Advanced Measurement Techniques for Tesla Coils

Part 1 – Vector Network Analysis

ESTC 2022 – Adrian Marsh Ph.D.

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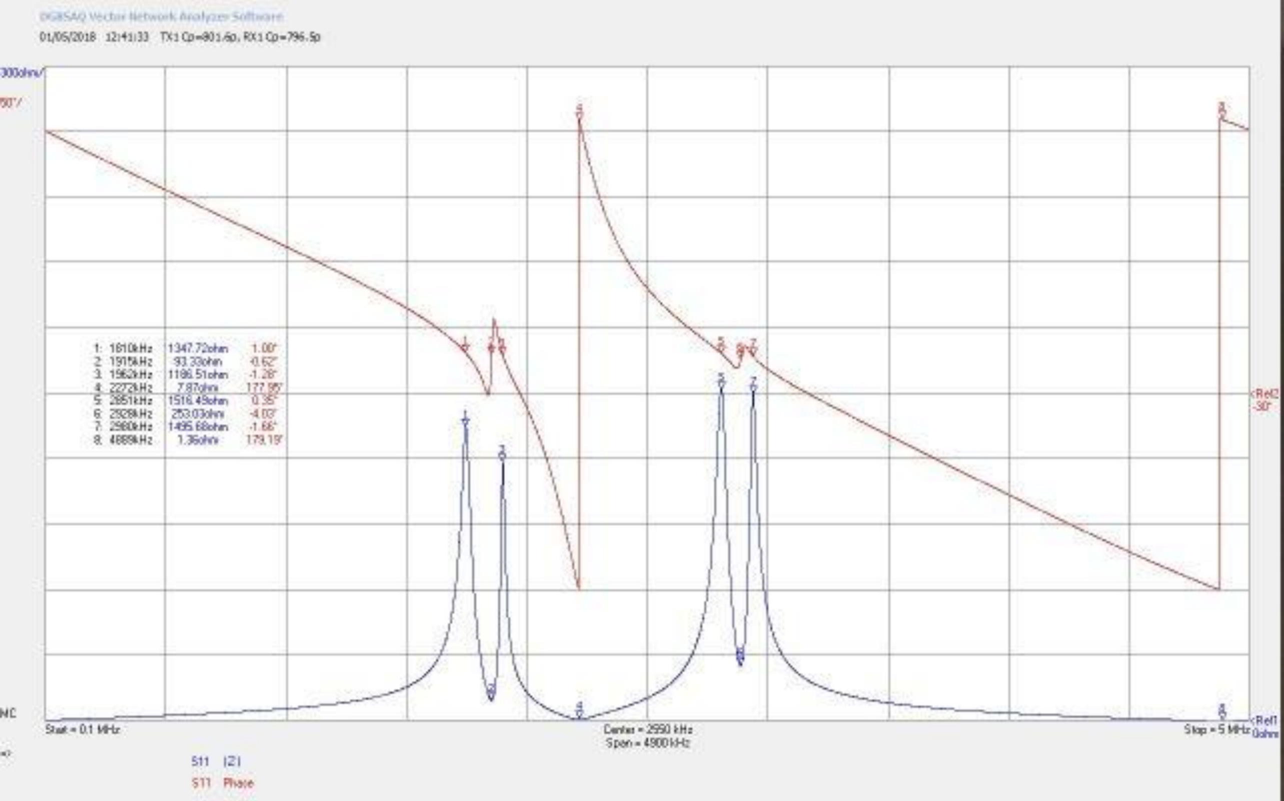

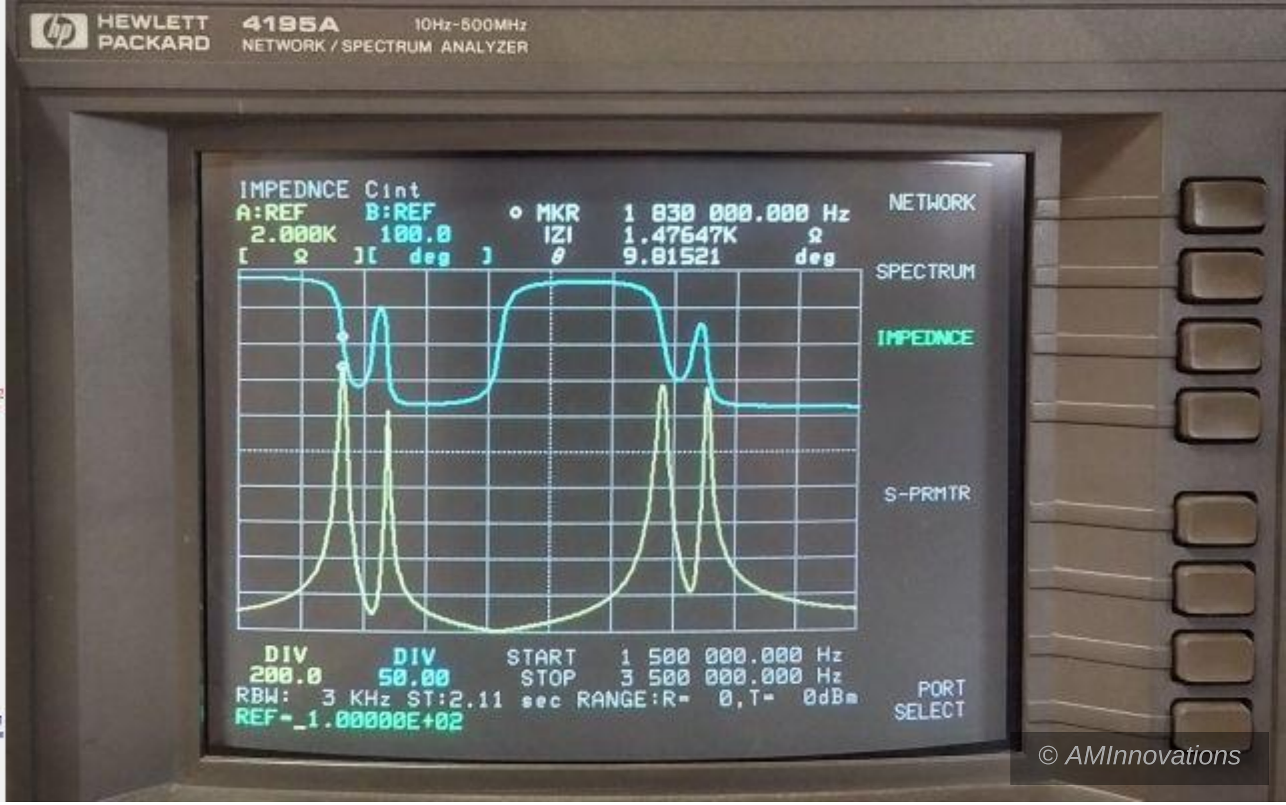

> *To measure is to know … If you cannot measure it, you cannot improve it.*
>
> *When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind …*

- Lord Kelvin 1883, Physicist, Engineer, and Natural Philosopher

Why make electrical measurements ?

- To explore and test our perception of the natural world – learning.
- To support or refute our observations, ideas, theories, conjectures and designs.
- To substantiate claims about our systems, (important in Over Unity systems).
- To establish credibility and reputation in the field, (important for the New Science field).
- To understand how something works, and to create and invent new embodiments.
- To discover the scope, boundaries, limitations, and safe operating of a system.
- To measure key system parameters – e.g. energy, power, frequency, impedance, current
- …

> *An experiment is a question which science poses to Nature, and a measurement is the recording of Nature's answer.*
>
> *- Max Planck 1949, Theoretical Physicist*

How to make electrical measurements ?

- With an impeccable approach – to make the best measurements with our current knowledge.
- With best scientific practice and method – establishes credibility, integrity, and quality.
- With the highest accuracy achievable based on the resources available.
- With a well defined measurement procedure, control experiments, and standards.
- With a good understanding of the measurement equipment and their limitations.
- With an understanding for the errors in the measurement procedure and equipment.
- With clear and organised communication and reporting.
- …

“ *The experimental investigation by which Ampère established the law of the mechanical action between electric currents is one of the most brilliant achievements in science … It is perfect in form, and unassailable in accuracy, and it is summed up in a formula from which all the phenomena may be deduced …*

- James Clerk Maxwell 1881, Mathematical Physicist, and Natural Philosopher

What electrical measurements to make ?

- Time domain:
  - Voltage and currents, (direct, alternating, oscillating, and transient).
  - Inductance, Capacitance and Resistance.
  - Input and output power, temperature, illumination, and energy transfer, storage, and dissipation.
  - Rate of change of quantities and parameters, (non-linear transients, pulses, and impulses).
- Frequency domain:
  - Impedance and admittance measurements, matching, transmission, and reflection
  - Resonance, bandwidth, magnification, and quality factor.
  - Network and Spectrum analysis.

