Analysis of Alternative Ring Resonator Designs

by Christopher S. Kenyon

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14. ABSTRACT

Variants of a ring resonator for measurement of dielectric constants of soil were modeled using FEKO computational electromagnetic software with the aim of improving performance. The variations explored included use of an alternative dielectric laminate, with lower dielectric constant and dissipation factor, various thicknesses of the laminates, and opening the ring on one side so as to change the ring strip to a "C" shaped strip. Comparisons of changes in the resonances appearing in the frequency dependent S21 parameter of the antenna were analyzed to assess potential performance improvements in the respective antenna designs. For these new designs computer modeling showed that the major sensitivity of the ring resonator was still within the first 2 mm of the surface of the soil in contact with the ring strip of the antenna as in the case of the original design. Both the alternative dielectric laminate and the increased thickness laminate reduced sensitivity to changes in the measured parameters, namely the frequency ratios and changes in the inverse Q. These alternatives did both generally increase the penetration of the sensing region, but they still left more than 80% of the sensing effect within the first 2 mm of the soil sample. The modeling further confirmed the limited sampling depth or volume for the soil helping to explain the difficulty in measuring all but very homogeneous samples. Also, it was inferred that finer sampling of the S21 curves could substantially improve the relative error in determining the soil dissipation factor.

15. SUBJECT TERMS

soil, dielectric, measurement, resonator, dissipation

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1. Introduction

Knowledge of soil electrical properties is crucial for understanding how electromagnetic waves interact with the soil. It is crucial for understanding how electromagnetic waves such as radar waves are reflected from soil and penetrate into it. In particular, knowledge of these properties is critical for detection and location of targets in and on soil.

Since targets may be buried in the soil and soil properties vary with depth, knowledge of the properties beneath the surface rather than just very near the surface would give more certainty to detection by radar for buried objects. Furthermore, for a radar detection system that is moving over the ground, the ability to determine soil electrical characteristics without touching the soil would also be a great advantage.

In this study I explore variations of a ring resonator designed by Gregory Mazzaro[1] with the aim of improving soil penetration. Specifically, my explorations are by means of computer models of the ring resonator variations. The ring resonator consists of a two-port circuit board antenna which, when placed in contact with soil or a sample thereof, reveals the real and complex dielectric constants of the soil. With this device as is, however, soil dielectric constants can only be measured at the surface or down through a depth of about 1 in, and even then, 90% or more of the sensitivity is for the first 2 mm of that depth.

Measurement of the antenna's S_{21} parameter as a function of frequency using a network analyzer allows computation of the soil dielectric constants. The measurement shows a sequence of resonance peaks on the analyzer. The resonance curves are measured with and without the soil. The frequency shift of the peaks gives the real dielectric constant, $Re\{\varepsilon_r\}$, of the soil, where ε_r is the dielectric constant or relative permittivity. Measurement of the change in Q of the peaks allows determination of the loss tangent, $\tan \delta$, or the imaginary part of the dielectric constant, $Im\{\varepsilon_r\}$, where $\tan \delta = Im\{\varepsilon_r\}/ Re\{\varepsilon_r\}$.[1]

Two approaches I explored through computer modeling were to use a different substrate and to open the central loop of the antenna. In the first case, as an alternative to the Rogers 4350B Laminate used in Mazzaro's ring Resonator I modeled resonators using Rogers Duroid 5880 Laminate. In the second case I explored opening the central ring in his Ring Resonator to change the field pattern and to allow lower frequency resonators, but with the same sized device. The Duroid 5880 has a lower dielectric constant, $Re\{\varepsilon_r\}$, at 2.3 and a much lower dissipation constant or "$\tan \delta$" where $\tan \delta = 0.001$. The Rogers 4350 Laminate has $Re\{\varepsilon_r\} = 3.66$ and $\tan \delta = 0.0031$. The effect of different thicknesses of the laminate on resonator performance was also explored.

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[1]Mazzaro, G. et al. *Portable Ring-Resonator Permittivity Measurement System*: Design and Operation by Gregory Mazzaro, et al.; ARL-TR-5993; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, April 2012.

In this study, I limited the modeling, with the exception of laminate thickness, to approximately the same geometry, and sizes as Mazzaro's resonators. For optimum input impedance some of alternative resonators might perform a little better with some adjustments to the geometry parameters.

2.   Ring Resonator Antenna Design

The ring resonator is a two port antenna consisting of a ring strip and two coupling strips on opposite sides of the ring, with all strips overlaying a dielectric laminate on a grounding backplane.[2] The feed port is on a coupling strip on one side of the ring while an output port is connected to a coupling strip on the opposite side of the ring. Figures 1 and 2 show two views of the ring resonator model. Figure 3 shows a top view of an alternative ring resonator with an open ring. The FEKO computer models in this report were basically variations of the Mazzaro 1100-MHz ring resonator design.

Ring and feed strips under the laminate.

