHz, 3 turn secondary



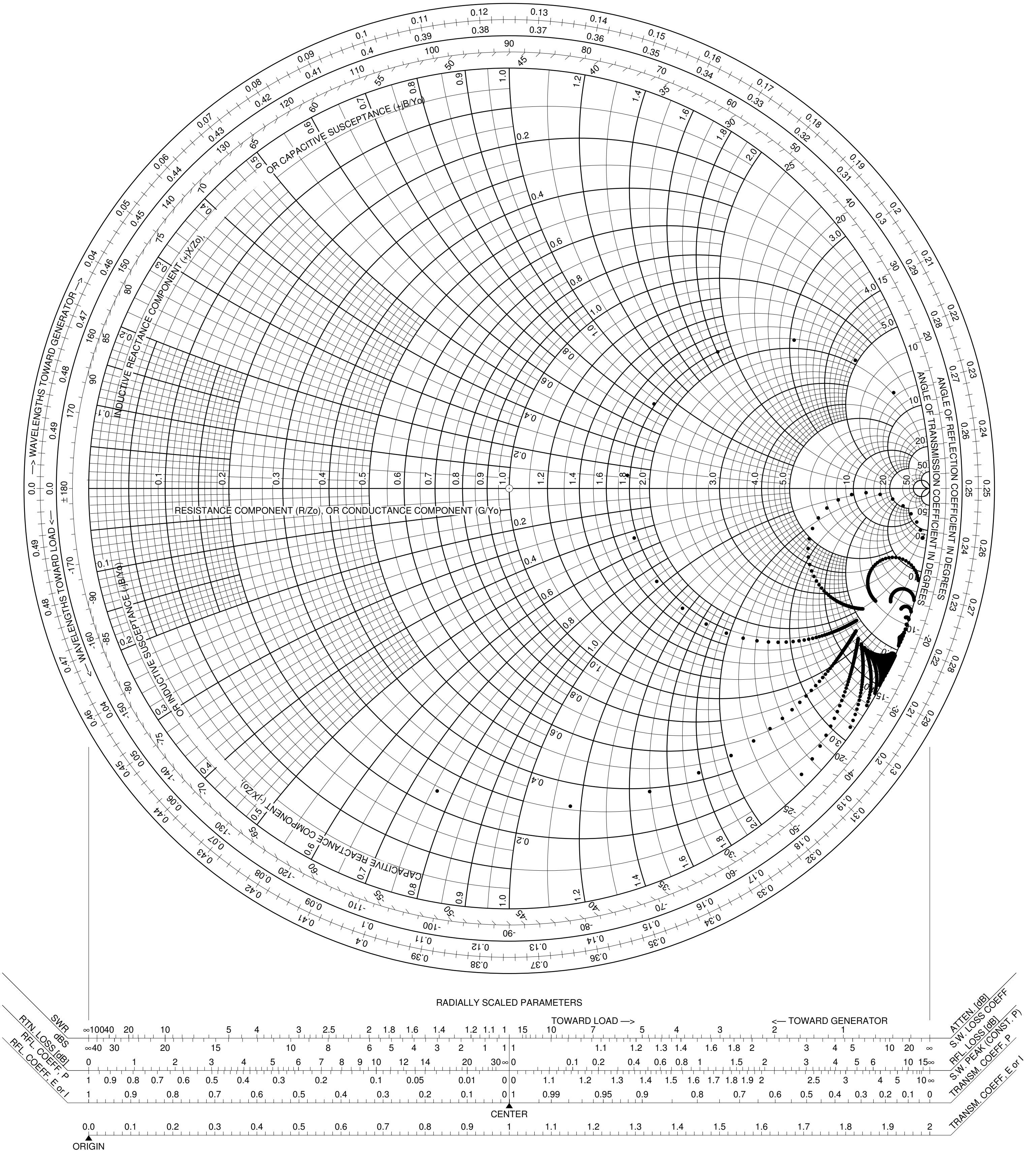
at 21.450 MHz, 3 turn secondary with L3



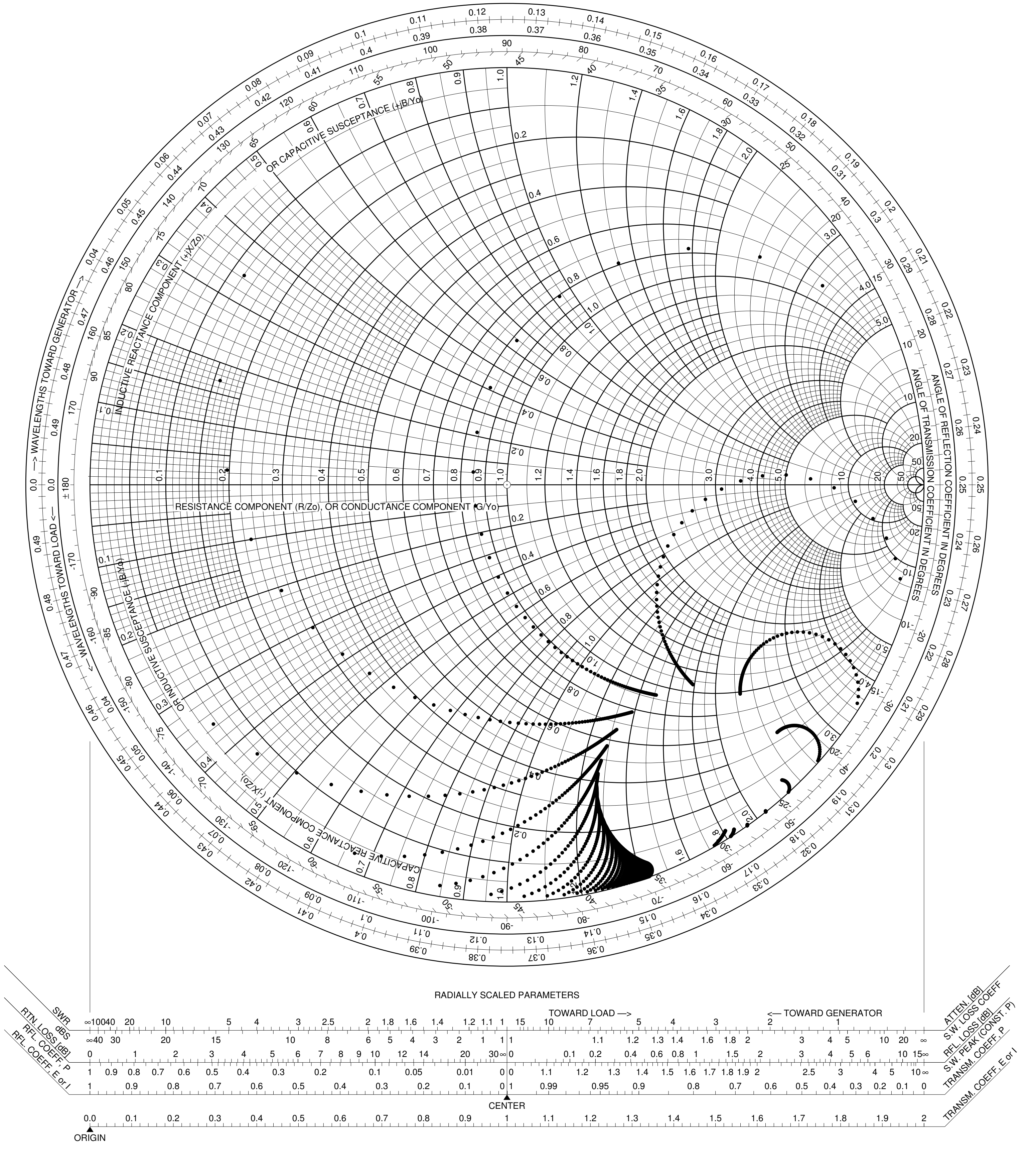
at 21.450 MHz, 4 turn secondary



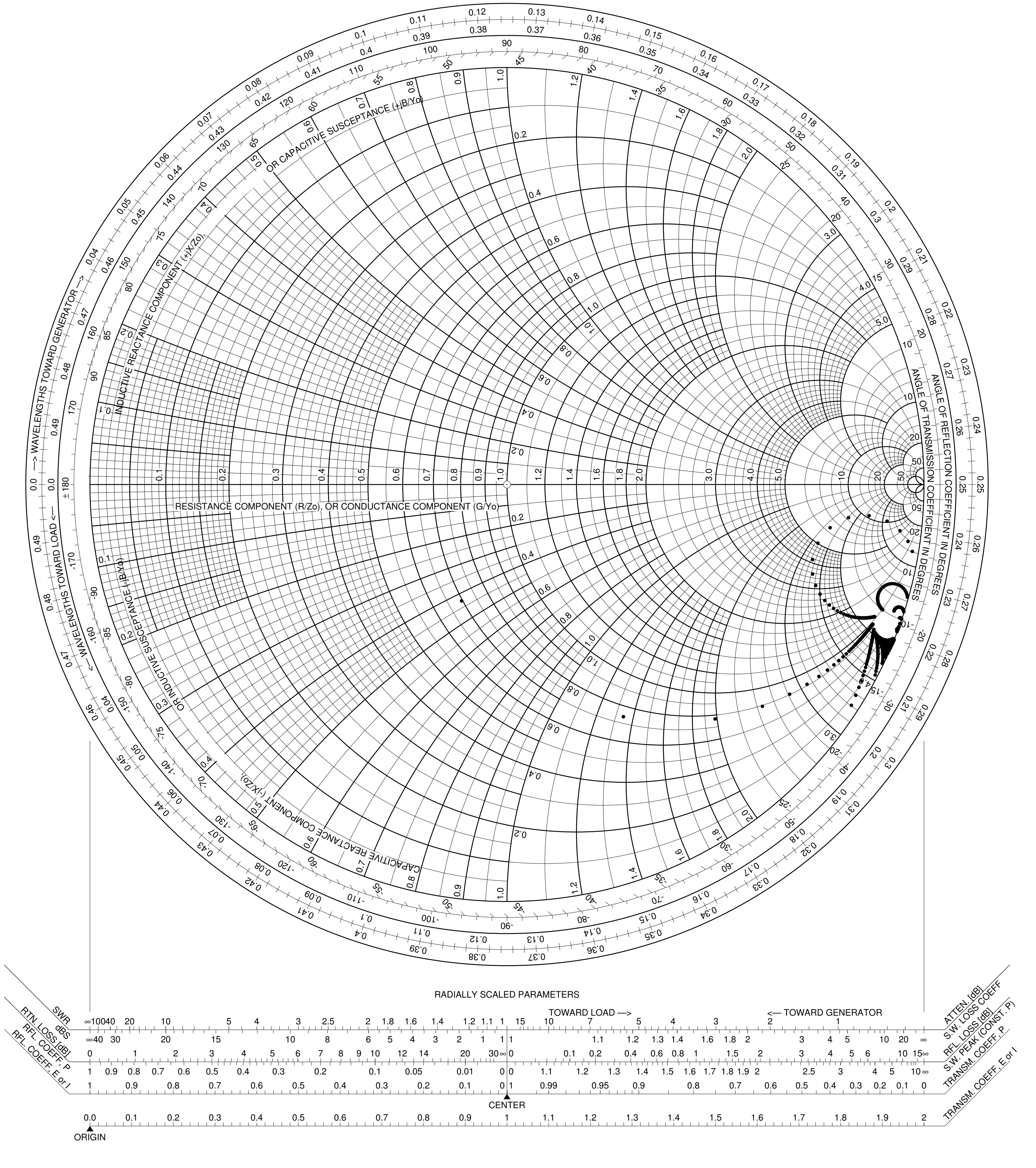