> “*Today’s scientists have substituted mathematics for experiments, and they wander off through equation after equation, and eventually build a structure which has no relation to reality.*
>
> *- Nikola Tesla 1934, Inventor, Engineer and Futurist*

Tesla Coils

- Invented by Nikola Tesla *c.1891*
- Tesla magnifying transformer (TMT)
- Resonant air cored transformer
- High-voltage, high-frequency electricity
- Can produce huge voltage magnification
- Generators include spark, linear, impulse
- Linear and non-linear electrodynamics
- Lightning study and exploration
- Single wire/medium, and Telluric transmission
- Radiant energy and matter phenomena
- Plasma and dielectric phenomena
- Experiments in the displacement and transference of electric power

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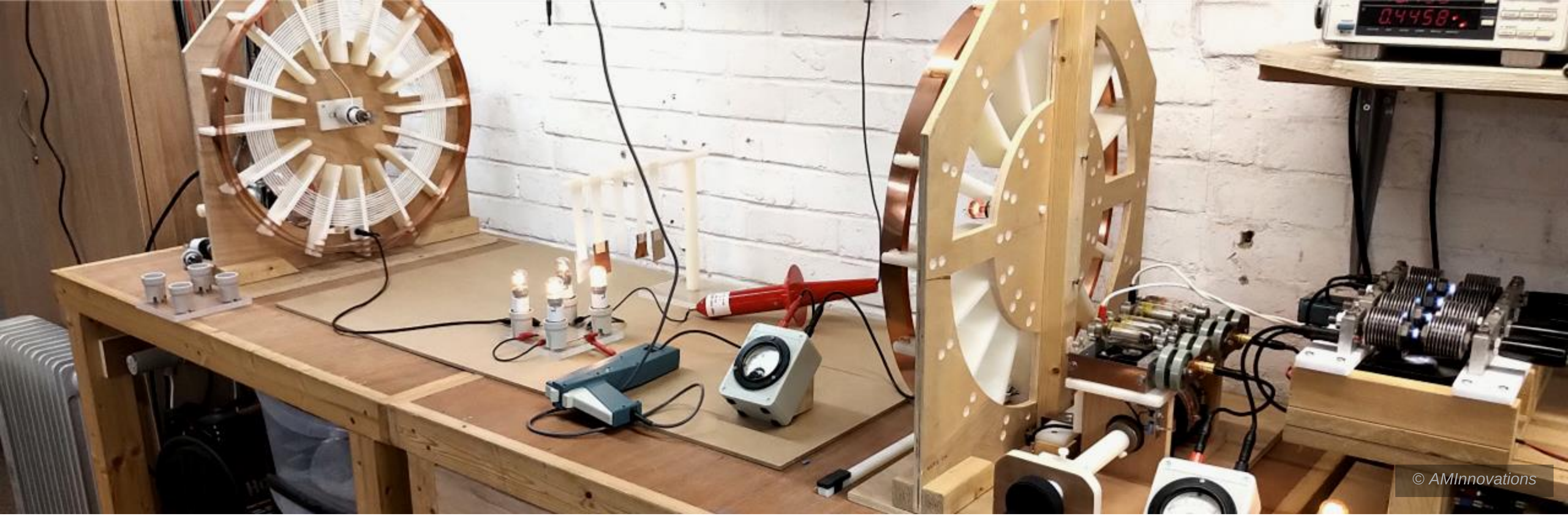
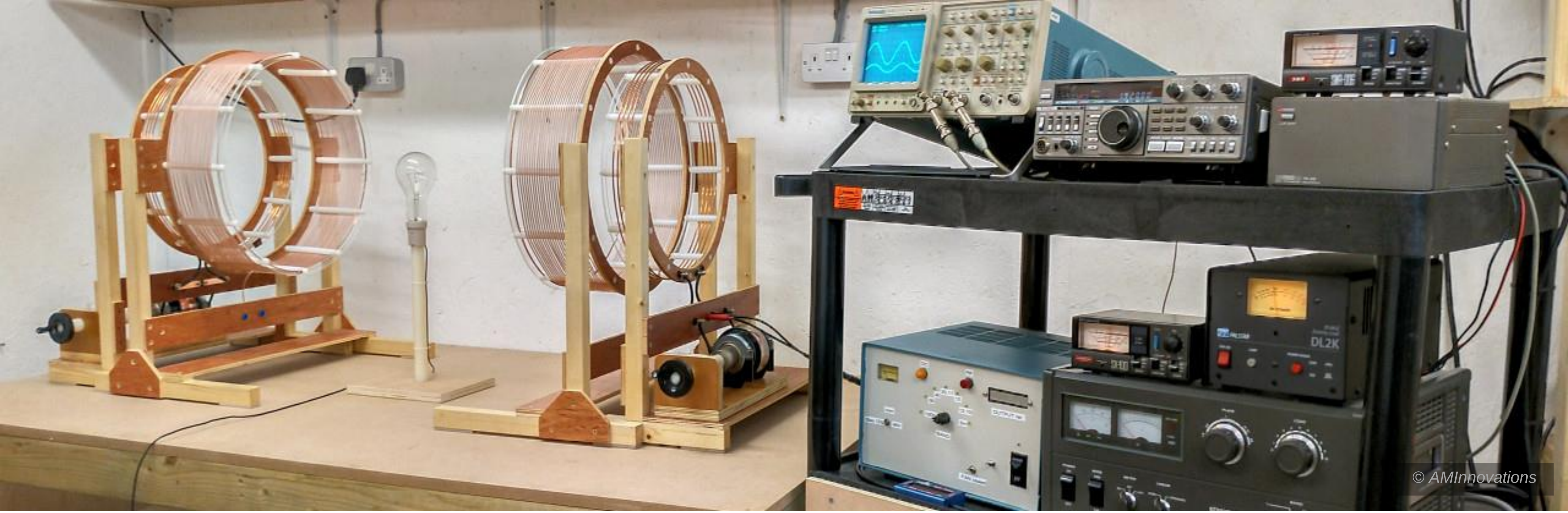


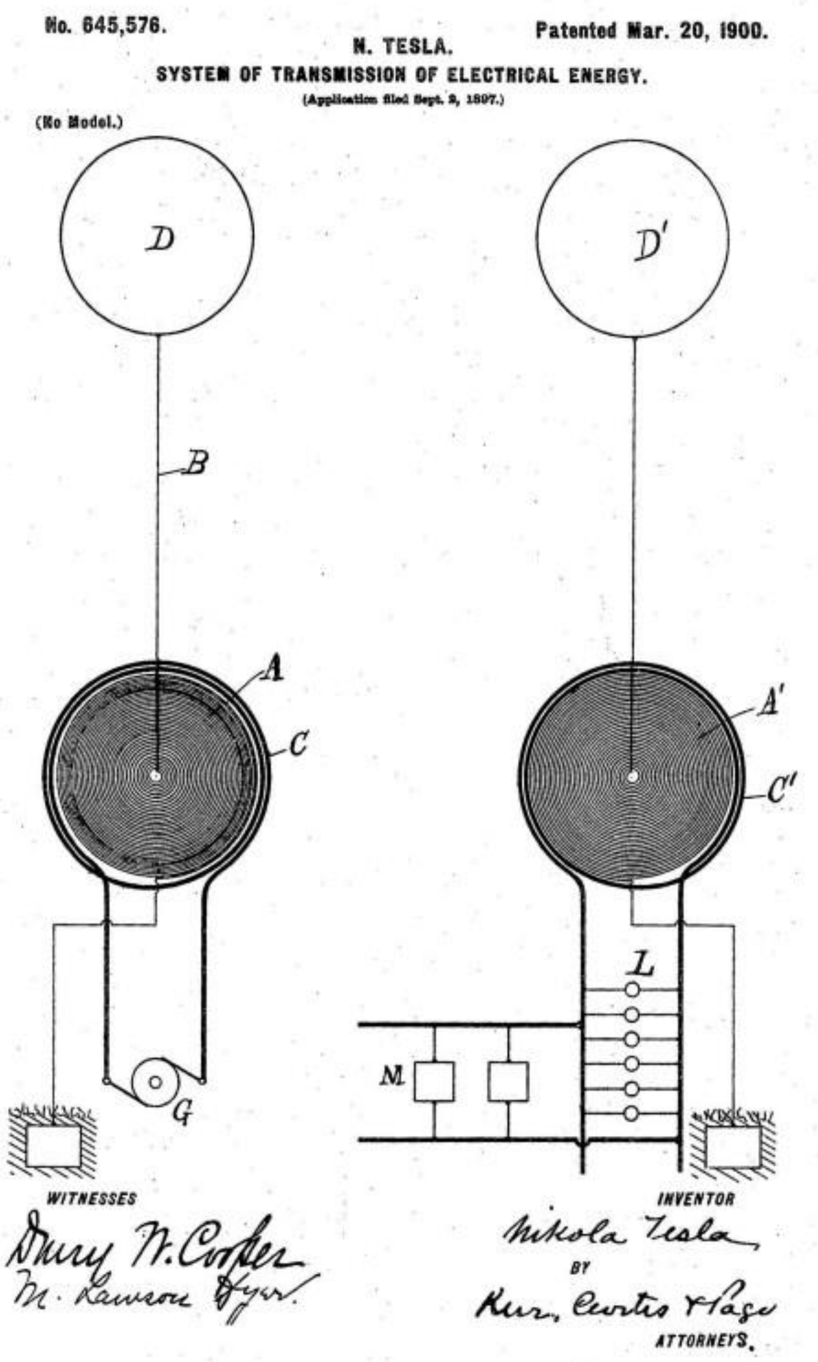
- Flat coil TMT system, similar to Tesla's original patent, and Eric Dollard *et al.* original replication.
- Used here for experiments in the transference of electric power via transverse and longitudinal modes.
- Generators include spark gap, vacuum tube oscillators, and non-linear impulse up to ~1.5kW.
- Single wire transmission of power with incandescent lamp loads in the cavity, and at the receiver.
- Tesla's radiant energy and matter phenomena can be observed when using non-linear generators.