Soil Sample
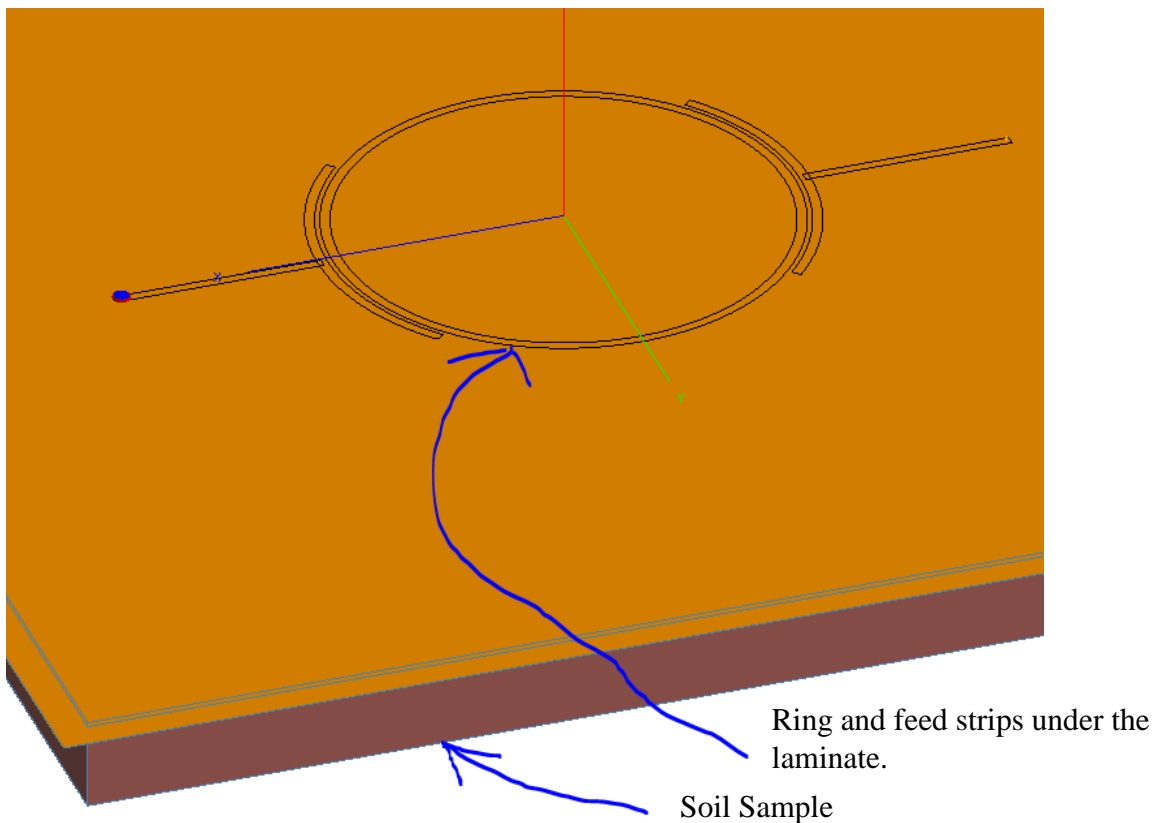
Figure 1.   View of ring resonator model from above the backplane that lies on top. The ring and feed strips below the backplane and substrate (laminate) are visible in this figure.

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[2]See reference 1 page 1.

Computer model current driver between feed/coupler strip and ground plane

Ring and feed coupling strips in this plane

Back plane

Laminate

Soil sample

Figure 2. Magnified side cross-section view of ring resonator.

Figure 3. Top view of open ring resonator showing underlying open ring and feed strips.

3. Comparisons of 4350 and 5880 Substrate Based Ring Resonator Results
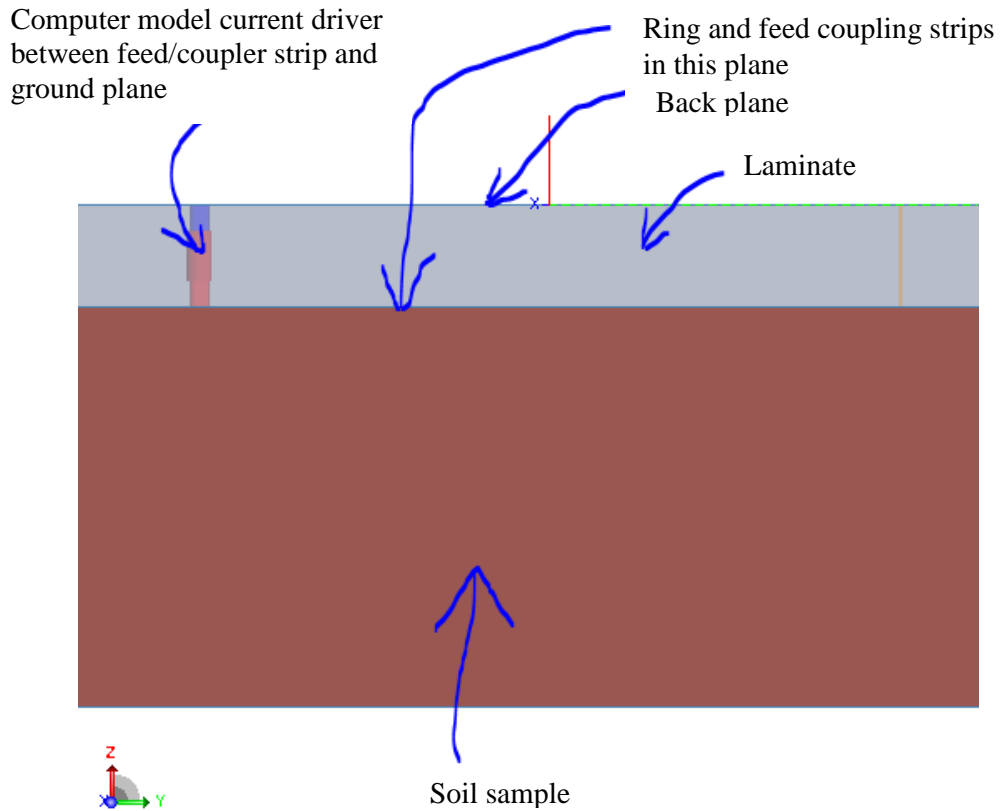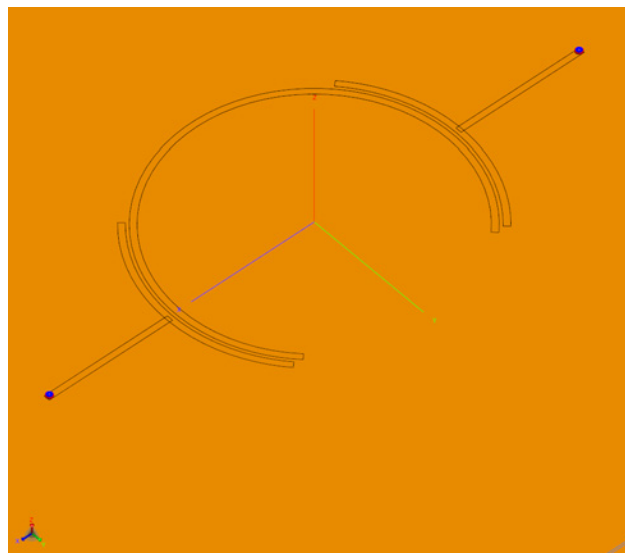
In this study Rogers duroid 5880 substrate was swapped for the Rogers 4350 substrate in the FEKO models. The FEKO software solved the electromagnetics of the designs and computed the S_{21} parameter for the models. Figures 4 and 5 show the S_{21} resonances for ring resonators using a Rogers 4350 laminate substrate and the Rogers RT/duroid[*] 5880 laminate substrate for both an "average soil" with a complex dielectric constant, $\varepsilon_r = (8, 0.40)$ and a "dry soil" with $\varepsilon_r = (4, 0.04)$ of various thicknesses. Accordingly, an "average soil" and a "dry soil" would have dissipation factors of 0.05 and 0.01, respectively. The laminate thickness here is 0.5 mm as in the Mazzaro ring resonator design. Full saturation of the response is modeled at an infinite soil thickness. However, these graphs show that the response is nearly saturated at a soil depth or thickness of only about 10 mm as those cases are nearly indistinguishable from the full saturation case. Of special note is that the sensors are less sensitive to dry soil in that there is a smaller frequency shift of the resonance peaks. The 4350 sensors are less sensitive than the 5880 sensors for both soils as the frequency shift is smaller there, too.
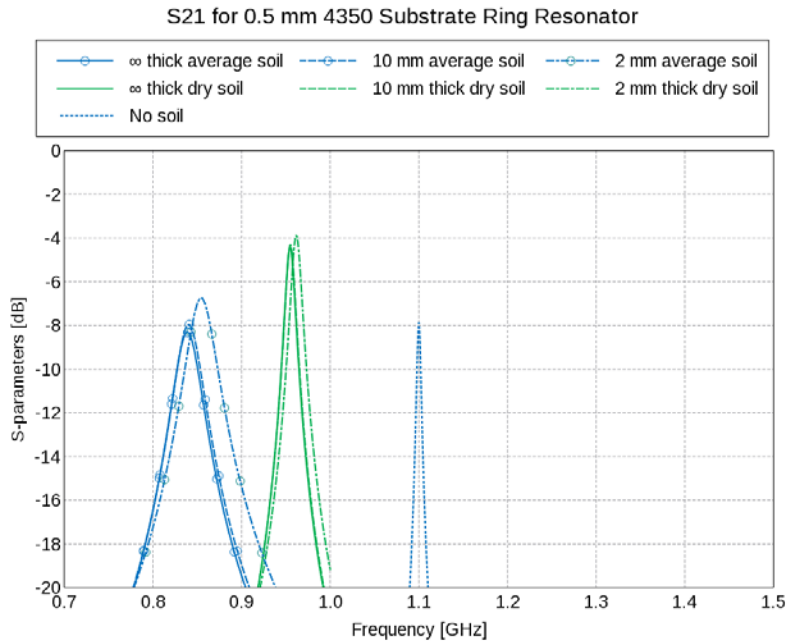