at 21.450 MHz, 4 turn secondary with L3



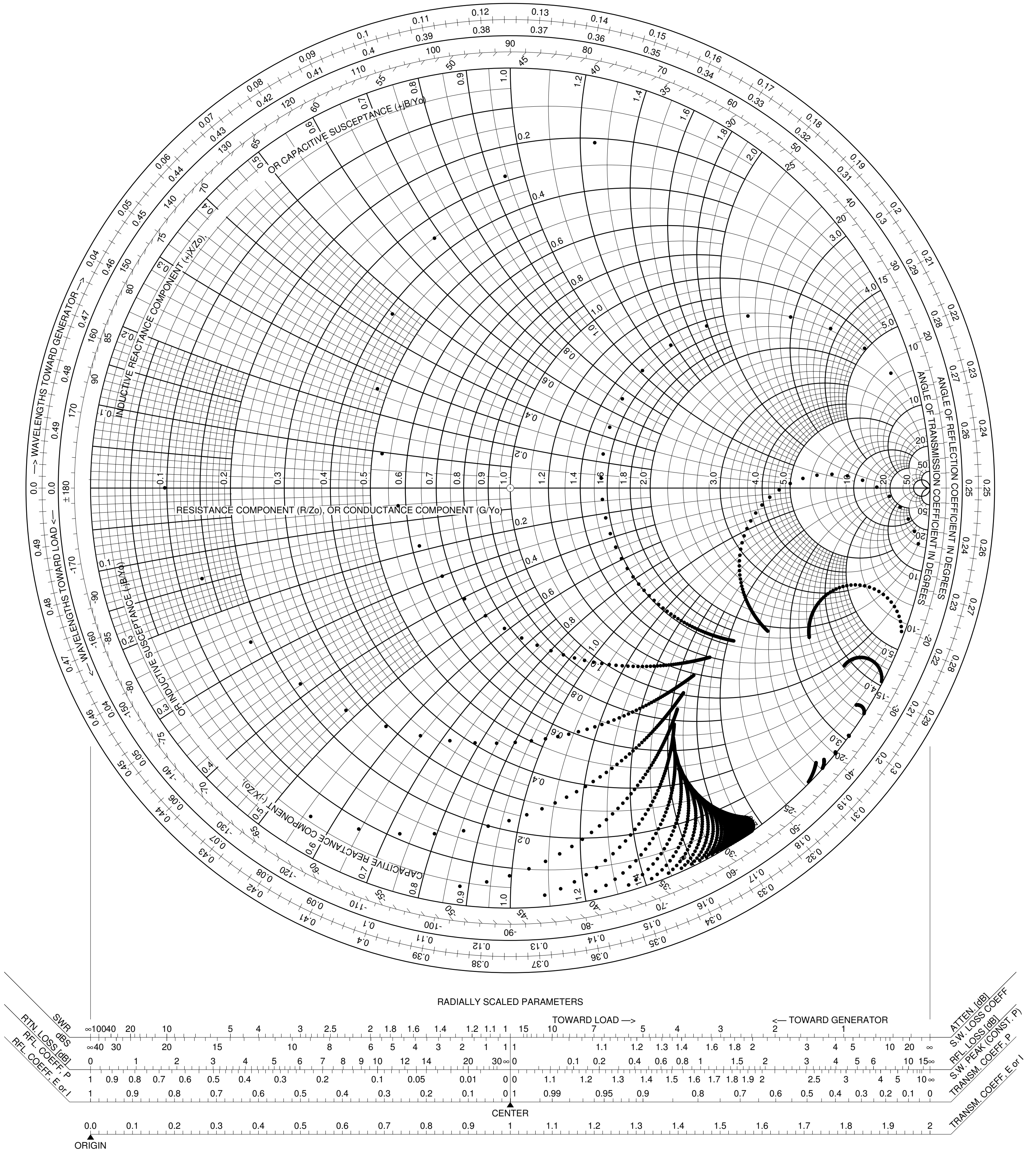
at 24.890 MHz, 3 turn secondary



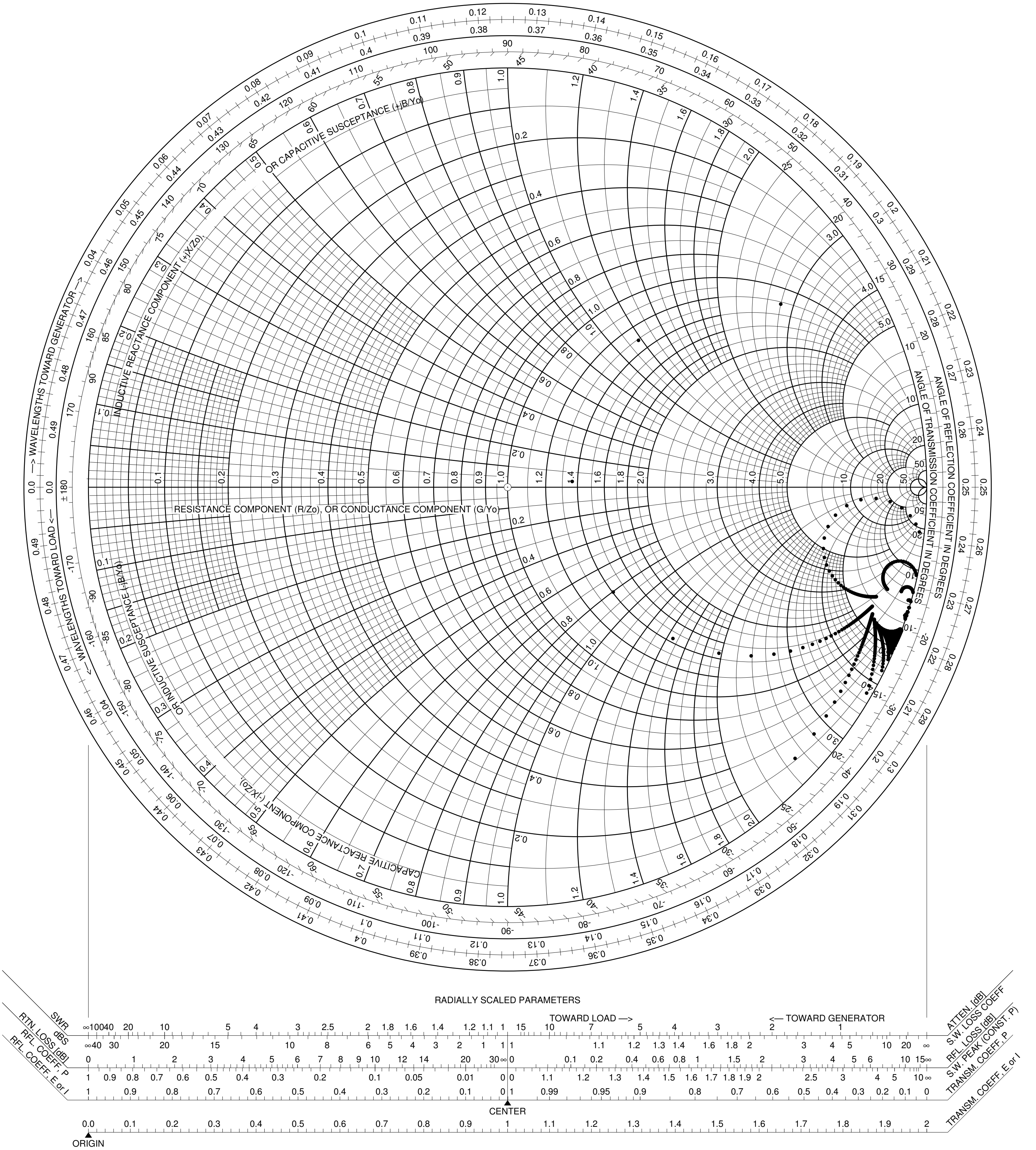
at 24.890 MHz, 3 turn secondary with L3