- Cylindrical coil TMT system, similar in design to Eric Dollard’s “Cosmic” Induction Generator.
- Used here for experiments in transference, telluric transmission, and plasma phenomena.
- Linear amplifier generator drives the two connected primary coils in phase relationship up to ~1.2kW.
- Interesting plasma and RF phenomena can be observed in vacuum and gas filled glass bulbs.
- Also suitable for telluric transference of electric power experiments in the 160m amateur radio band.

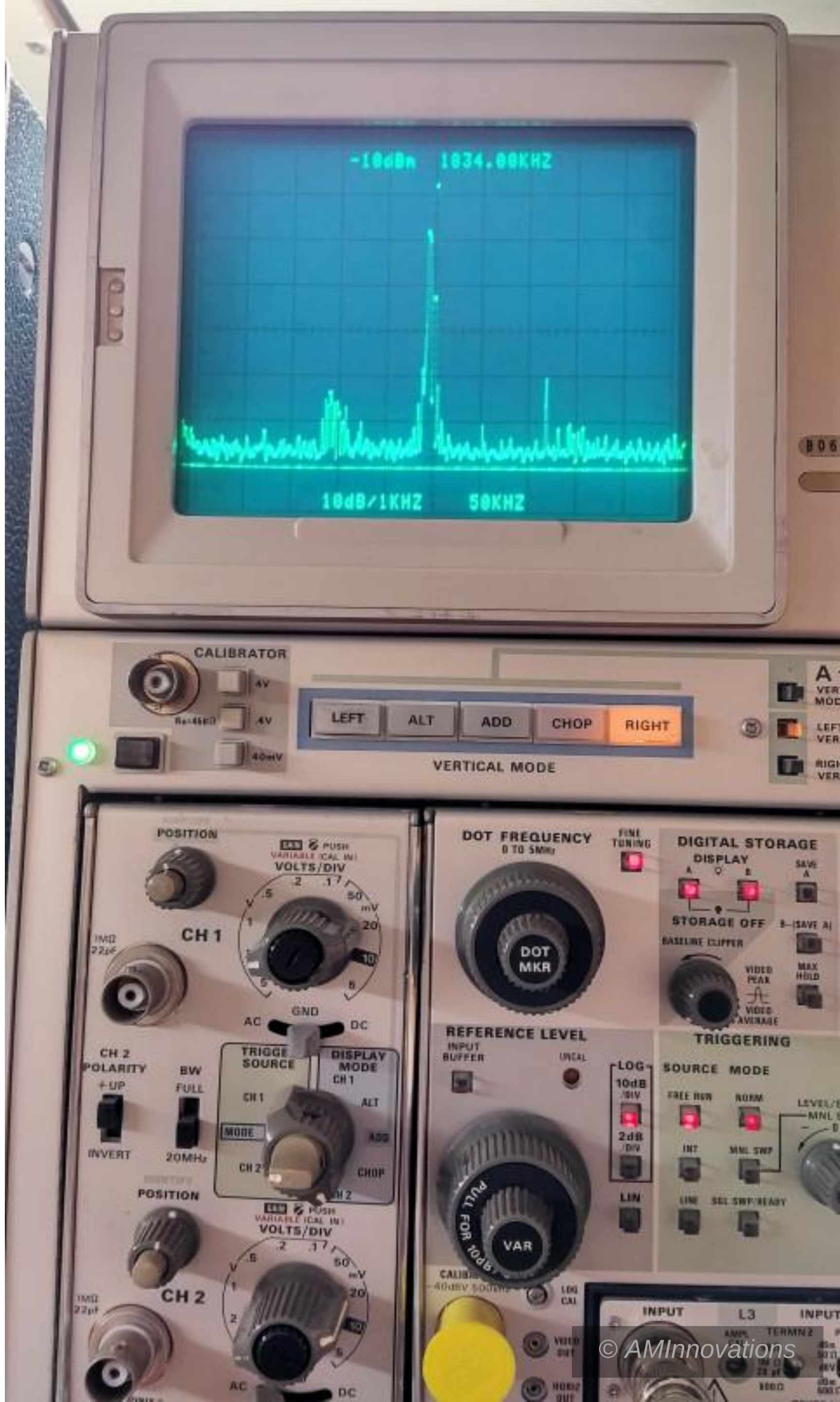
Design Considerations for Tesla Coils

- Coil Purpose e.g. long sparks, TMT, Telluric transmission, Tesla phenomena, displacement/transference experiments.
- Type of coil to fit purpose e.g. flat, cylindrical, conical, extra.
- Number of coils in the TC e.g. single, 2-coil, 3-coil, or more.
- Secondary form factor and size, to fit purpose and power e.g. tall-thin, equal proportion, inter-leaved, Golden-ratio etc.
- Secondary fundamental resonant frequency to fit purpose e.g. 160m amateur radio band 1.8-2.0Mc (UK).
- Secondary coil turns spacing and ratio, and wire/insulator type.
- Primary coil form factor and size, inductance, and tank circuit.
- Primary to Secondary equal weight/volume of conductor.
- Primary to Secondary coupling coefficient, mounting, positioning.
- Generator type and matching to fit purpose e.g. spark, linear amplifier, vacuum tube, solid-state, pulse or impulse.



Electrical Measurements for Tesla Coils

- Secondary coil fundamental resonant frequency e.g. as shown by the spectrum analyser at 1834kc.
- Secondary coil harmonic frequencies, and quality factor.
- Secondary coil impedance as a free resonator (series-fed).
- Primary coil fundamental resonant frequency if relevant.
- Primary coil impedance and tank resonant circuit.
- Primary to secondary coupling coefficient.
- Input Impedance Z_{11} of the Primary and Secondary together as a complete system, (primary-fed).
- Transfer gain S_{21} of the complete system, (primary-fed).
- Impedance Z_{11} and S_{21} change with tuning and loading.
- Generator to primary impedance matching, tuning for maximum power transfer, and other points of interest.
- Input and output power as a function of tuning and loading.



Measurement Techniques for Tesla Coils

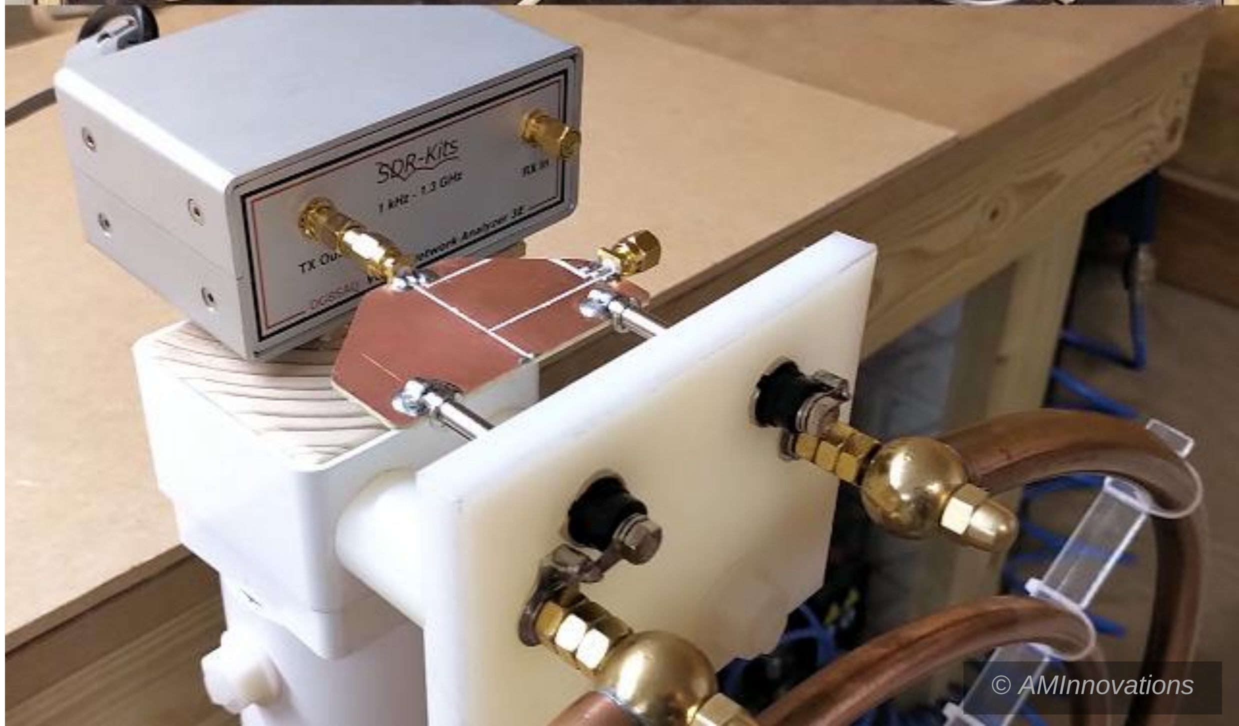
- Empirical tuning for maximum secondary magnification and power output:
  - Trial and error by the streamer length – usually through adjusting primary tap, or tank capacitor.
  - Primary matching by spark gap strength, colour, sound, and stability.
  - Streamer form, density, strength, colour, and sound quality.
- Secondary coil resonant frequency:
  - Signal generator and voltmeter/oscilloscope, or “dip” meter.
  - Fluorescent tubes, neon/inert-gas bulbs and tubes, field strength meters (electric and magnetic).
  - Spectrum analyser during operation.
- Primary coil resonant frequency and matching:
  - Signal generator and oscilloscope – phase change easy to observe despite very low impedance.
- Complete system impedance, transfer characteristics, coupling and matching:
  - Vector network analysis - small signal ac analysis, and best combined with other techniques.
  - Primary-fed and series-fed impedance measurements – provide considerable system insight.