Figure 4. Rogers 4350 substrate Ring resonator response over average and dry soil of several depths or thicknesses.

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[*]Rogers RT/duroid is a registered trademark of Rogers Corporation.
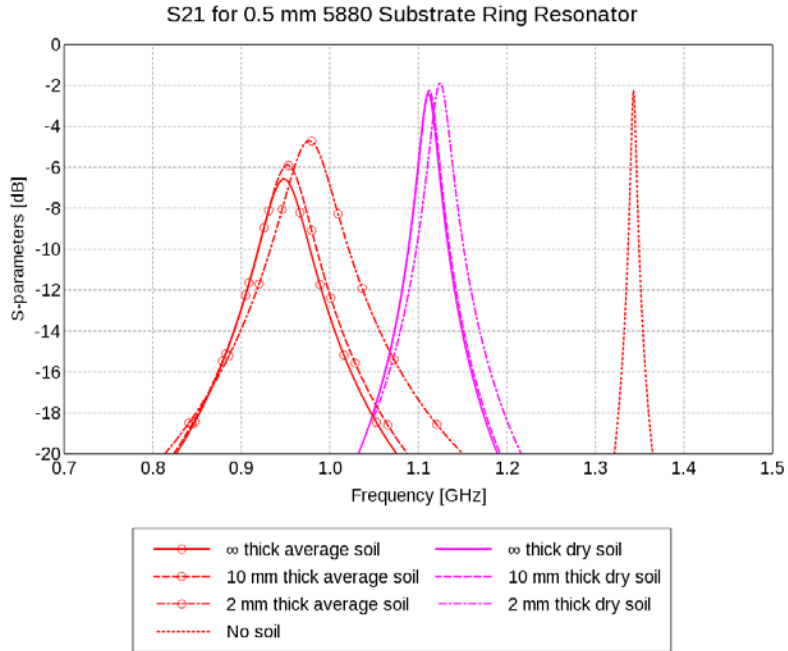
Figure 5. Rogers duroid 5880 substrate Ring resonator response
over average and dry soil of several soil depths.

Figures 6 and 7 show the consequence of thickening the laminates on the S_{21} resonances for average soil while figures 8 and 9 show the consequences for dry soil. In each case here the effect of increasing laminate thicknesses is to modestly increase the resonance shifts except in the case of the 1.5-mm 4350 laminate with dry soil. In this latter case not only is the shift with soil thickness for the 0.5-mm 4350 laminate quite small, but the shift for the 1.5-mm laminate is very large. Also, the S_{21} curves become more distinct between soil thickness cases, except for the cases of the 4350 laminate with the dry soil.