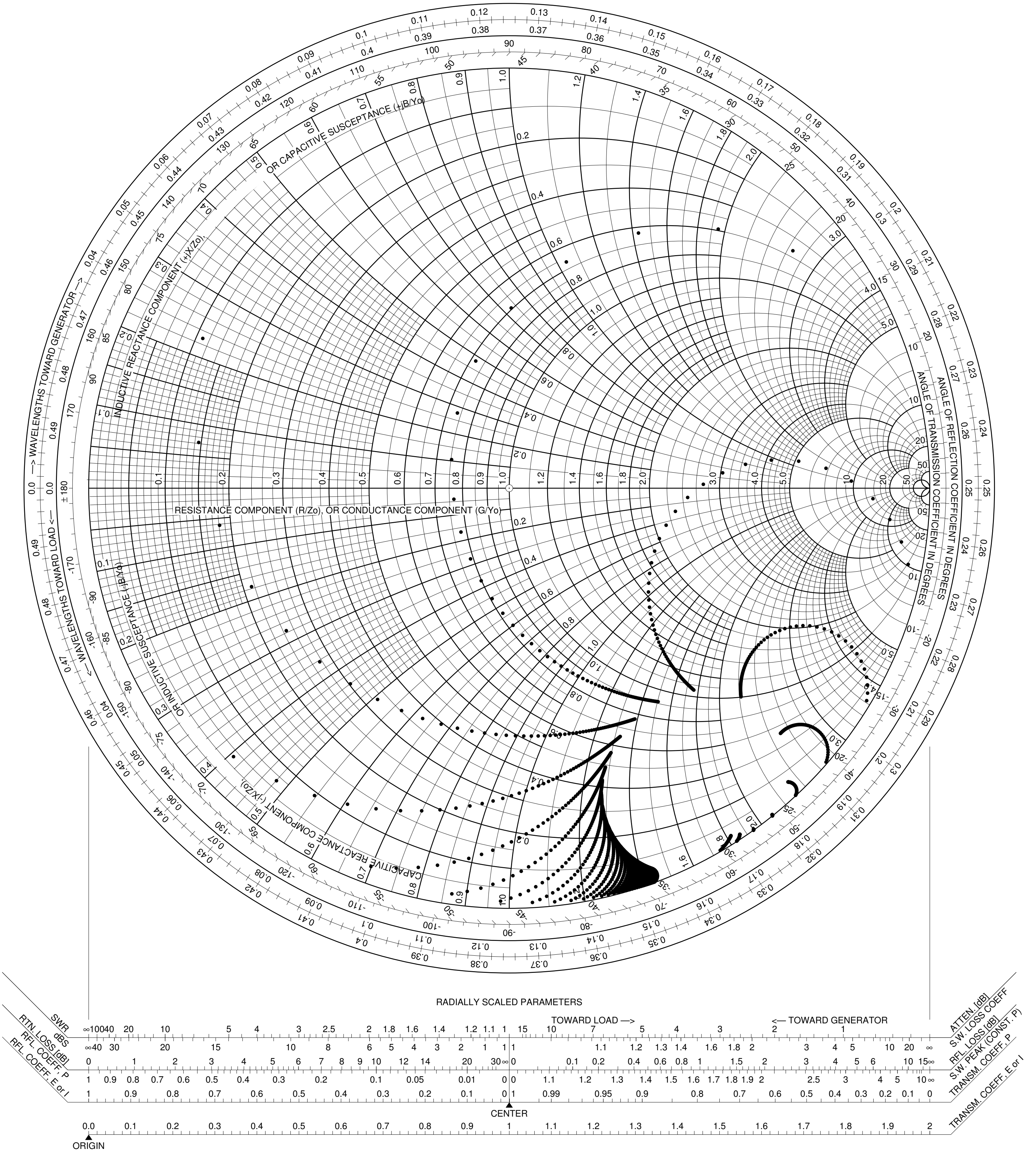
at 24.890 MHz, 4 turn secondary



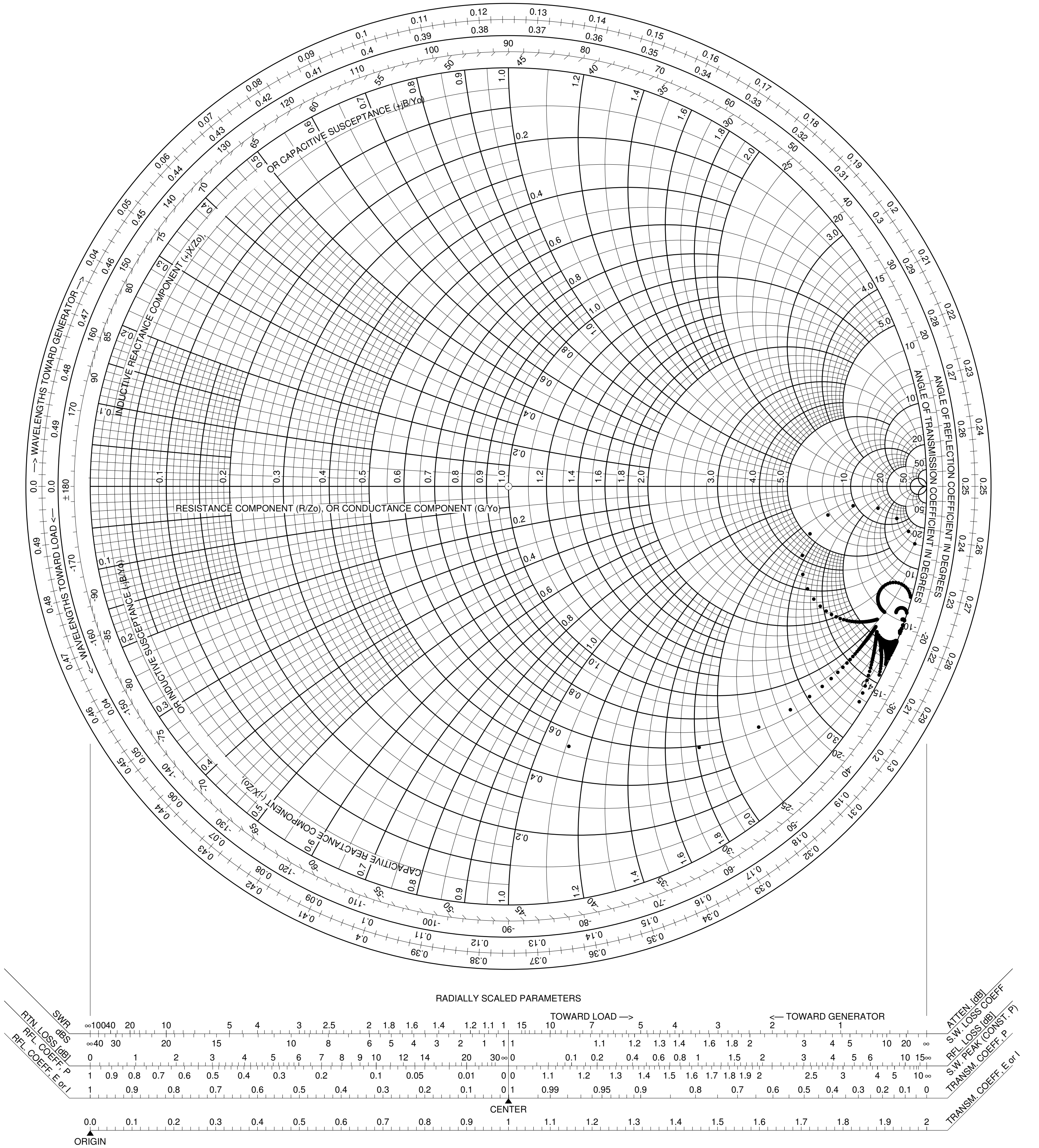
at 24.890 MHz, 4 turn secondary with L3



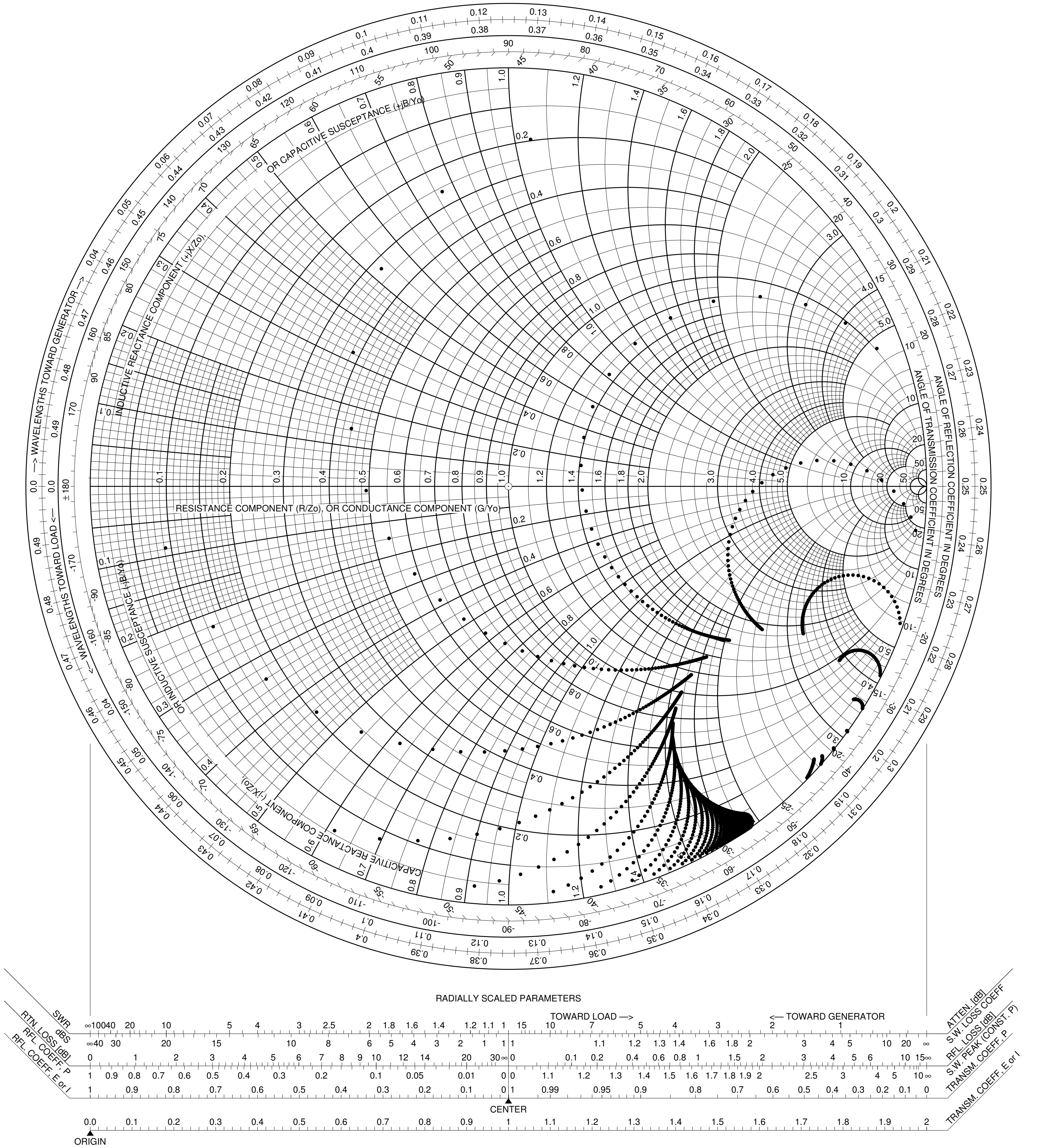
at 24.990 MHz, 3 turn secondary