Tesla Coil Phenomena and Measurement - The Frontier

- Transference (the known) - *electromagnetism, or the outer workings of electricity:*
  - Field of electromagnetism considered largely complete in conventional science.
  - Measuring the response of an electrical system to a defined stimulus.
  - Ultimately reduces to measuring voltages and currents as a function of time.
  - Electric and magnetic field measurements also voltages and currents in suitable sensors.
  - Frequency domain measurements from voltages and currents with swept reference.
- Displacement (the unknown) - *macroscopic coherence in the inner workings of electricity:*
  - Not directly measured by test equipment, and no well formulated theory or mathematical basis.
  - Radiant energy and matter - electric charging and forces on matter.
  - Dielectric discharge effects - natural electricity generation e.g. “fractal fern effect”.
  - Longitudinal Magneto-Dielectric modes, and telluric transmission and amplification.
  - Plasma discharge effects - dielectric and magnetic induction field inter-action e.g. “galaxy in a bulb”.
  - Single wire currents, transmission, and power transfer.
  - Non-linear dynamics, transients, amplification, regeneration, and ultimately over-unity.

Vector Network Analysis

- Response of a linear network to an ac stimulus, measuring reflection and transmission of this stimulus.
- Characterises distributed electrical linear network through scattering (S)-parameters.
- Calibration yields network properties from S-params, and defines a clear reference plane.
- Vector measurement of network properties e.g. magnitude and phase of circuit impedance.
- Mostly used in high-frequency/microwave/mm-wave technology and measurements.
- Well established field, with well defined circuit theory, analysis, and mathematics from electromagnetism.
- Complete analyzer in a single instrument by Hewlett Packard (8407) in the early 1960s.
- Traditionally very expensive equipment typically used by professionally trained designers and engineers.
- Computer connected analyzer (usb) can provide an accurate, yet cost effective, alternative.

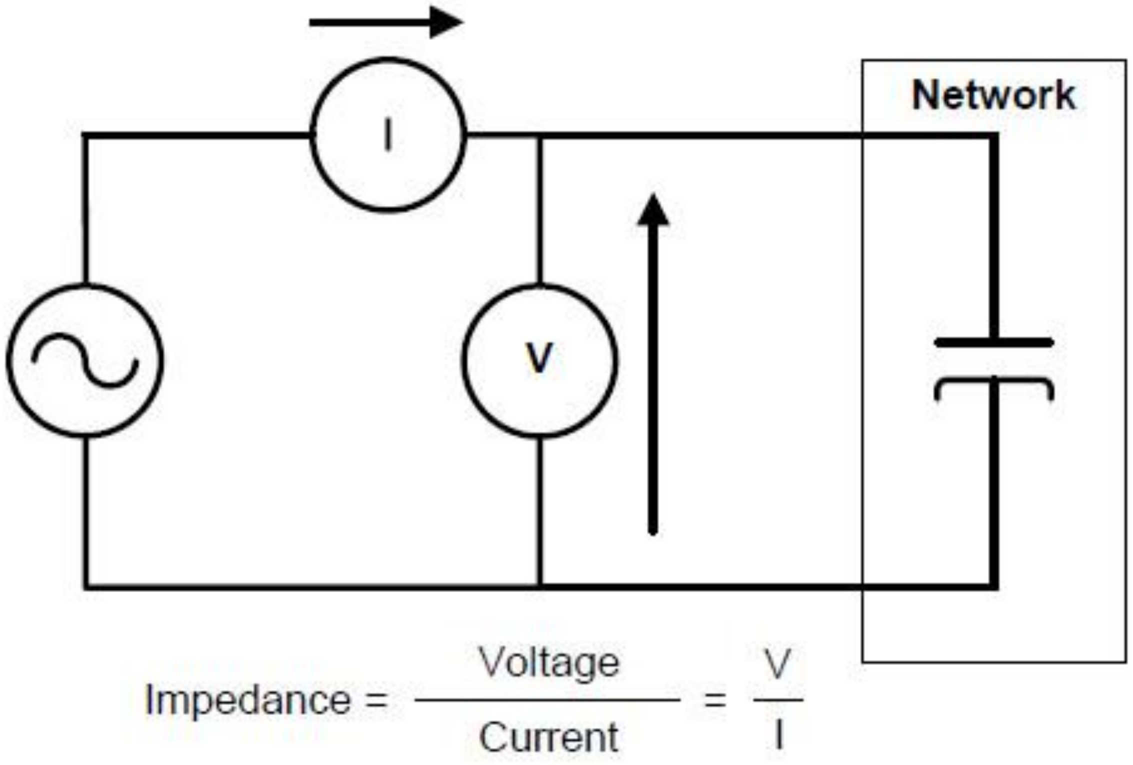


- High-end professional VNAs by companies like Rohde & Schwarz, Keysight, National Instruments etc.
- Vector network measurement up to 500GHz (sub mm-wave) for both active and passive circuits.
- Typical applications include aerospace, defence, satellite, communications, fundamental R&D etc.
- Very high accuracy, high stability measurements, including automation, and sophisticated software.
- Very expensive, requires professional training, very excessive for expert amateur measurements.

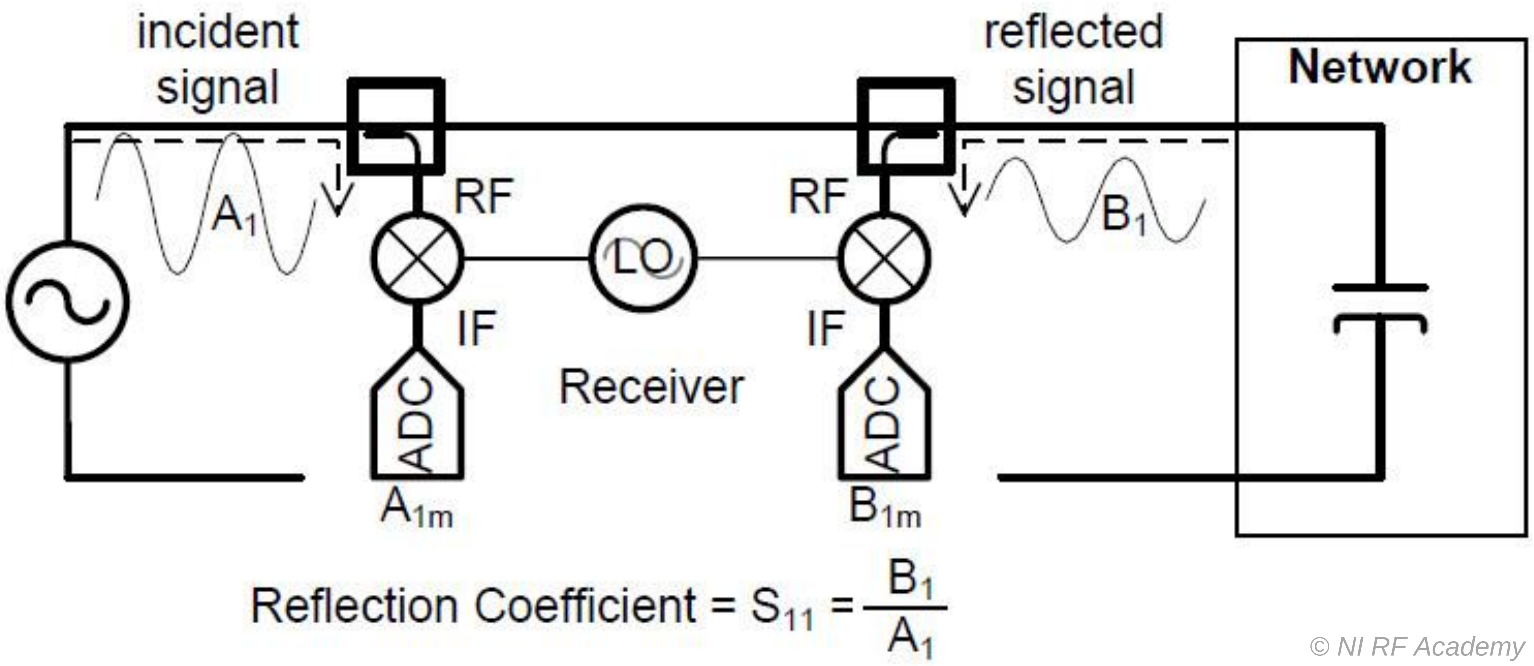
- Portable usb connected VNA, designed by Thomas Baier (DG8SAQ), and supplied as a set by SDR-Kits.
- Vector network measurement up to 1.3GHz in two ranges 1kHz-500MHz, and 500MHz-1.3GHz.
- Applications include amateur radio, antenna and filter design, Tesla coils, active and passive networks.
- Good accuracy and reasonable dynamic range in the first range up to 500MHz, compared to HP 4195A.
- Affordable price for the enthusiast or expert amateur, and connects to a Microsoft Windows based PC.