S21 with Two 4350 Substrate Thicknesses for eps 8, tand 0.05 Soil

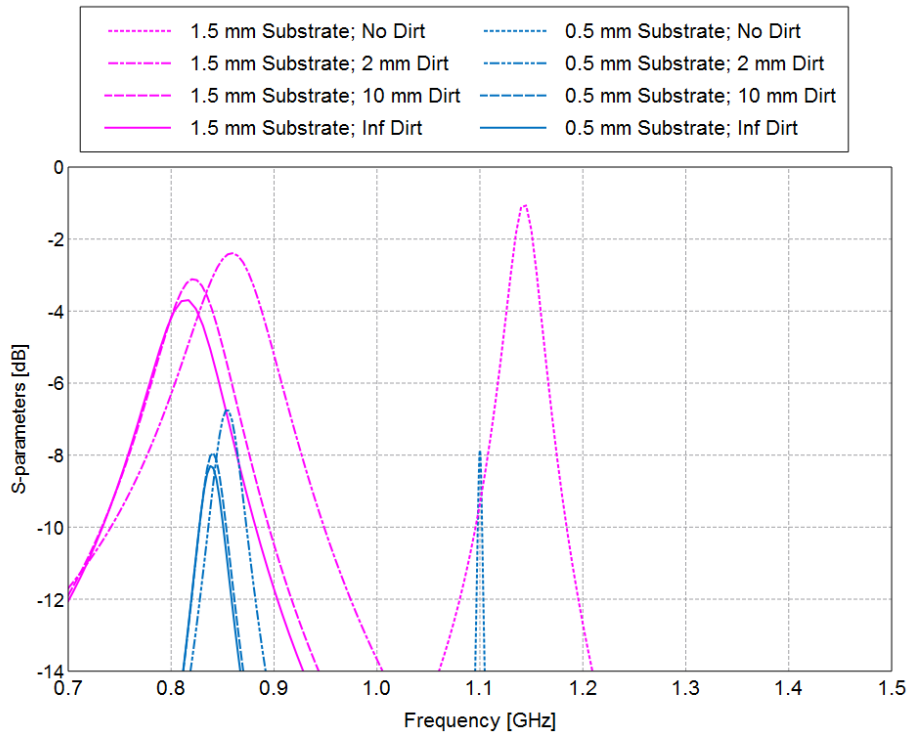|	
········· 1.5 mm Substrate; No Dirt	········· 0.5 mm Substrate; No Dirt
─·─·─ 1.5 mm Substrate; 2 mm Dirt	─·─·─ 0.5 mm Substrate; 2 mm Dirt
── ── 1.5 mm Substrate; 10 mm Dirt	── ── 0.5 mm Substrate; 10 mm Dirt
──── 1.5 mm Substrate; Inf Dirt	──── 0.5 mm Substrate; Inf Dirt

Figure 6. S21 response of Rogers 4350 substrate ring resonator for average soil of several soil depths.

S21 for Average Soil with Two 5880 Substrate Thicknesses

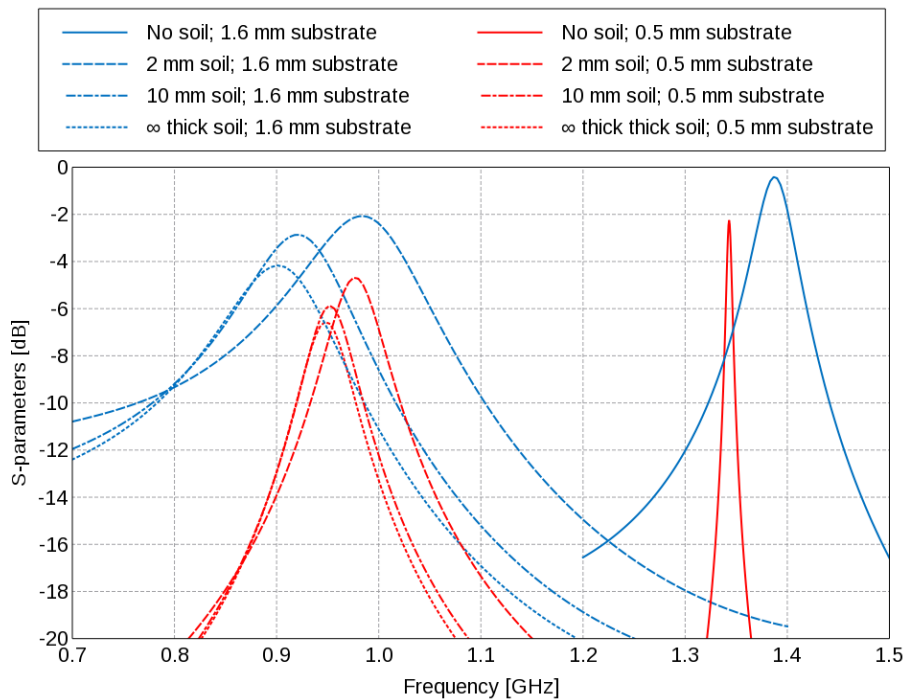|	
──── No soil; 1.6 mm substrate	──── No soil; 0.5 mm substrate
── ── 2 mm soil; 1.6 mm substrate	── ── 2 mm soil; 0.5 mm substrate
─·─·─ 10 mm soil; 1.6 mm substrate	─·─·─ 10 mm soil; 0.5 mm substrate
········· ∞ thick soil; 1.6 mm substrate	········· ∞ thick thick soil; 0.5 mm substrate

Figure 7. S21 response of Rogers 5880 substrate ring resonator for average soil of several soil depths.