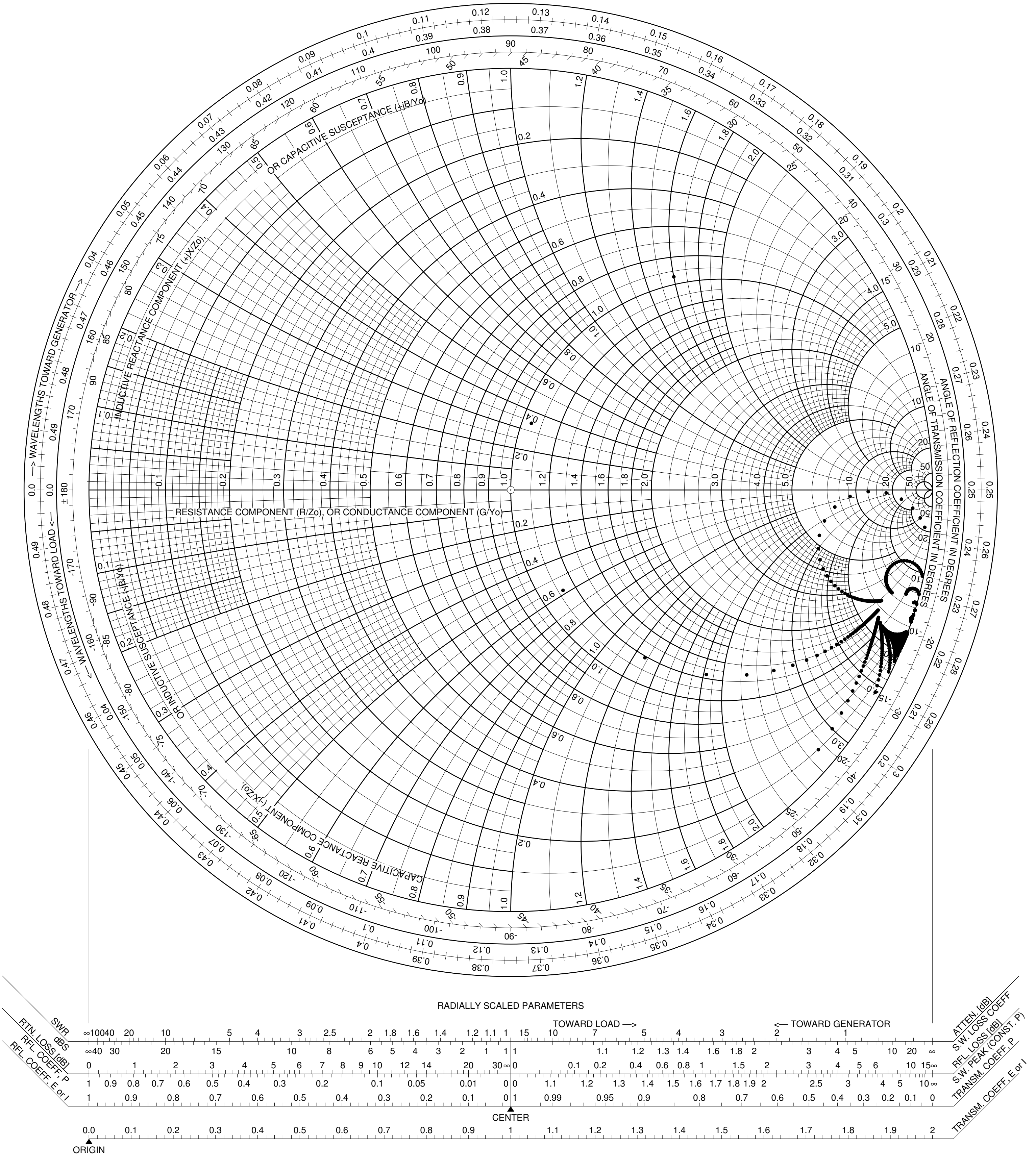
at 24.990 MHz, 3 turn secondary with L3



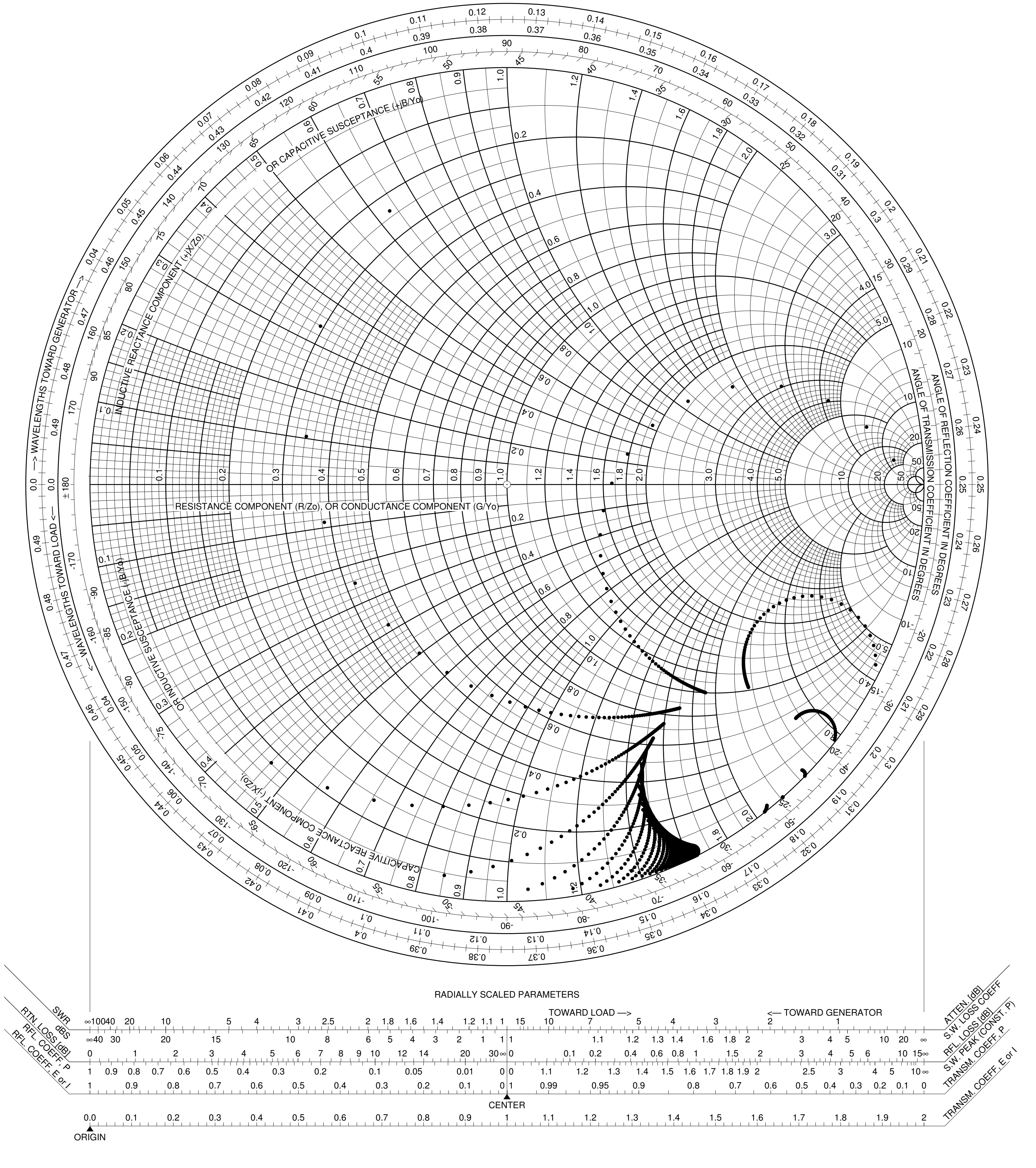
at 24.990 MHz, 4 turn secondary



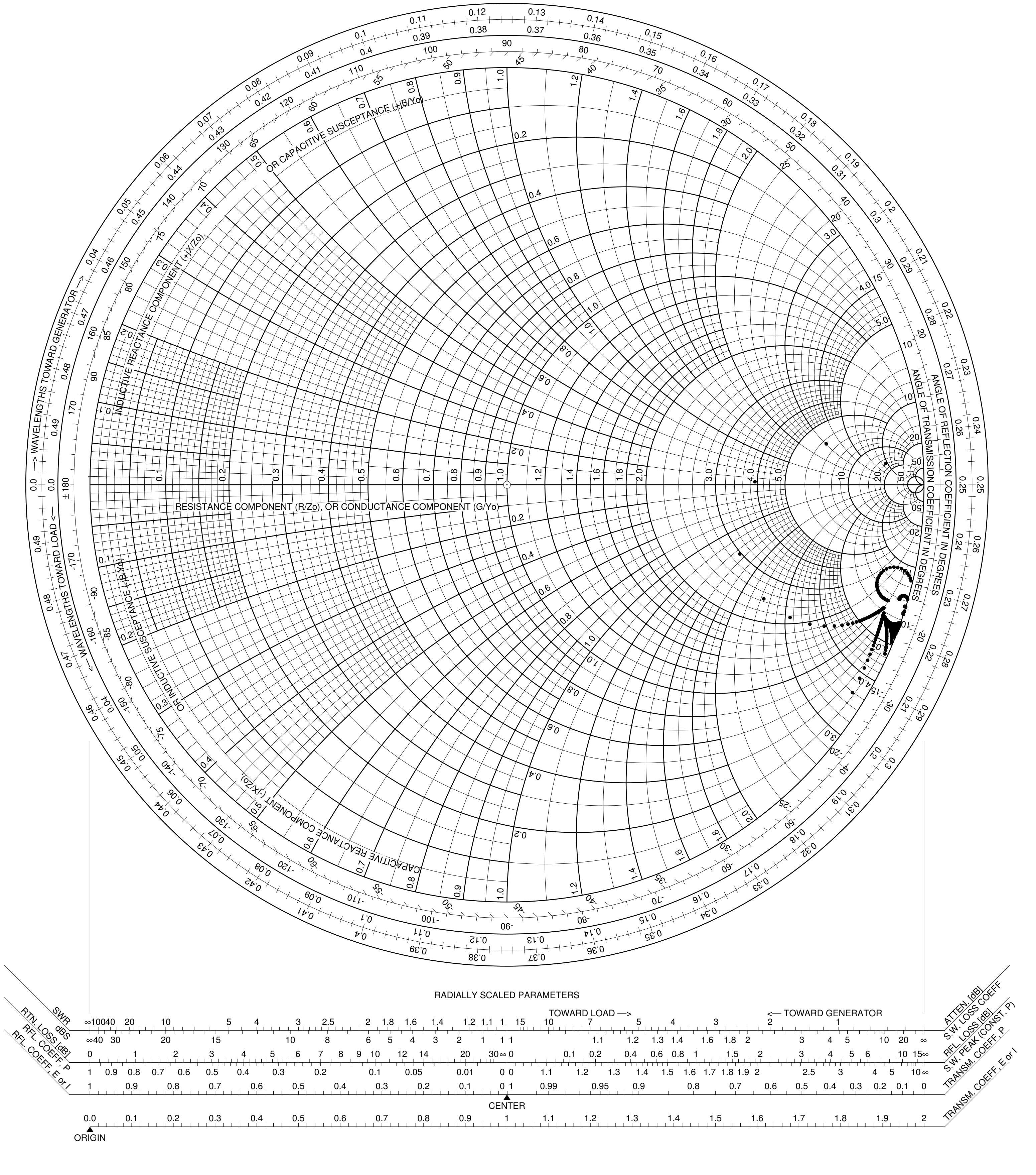