Basic Impedance

- At lower frequencies impedance (Z) is easily measured.
- A sine wave generator provides the stimulus.
- A volt meter measures the voltage (V).
- A current meter measures the current, (I).
- Impedance is the ratio between the voltage and current.
- The measured voltage and current have a magnitude, and a phase relationship.
- Hence the impedance also has a magnitude and a phase relationship.
- Lower frequencies are where network component electrical size is < $\lambda_{/10}$
- At this electrical size components can be considered to be discrete or lumped elements.



High Frequency Impedance

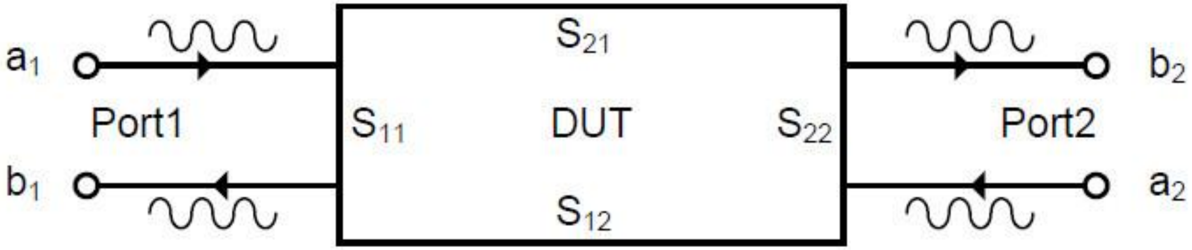


- Network elements are distributed, geometric, and complex at any electrical size > $\lambda_{/10}$
- Impedance measurement is by the ratio of the incident and reflected signals from the network.
- These ratios define S-Parameters of the network e.g. S_{11} the input port reflection coefficient.
- Calibration against a known set of references allows impedance to be calculated from S-params.

S-Parameters (Scattering parameters)

$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$



$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} \qquad S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$$

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} \qquad S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$

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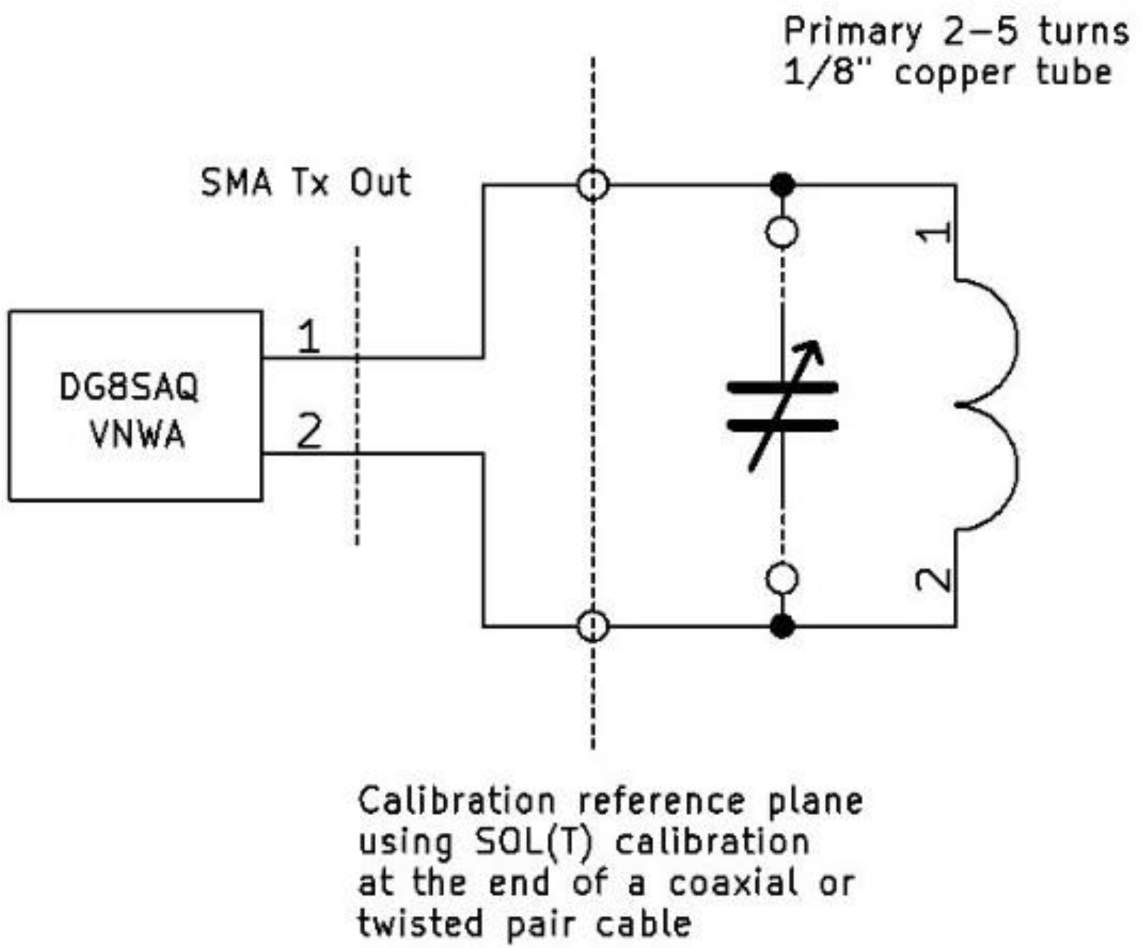
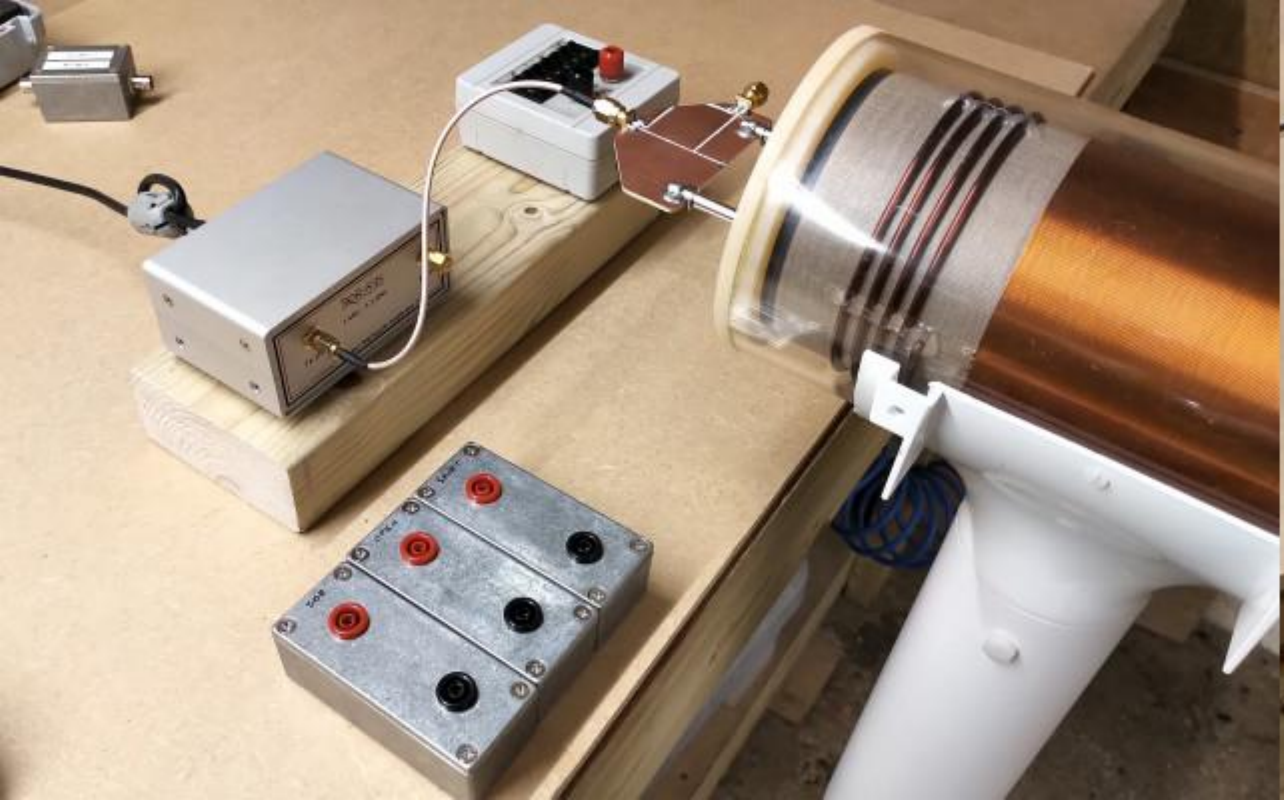
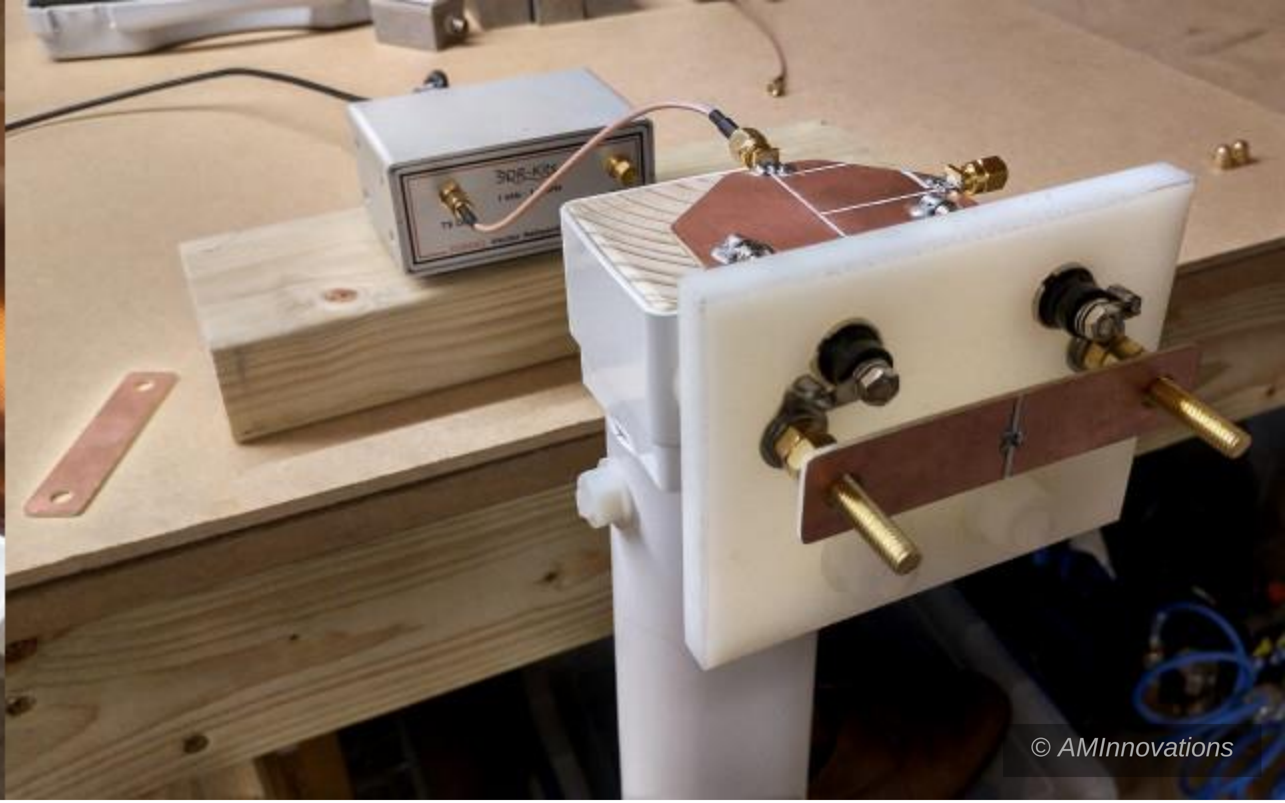
- Provide complete insight and characterisation of the linear behaviour of the device under test (DUT).
- Describe the magnitude and phase relationship between incident and reflected waves at input and output.
- Through VNA calibration are independent from instrument errors, impairments, and non-linearity.
- Can be applied to any DUT e.g. filters, transmission lines, amplifiers, discrete components, Tesla coils etc.
- A linear two port DUT can be entirely described by parameters S_{11}, S_{12}, S_{21}, S_{22}.
- These parameters can be defined when the opposing port is properly matched e.g. S_{11} when $a_2 = 0$.
- With a known calibration reference these can be converted to other properties e.g. impedance Z_{11}.
- For Tesla coils Z_{11} the input impedance, and S_{21} the transfer gain are most useful and sufficient.