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At 10 mm of soil thickness the separation from the saturated case is 2 to 3 times greater for the thick than the thin laminate ring resonators except in the case of the 4350 over dry soil. In this latter case the thicker laminate provides no improvement in resolution of the curves. The 5880 laminate shows the best separation or resolution of soil sample depth and the thicker 1.575-mm 5880 laminate shows the better resolution than the thin 0.5-mm 5880 laminate model.
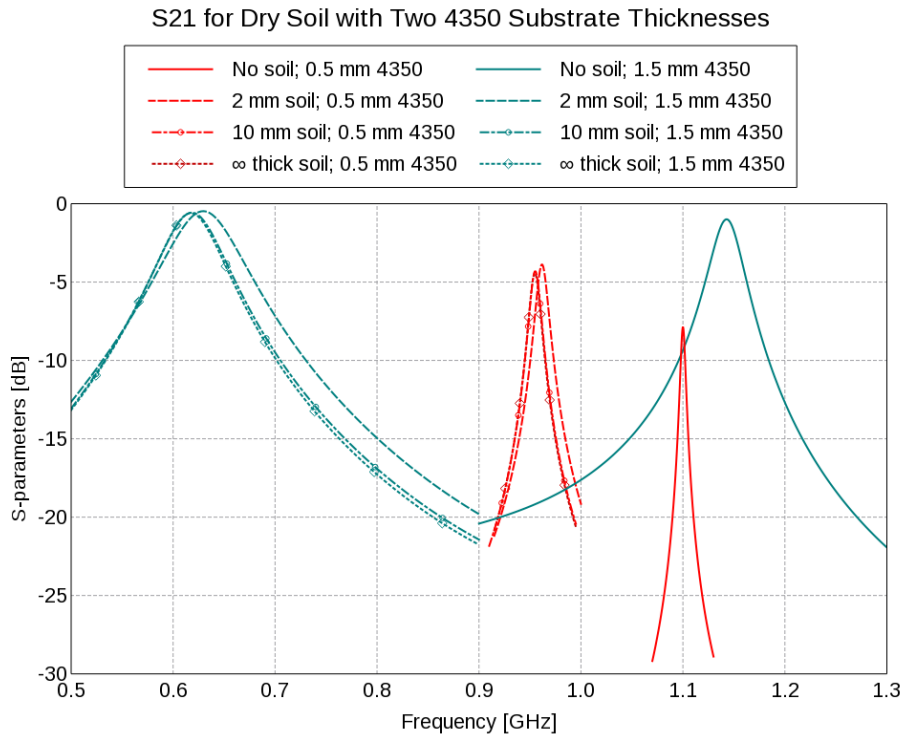

Figure 8. S21 response of Rogers 4350 substrate ring resonator for dry soil of several soil depths.
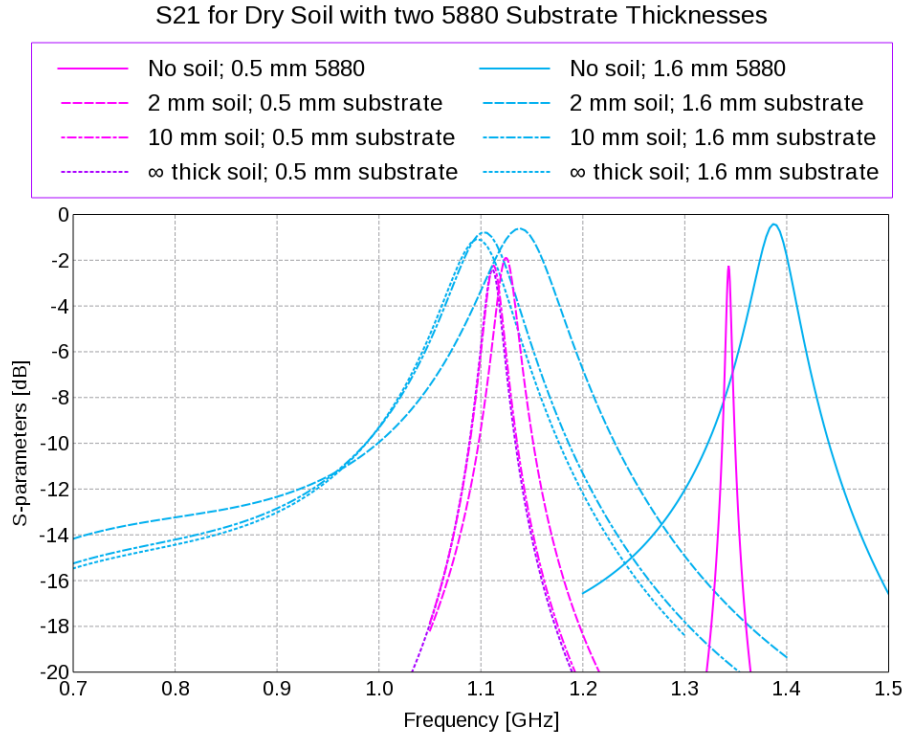
S21 for Dry Soil with two 5880 Substrate Thicknesses

Figure 9. S21 response of Rogers 5880 substrate ring resonator for dry soil of several soil depths.

4. Analysis of Results

The spreading of the resonant frequencies for measurements among soil samples of differing thicknesses for resonator antennas of the same design suggests that the RF fields penetrate slightly more or that the resonator can "see" a little deeper into the soil in those cases. Furthermore, comparison of figure 6 with 8 and figure 7 with 9 suggests that the ring resonator can "see" a little farther into wet soil than dry soil. Also, figures 6, 7, and 9 show that use of thicker substrates allows "seeing" a little deeper into the soil. The ring resonators with the 5880 substrate can see a little deeper than the 4350, so that the best "penetration" is seen with the thick 5880 substrate into the moister soil. The actual mechanism for the seeing or penetration into the soil is not clear. Perhaps in these cases current paths are altered by the different electrical properties of both the soil and the substrates causing different behaviors in the ring resonators. Still in each of these cases the soil that has the greatest effect on these sensors is within 2 mm of the sensor, so no variation greatly improves soil penetration. The effect is a very near field effect and the results, over all, agree with that.

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Although in the 5880 case this improved penetration suggests that one could see slightly deeper into the soil it also means that thicker samples would be required to saturate the sensor to get an accurate reading. This requirement would suggest a tradeoff in the use of such a sensor.

The uncertainty or error in the determination of the soil dielectric constant using the ring resonator comes from two, or possibly three, general sources. Exploration of these can lead to some improvement of the resonator system performance or highlight its limitation. One error or uncertainty source is the instrument system itself and the other is from the physical difficulty in measuring what one really wants. Uncertainty in the directly measured parameter is more of an instrumental error that can translate directly to error in the measurement of even a good sample. In the first case I discuss measurement of the real dielectric constant. In the second, I discuss measurement of the imaginary part of the dielectric constant. Then I briefly discuss sampling error.