at 24.990 MHz, 4 turn secondary with L3



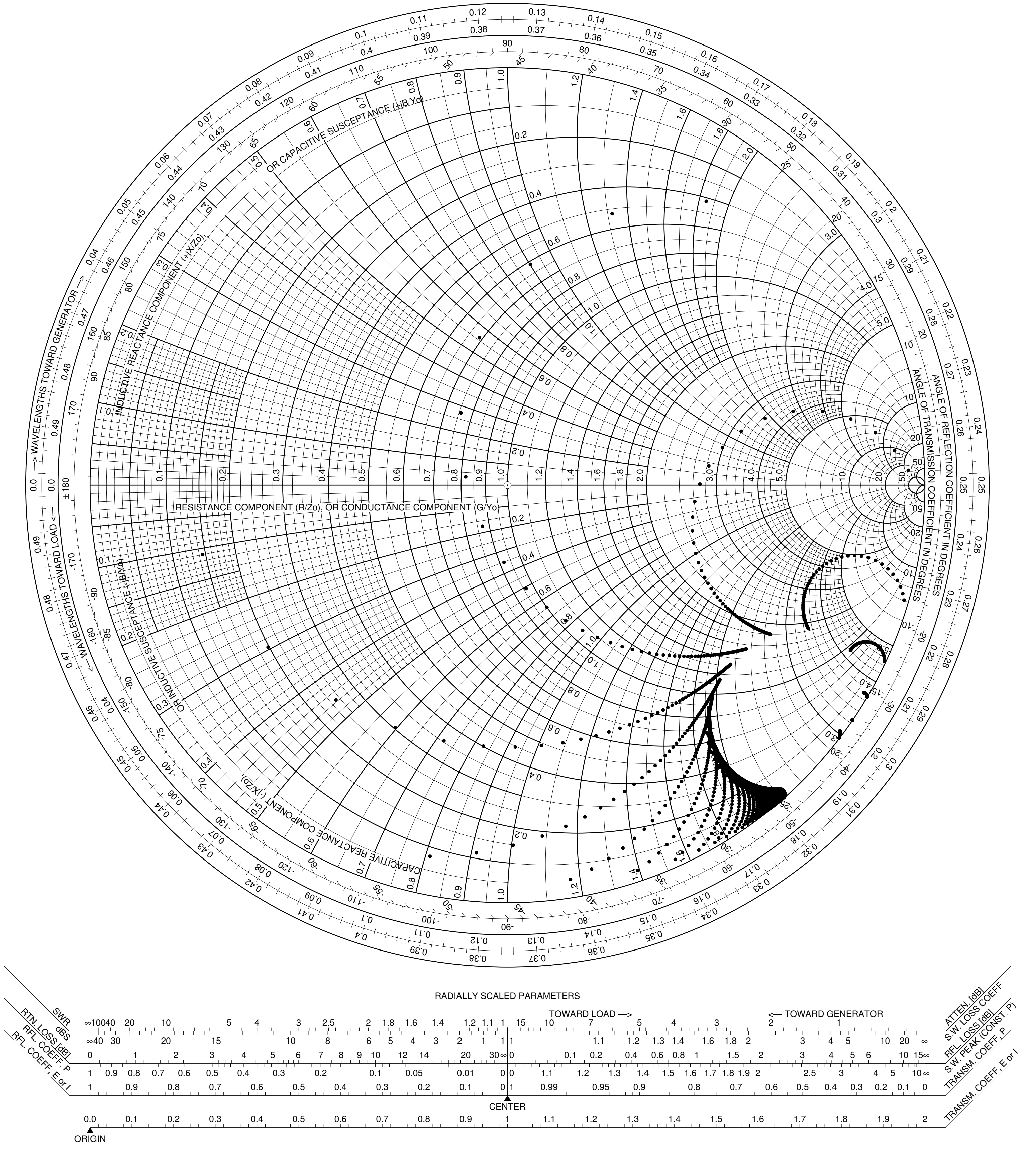
at 28.000 MHz, 3 turn secondary



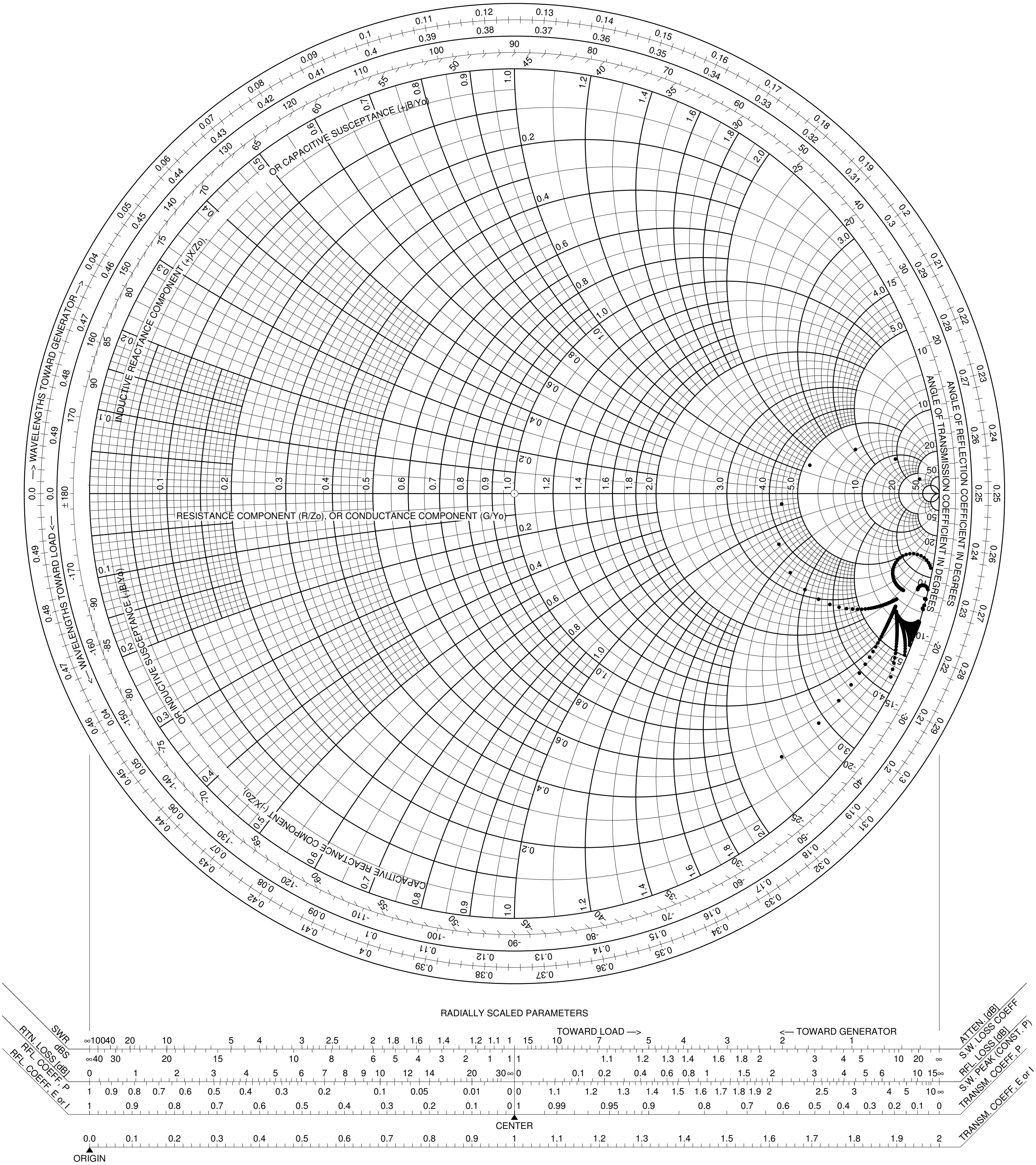
at 28.000 MHz, 3 turn secondary with L3