Calibration and Reference Plane

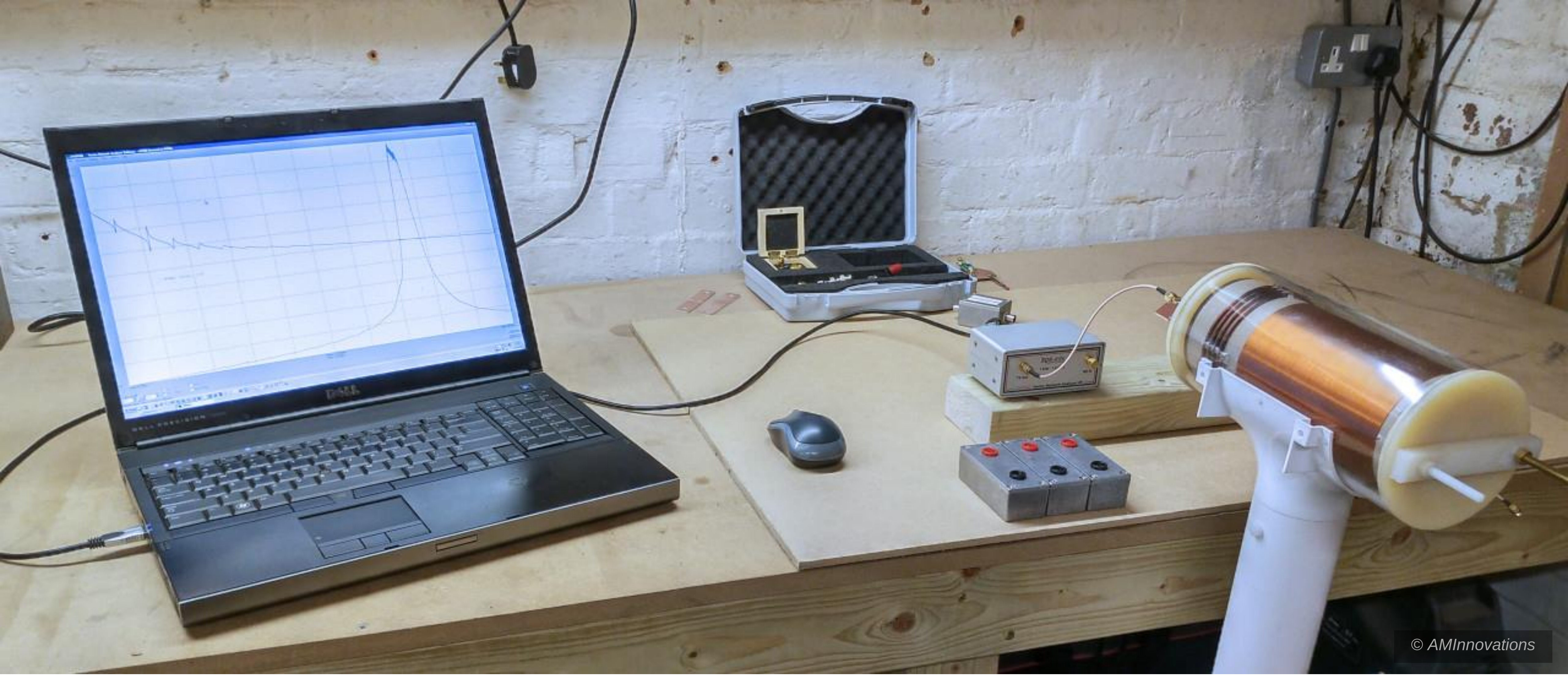
- Calibration transforms S-parameters to circuit characteristics e.g. $S_{11} \rightarrow Z_{11}$.
- Calibration removes electrical effects of circuit impedance between the VNA and the reference plane e.g. cables and other stray or self impedance.
- Errors and non-linearity can be reduced through careful calibration
- With calibration the reference plane is extended to a defined point outside of the VNA e.g. to the input of the primary coil.
- Calibration and subsequent measurement is over a defined frequency band.
- The SOLT calibration method is the standard approach to establish a known calibration for a VNA.