As the ultimate goal of a ring resonator is the measurement of the real and imaginary parts of the soil dielectric constant, I have examined how the changes in the S_{21} resonance curves affect those measurements for the alternative ring resonator designs. In Mazzaro's report the real part of the dielectric constant of the soil is approximately related to the load-shifted and unloaded resonant frequencies by $Re\{\varepsilon_r\} \sim (f_l/f_u)^{-1}$, where f_l is the resonant frequency of the soil loaded sample and f_u is the resonant frequency of the unloaded sensor. Figure 10 shows the computed relationship between $Re\{\varepsilon_r\}$ and f_l/f_u for all five variants of the original ring resonator design.
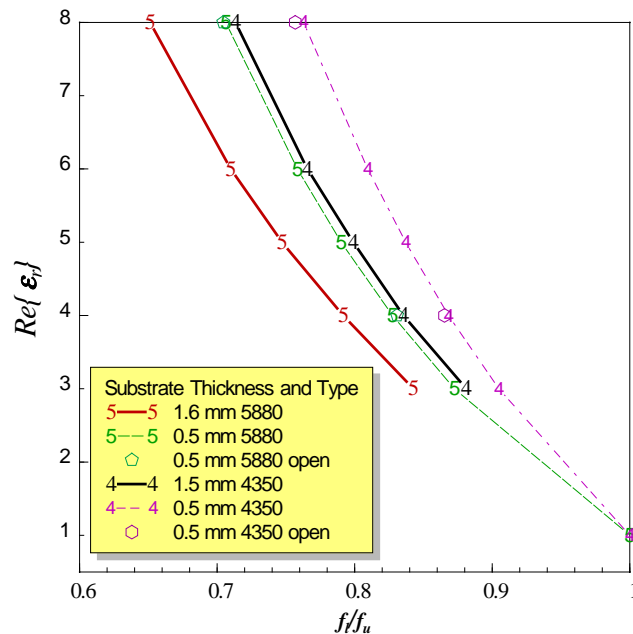

Figure 10. Relations between soil real dielectric constant and the relative shift in FEKO computed resonant frequencies from S21 parameter curves for the alternative resonator designs. "Open" refers to the open ring design.

Curves, or portions of curves, in figure 10 with steeper slopes would give less precise measurements of Re{ε_r}. This follows from the observation that a small change or error in the relative change of the resonant frequency would produce a larger change or error in the corresponding Re{ε_r} for the steeper curve. Therefore, since curves that shift the most with frequency are a little less steep, a little more precise measurements of Re{ε_r} would result in these cases, other factors being equal. This suggests that the thicker substrates and 5880 instead of 4350 would give more precise measurements of Re{ε_r} in proportion to the ratio of the slopes in the curves shown in figure 10. However, the slopes are not greatly different so the resulting precision improvement would be very modest.

Looking further into the error we consider the sampling frequency of the measured S_{21} curves. Sampling with frequency steps of 4-Mhz results in frequency errors of only about 0.1%. For the computation of f_l/f_u and the Re{ε_r} as in figure 10, this kind of error does not make much difference. So the precision improvement above would be even smaller.

Sections I and II of this report refer to a second alternative to the changing or thickening of the ring resonator substrate. That alternative was to open the ring as shown in figure 3. While the Q shift behavior for this variation was nearly the same as in the closed ring counterpart as is shown in figure 10 it did offer one advantage. The advantage for the open ring resonators is that the absolute operating frequency would be roughly 30% lower for the same size resonator with the size of the ring opening in those resonator models. While meandering of the ring line can accomplish the same thing,[3] an opening of the "ring" can also be performed on a meandered ring gaining a further reduction in size for the same principal frequency.

The soil complex permittivity can be expressed as $\varepsilon = \varepsilon_0 \cdot \varepsilon_r \cdot (1 - j \cdot \tan \delta)$ or also as $\varepsilon = \varepsilon_0 \cdot \varepsilon_r - j \cdot \sigma/\omega$, where ε_0, ε_r, σ, and ω, are respectively the permittivity of free space, the dielectric constant, the soil electrical conductivity, and the radio frequency in radians per sec. Consequently, we can compare the $\tan \delta$ parameter with the soil conductivity using $\tan \delta = \sigma/(\omega\varepsilon_r)$ and conclude that $\tan \delta$ is a kind of measure of the soil conductivity.