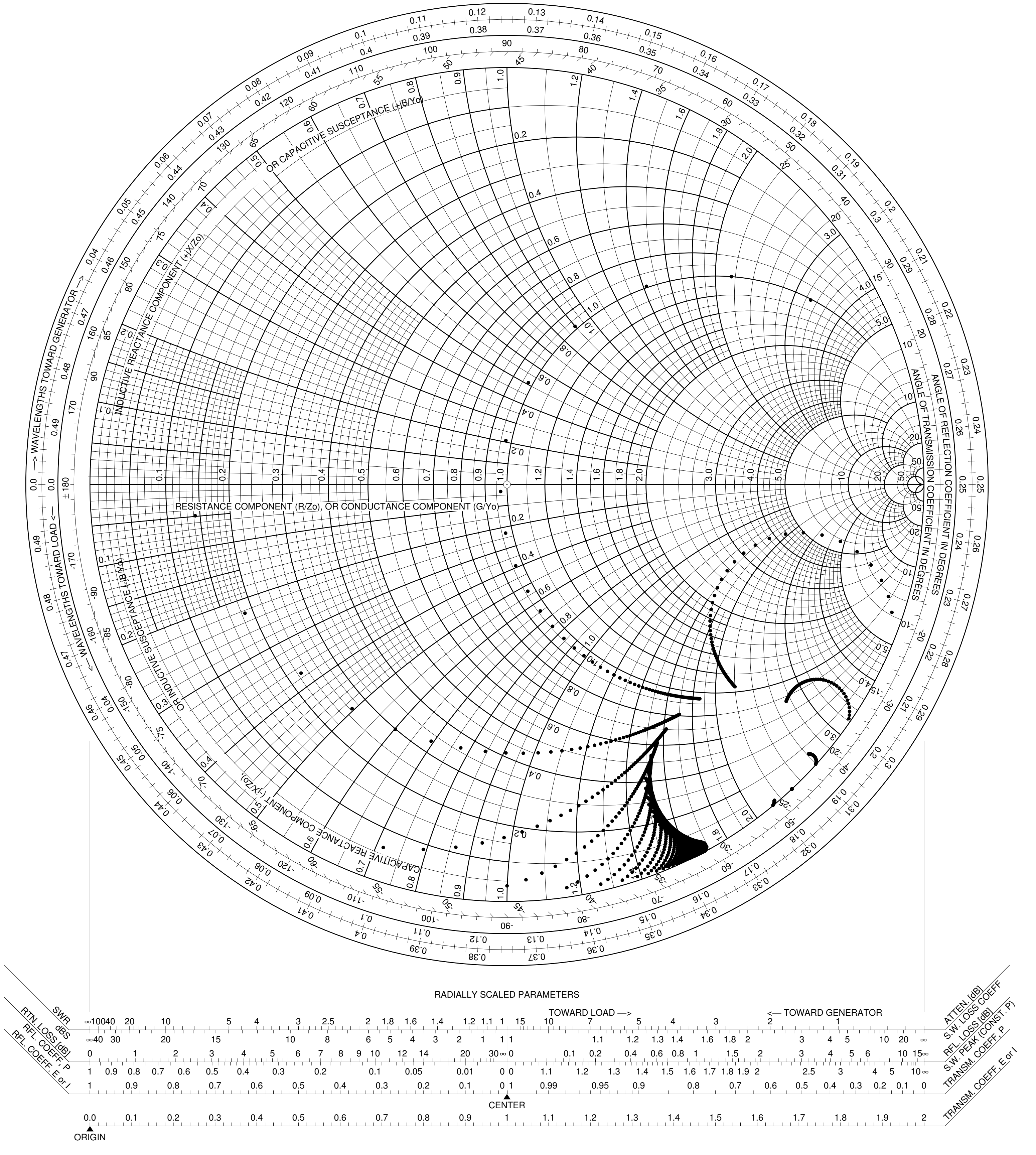
at 28.000 MHz, 4 turn secondary



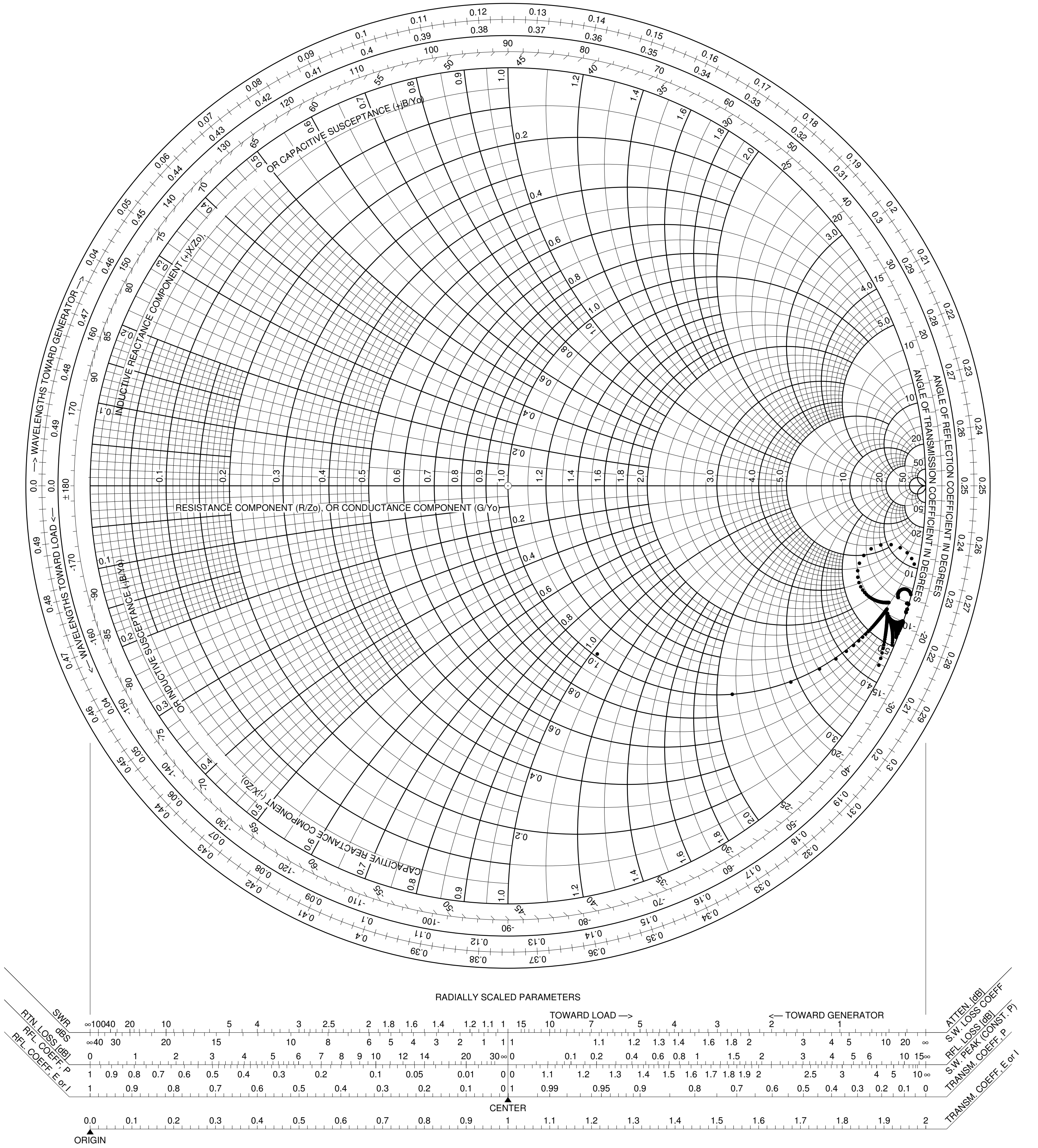
at 28.000 MHz, 4 turn secondary with L3



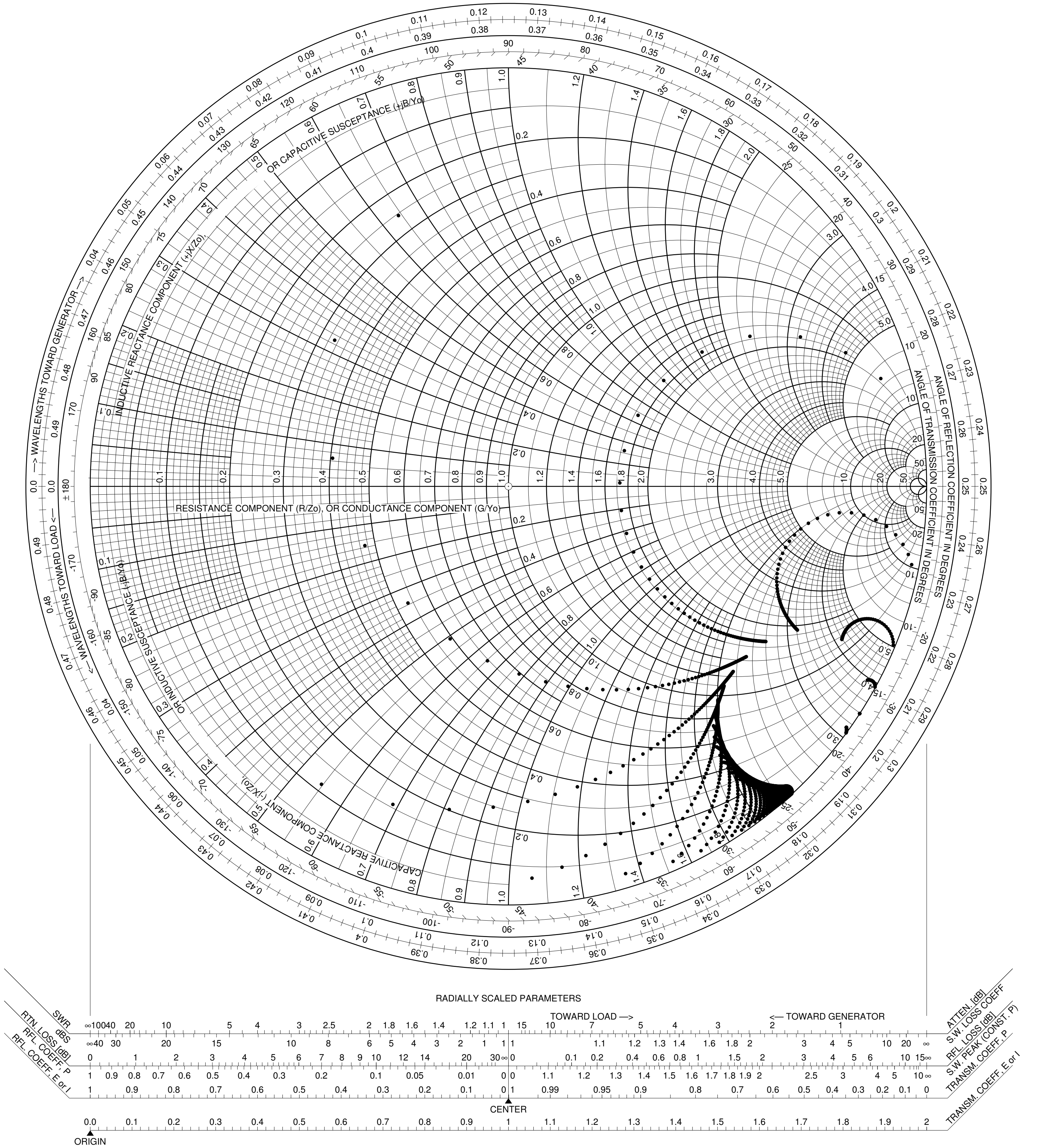
at 28.600 MHz, 3 turn secondary