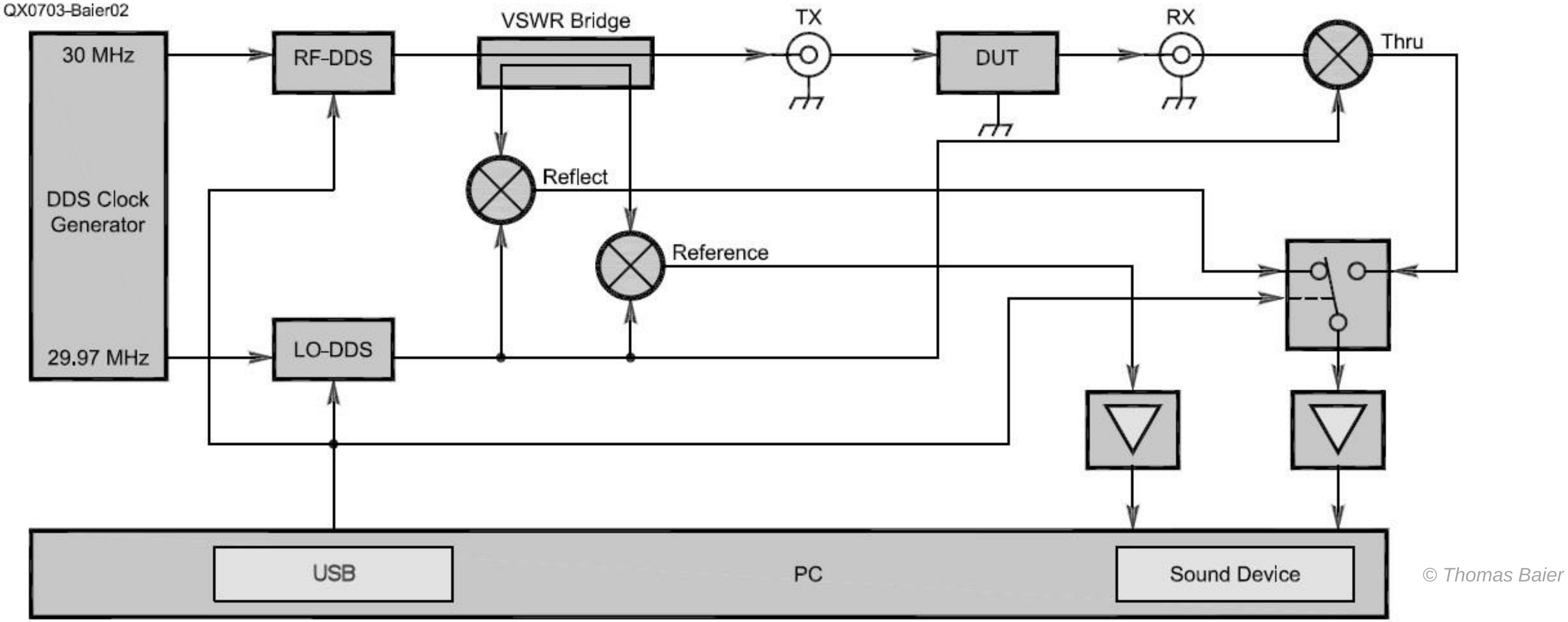


- DG8SAQ can measure in a double sweep S_{11} and S_{21}, or S_{22} and S_{12} with DUT reversed.
- SOLT Calibration:
  - **S**hort - an element with very low impedance $\rightarrow$ 0 Ω, and where phase change $\rightarrow$ 0°.
  - **O**pen - an element with very high impedance $\rightarrow \infty$ Ω, and where phase change $\rightarrow$ 180°.
  - **L**oad - an element with usually a good match to the VNA output impedance, which in this case is 50 Ω.
  - **T**hru - required for S_{21} and S_{12} measurement, and normally a short section ($< \lambda_{/10}$) of 50 Ω transmission line.

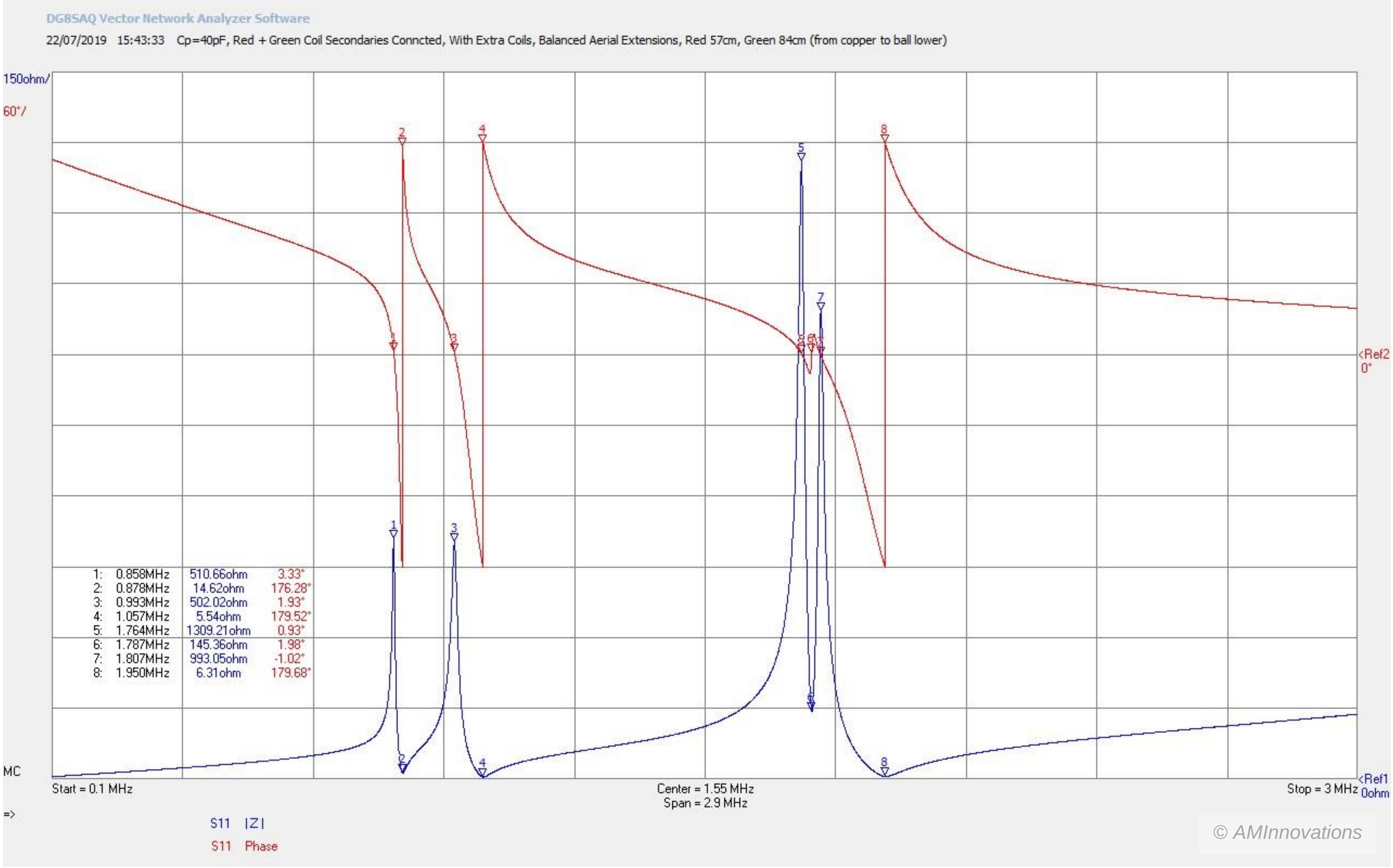


Complete DG8SAQ measurement setup for a Multi-Wave Oscillator (MWO) Tesla coil driver.