Figures 11 a and b look at the effect of substrate thickness and type on the $\tan \delta$ parameter for two soils of different real dielectric constant, Re{ε_r}, where $\tan \delta = $ Im{ε_r}/ Re{ε_r} is the ratio of the imaginary to the real part of the dielectric constant. The soil with Re{ε_r} = 4 is usually a dry soil while a constant of 8 would be more likely with a soil closer to average moisture. Both figures 11 a and b show stronger changes in the resonant Q for the 5880 dielectric substrate and the thicker substrates, rendering the model with the thick 5880 substrate as the one with the greatest shift.
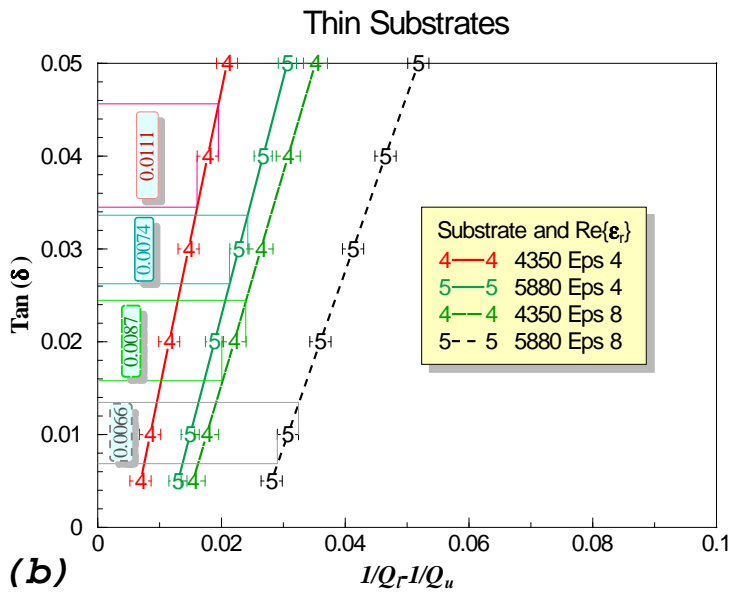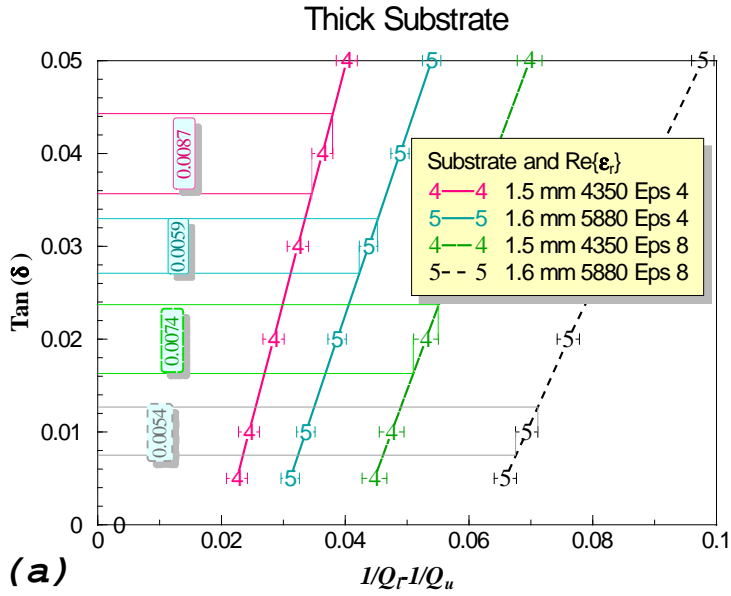
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[3]See reference 1 on page 1.

Figure 11. Soil tan δ vs. computed 1/Q change for different substrate types and thicknesses. Computations are for two soil real dielectric constants, 4 and 8. The thin substrates are both 0.5 mm thick. Error bounds shown related to the inverse Q difference result from the coarseness of the frequency sampling. Projections onto the abscissa show the relative magnitude of the error in the tan δ (blue boxes) resulting from coarseness of the frequency sampling.

The quantity change from which the tan δ can be determined is the measured difference parameter, $[1/Q_l - 1/Q_u]$. Q_l and Q_u refer to the resonant Q of the ring resonator when loaded with soil and when unloaded, respectively. If we take the coarseness of the frequency sampling of 4 MHz in the digitized network analyzer S_{21} curves we get an uncertainty in the frequency of 1.15 MHz. The Q's are derived from the resonant frequency using $Q=f_{res}/(width)$ so that the uncertainty propagates into the Q's[4,5] from the uncertainty in the resonant frequency, f_{res}, and the resonance width. The error for the measured difference parameter is $\delta_{err}=\sqrt{[(\delta_{Q_l})^2/Q_l^4 + (\delta_{Q_u})^2/Q_u^4]}$ where we have dropped the covariance term with the assumption that Q_l and Q_u are independent.

Figures 11 a and b also show the error propagated into $[1/Q_l - 1/Q_u]$ quantity from the 4-MHz frequency sampling. The error in the estimated tan δ parameter is estimated by projecting the uncertainty in $[1/Q_l - 1/Q_u]$ onto the FEKO generated tan δ functions and then by projecting that onto the tan δ axis. The 5880 substrates yield smaller errors than the 4350. The thicker substrates show a smaller error, and the error is a little smaller at the higher soil dielectric, $Re\{\varepsilon_r\}=8$.

Figures 12 a and b show error in the tan δ parameter when the frequency sampling is done at 1 MHz intervals. The tan δ parameter error in this 4 times higher sampling rate is reduced by a factor of 3 or 4. Unlike the case of the real part of the dielectric constant, sampling the frequencies at smaller intervals can lead to a significant improvement in measurement of the imaginary part of ε_r, or tan δ.

[4]Wikipedia. http://en.wikipedia.org/wiki/Propagation_of_uncertainty (accessed 8/14/14).

[5]Bevington, P.; Robinson, K. *Data Reduction and Error Analysis for the Physical Sciences.* McGraw-Hill: New York, NY 10020, 1996.
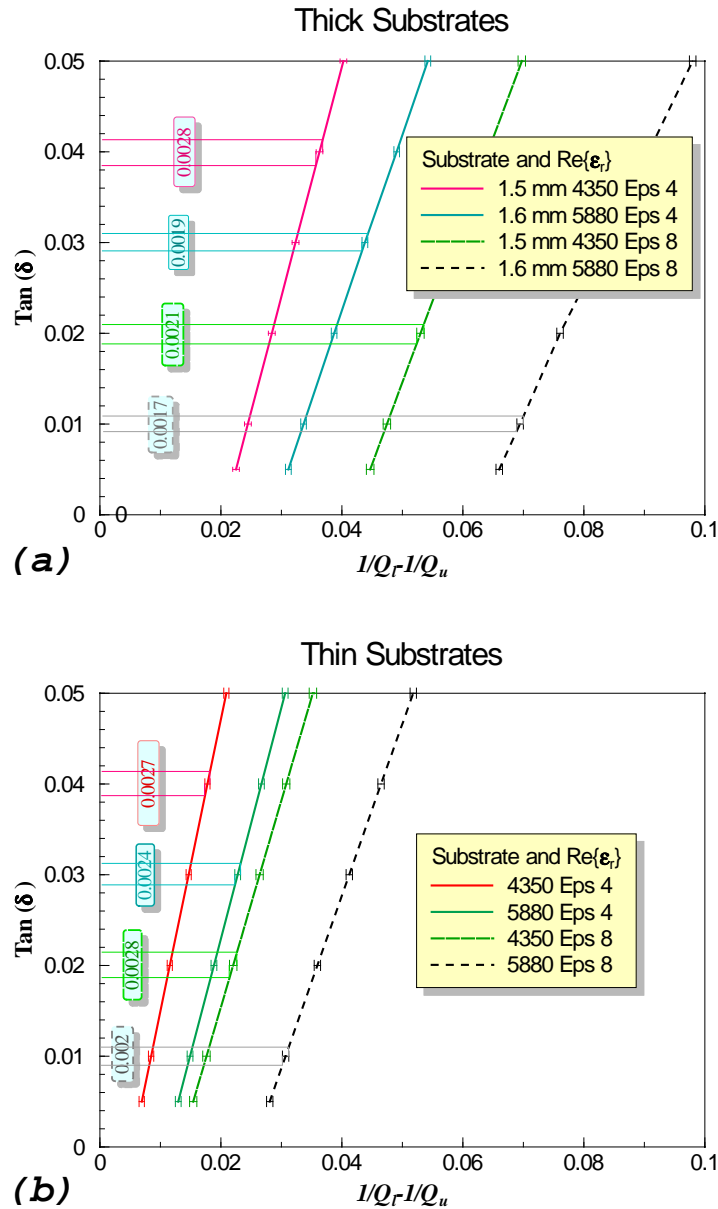
Thick Substrates