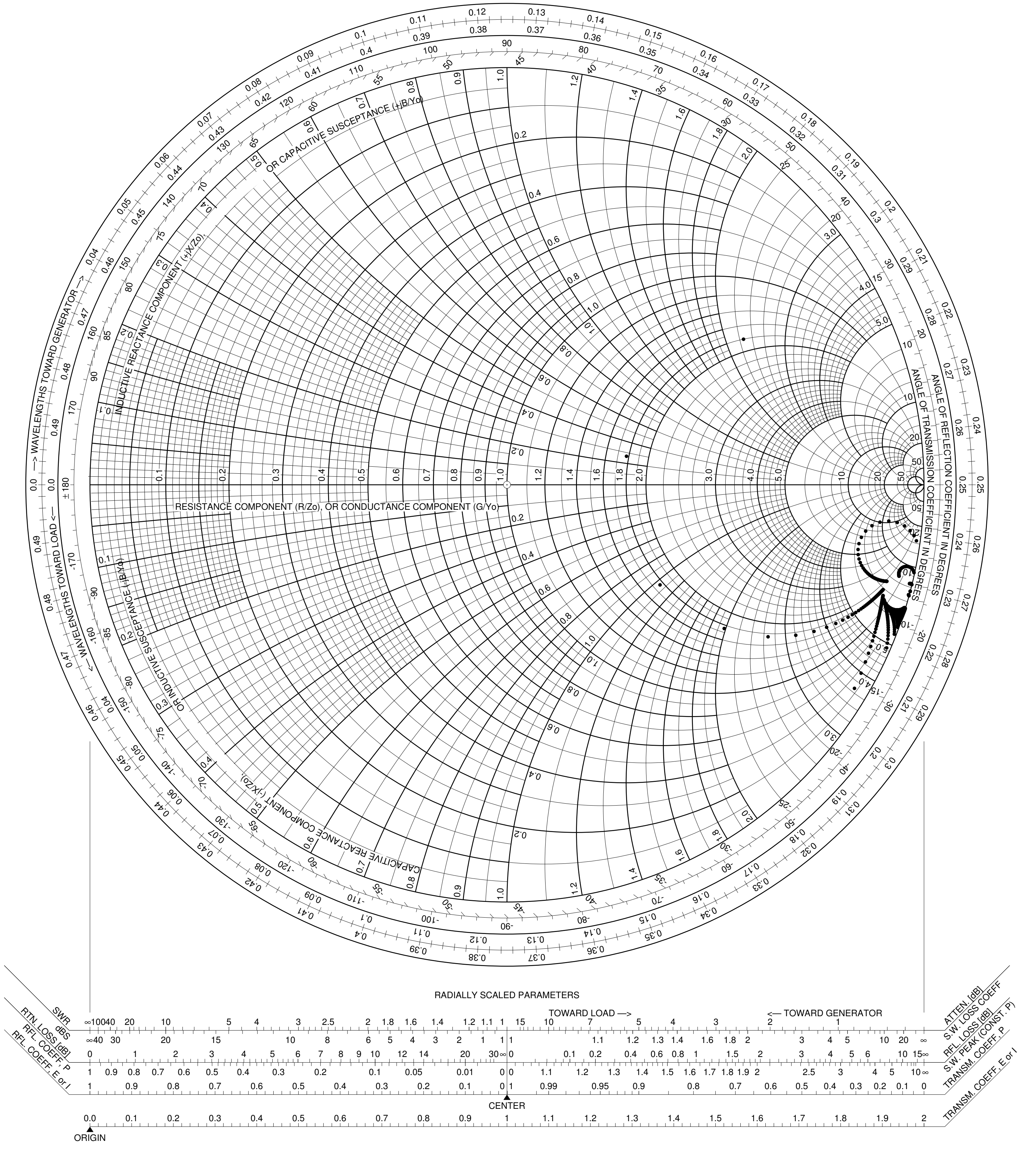
at 28.600 MHz, 3 turn secondary with L3



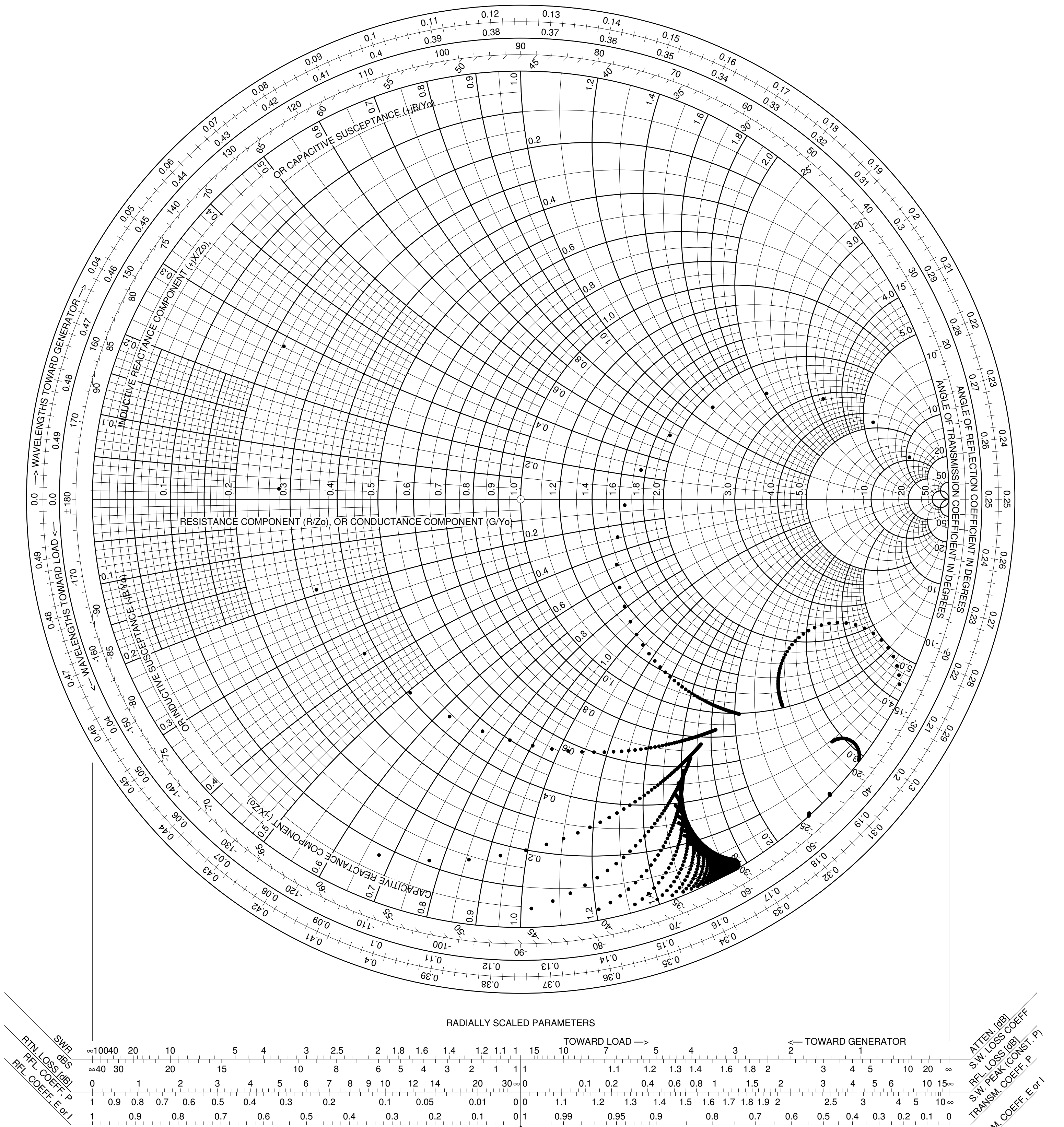
at 28.600 MHz, 4 turn secondary



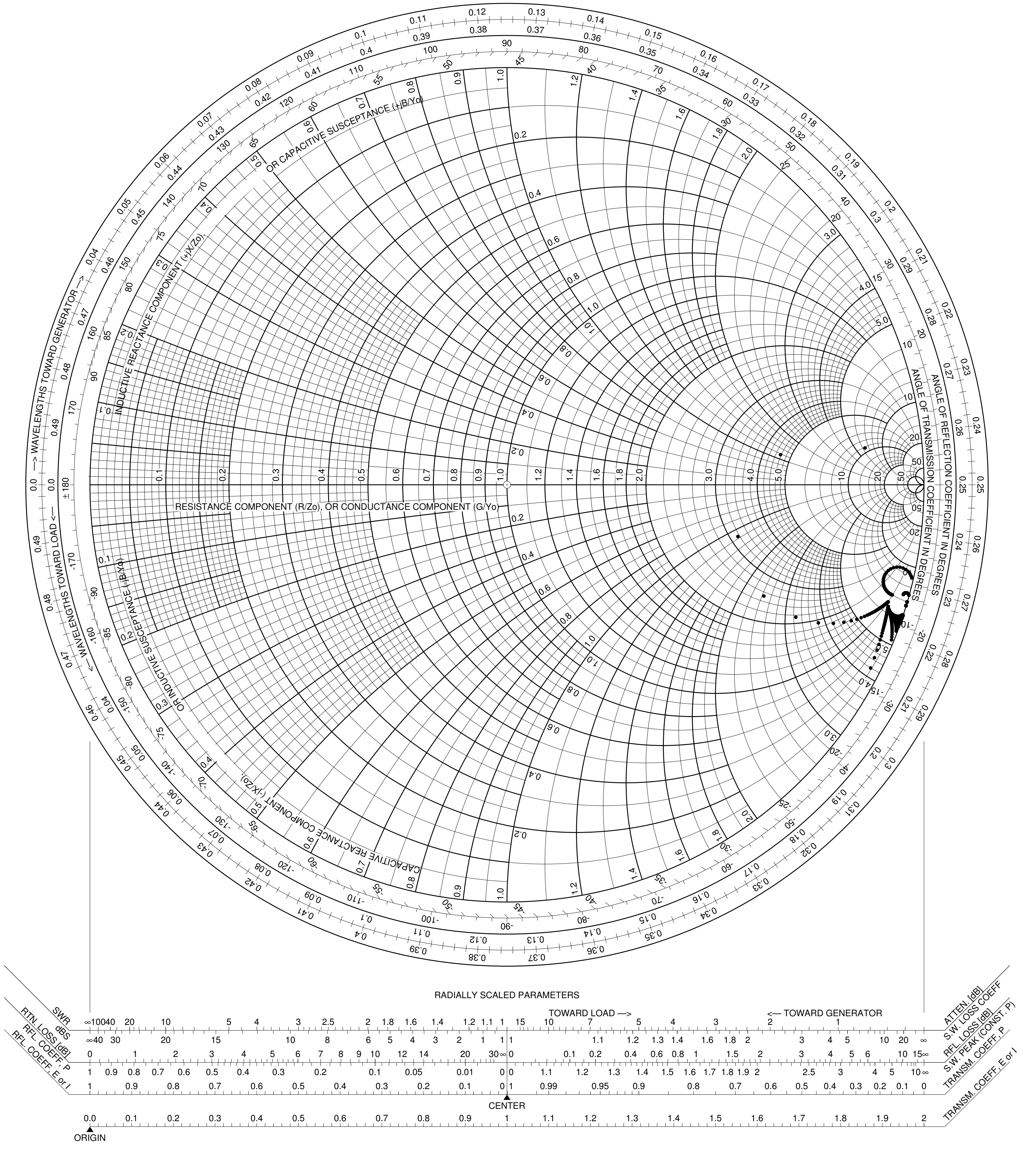
at 28.600 MHz, 4 turn secondary with L3



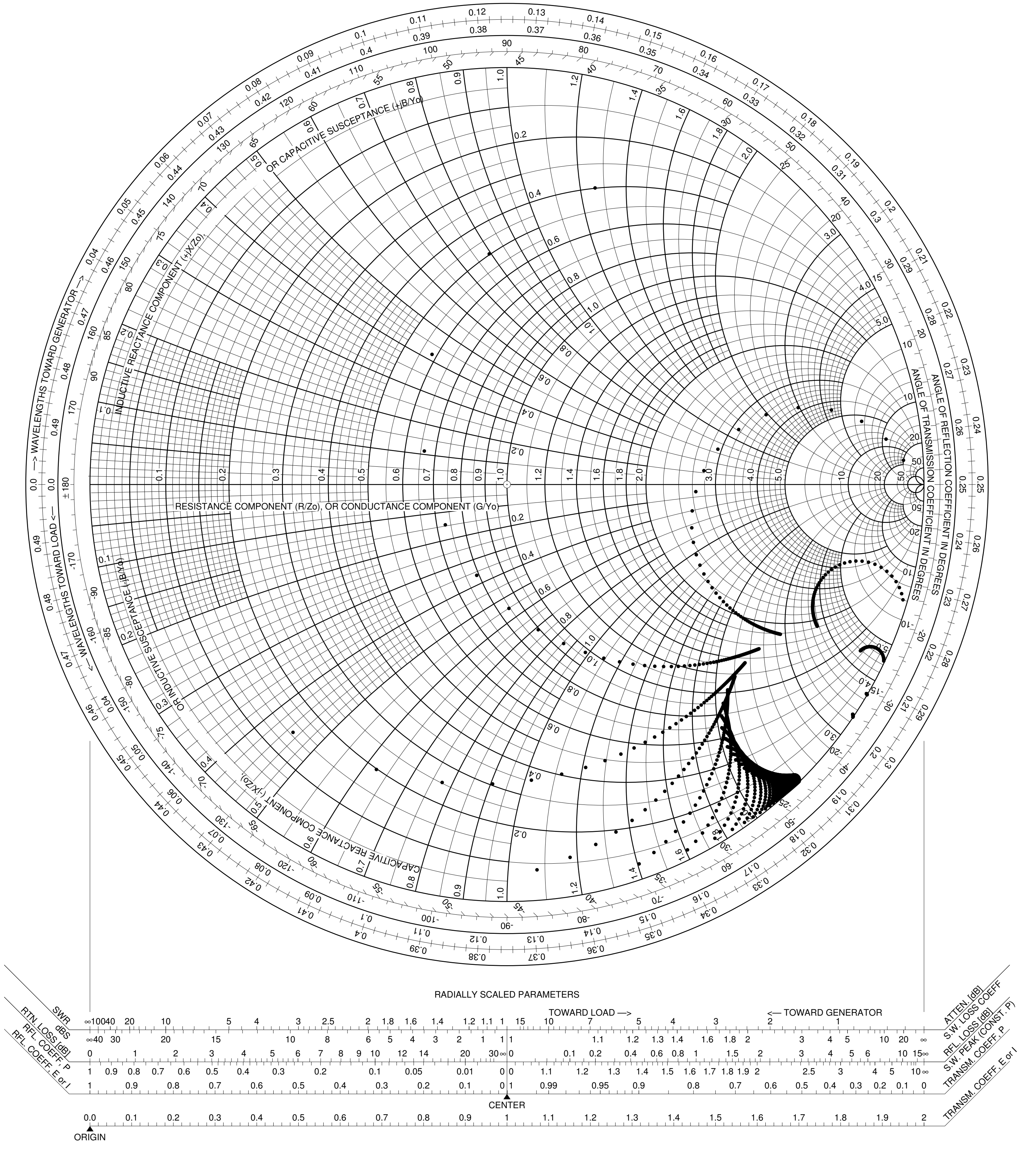
at 29.700 MHz, 3 turn secondary



at 29.700 MHz, 3 turn secondary with L3



at 29.700 MHz, 4 turn secondary



at 29.700 MHz, 4 turn secondary with L3