(a)

Thin Substrates

(b)

Figure 12. Soil tan δ vs. Reciprocal Q change. Tan δ
error with 1-MHz sampling.

The physical measurement difficulty to which I earlier referred is soil sampling error. In this case the resonator may be correctly measuring the sample, but it is not the right sample. The soil samples vary considerably in consistency and coarseness. They may have grass, pebbles, or large grains. A sample of fine clay can be easily pressed against the bottom of the sensor and presents a very good dielectric representation to the sensor. Samples with grass or large grains will have major pockets of air against the sensor. In these latter cases they are unlikely to properly represent the compacted soil below, especially because most of the sensing takes place within 2 mm of the bottom of the ring resonator. If the sample can be properly crushed and well

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compacted against the sensor and lie within about 2 mm of it, the measurement may be good. If not, some error will result, because the sample did not properly represent what was intended. This kind of error is hard to quantify because it varies so much with the type of sample and the skill of the operator. It can be reduced by averaging over many measurements.

Also, experience in measuring a finely ground soil sample several times shows that a very small difference in the same sample can produce rather variable results,[6] to the point of random variations out of control of the operator. Though it is beyond the scope of this study to pinpoint the cause, such a random response could possibly be due to variations in contact of soil grains with each other or the resonator antenna. Such variations could introduce variations in electrical resistance of the small grainy soil samples within that critical 2 mm of the antenna. These variations could also change the current path in the soil possibly introducing small inductances or capacitances into the resonator antenna system. Since Q of a circuit can be expressed as $\omega_0 L/R$ or $1/(\omega_0 R C)$ and the resonant frequency, $\omega_0 = \sqrt{(1/LC)}$, it is likely that these small changes in the resistance, R, inductance, L, and capacitance, C, of the effective ring resonator circuit could then change its resonance and therefore the result of the measurement. Here, again, averaging over several measurements will reduce the error.

Sample error most certainly will usually dominate the total uncertainty except for the most homogeneous samples, since the dielectric constant of air is so low, the space within which the sample must reside is so small, and the potential "micro-current" paths and resistances within that space may be so varied.

5. Conclusions

Comparisons of the resonant frequency shifts for various soil sample depths indicates that most of the measureable response is from within 2 mm of the resonator antenna strip surface. For the thin substrate models 95% of the response comes from that volume. For the thick substrate models more than 83% comes from that volume. For wet soil a little more of the response comes from outside that volume than for dry soil. Although for some of the models full saturation of the measurement of soil is not reached for 10 or 30 mm of sample depth, the very small critical sample depth is a very severe limitation of the type of samples that can be measured accurately.

Analysis of the frequency sampling of the S_{21} resonance curves did not indicate that an increase in the sampling rate would improve the $Re\{\varepsilon_r\}$ accuracy, but it did indicate it could significantly improve the accuracy of the $\tan \delta$ parameter. Sampling at 1 MHz instead of 4 MHz could reduce the uncertainty of the $\tan \delta$ computed from the changes in the resonator Q from about 0.01 to

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[6]Smith, G. Adelphi Laboratory Center, MD. Private communication , March 2014.

about 0.003, for example, over a tan δ range of 0.01 to 0.05. This could be an improvement in the measurements of good, homogeneous samples.

Much of the time, however, the difficulty in measuring the soil characteristics with these resonators is likely to lie in getting a good sample, one characteristic of what is desired within that critical 2 mm of the bottom of the ring resonator. The resonator may be properly measuring what is there but if it is not characteristic of what you want then it will not do. A fine clay with grain size << 2 mm may reliably give a good result, but larger graininess, clumped plant material, and air pockets are likely to give highly variable or uncharacteristic results, because it does not fit properly into that critical 2 mm. For some materials that fit somewhat, averaging of samples will probably improve the results.

The ring resonator sensor, as the modeling of the shifts in its resonances with various soil sample depths affirm, is a very local sensor. The Q shifts with frequency upon which it is based are highly sensitive to soil composition and structure in the immediate vicinity of the ring strip at the base of the antenna.

In order to measure local soil dielectric properties to a much greater depth in the soil, especially to reduce the variability resulting from normal soil in homogeneities, a radar system[7] might be a better approach than a ring resonator. Perhaps such a radar system might consist of two or more small radars with receivers aimed into the ground at different incident angles. A radar antenna is designed to send RF radiation a significant distance, but a ring resonator is not.

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[7]Arcone, S. A.; Larson, R. W. As an example, Single-Horn Reflectometry for In Situ Dielectric Measurements at Microwave Frequencies, *IEEE Trans. on Geoscience and Remote Sensing*. **1988**, Vol. 26, No. 1, p 89.