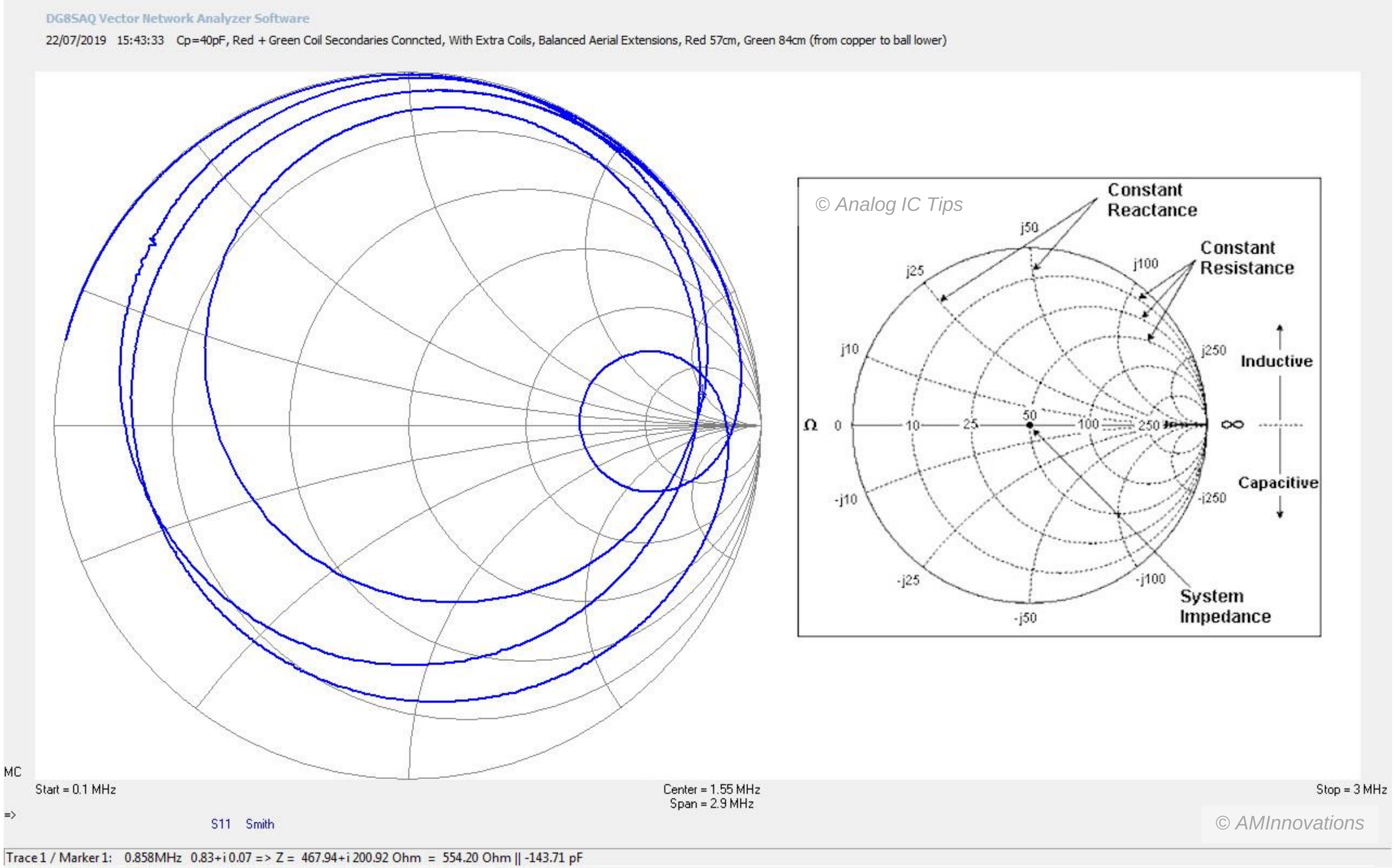
DG8SAQ VNWA Principles



A Low Budget Vector Network Analyzer for AF to UHF - Thomas Baier, DG8SAQ



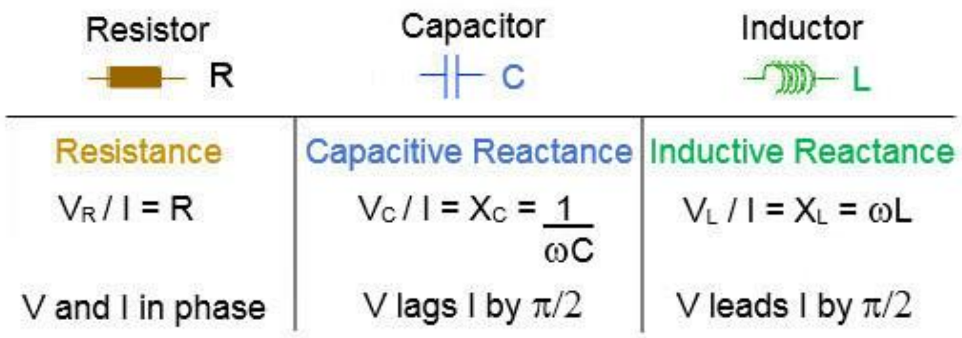
Impedance Magnitude and Phase - Rectilinear : ESTC 2019 Eric Dollard's Colorado Springs Experiment

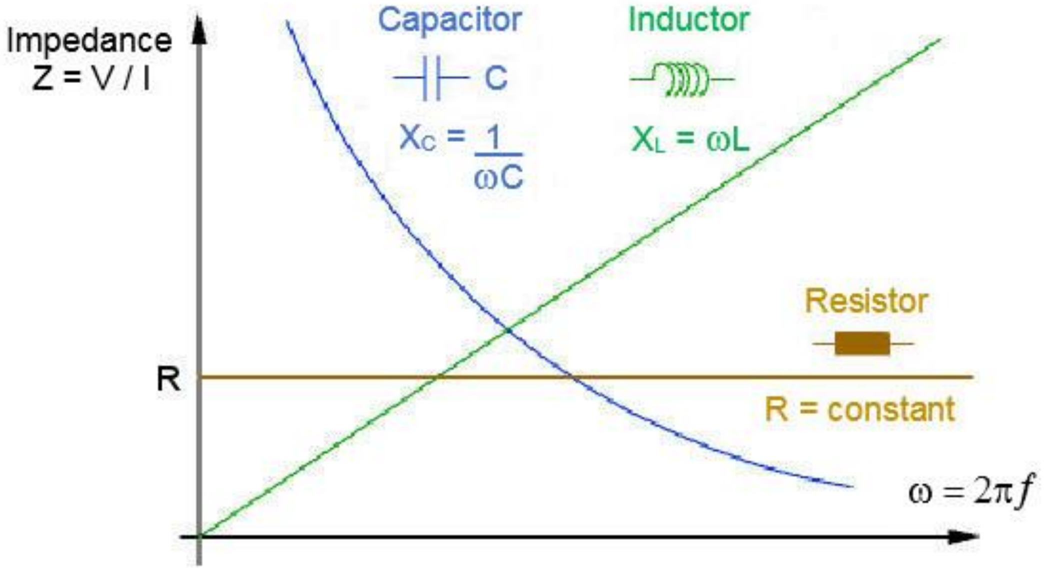


Impedance Smith Chart - Polar : ESTC 2019 Eric Dollard's Colorado Springs Experiment

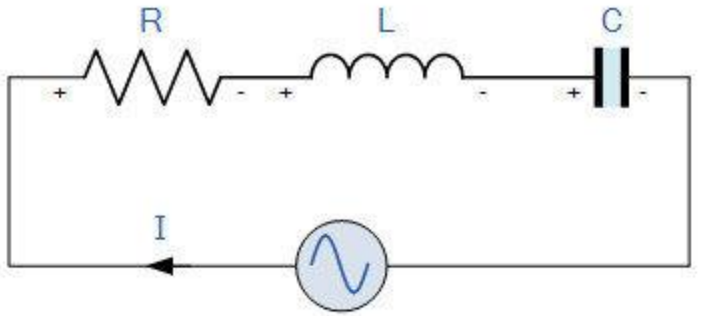
Basic Component Impedance

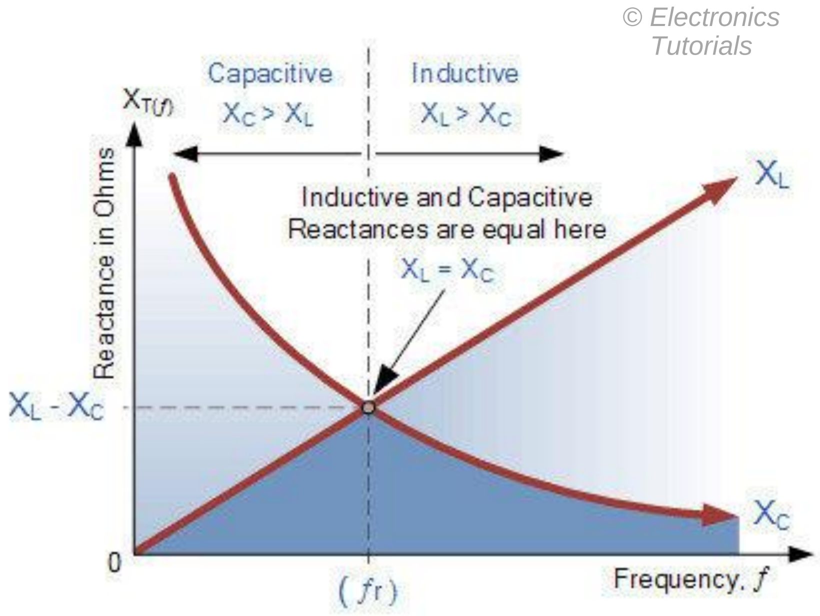
- Ideal resistance R is constant with frequency.
- Ideal capacitive reactance X_C reduces as the inverse with frequency, voltage lags current.
- Ideal inductive reactance X_L increases linearly with frequency, voltage leads current.
- Combinations of R, L, and C both discrete and distributed result in complex impedance characteristics of a network.
- R combined with L or C form filter circuits e.g. low-pass, high-pass, band-pass etc.
- L and C combined either in series or parallel form an ideal resonant circuit.
- A real resonant circuit combines L, C, and R.
- A Tesla coil is a complex distributed resonant circuit, with both series and parallel resonance.



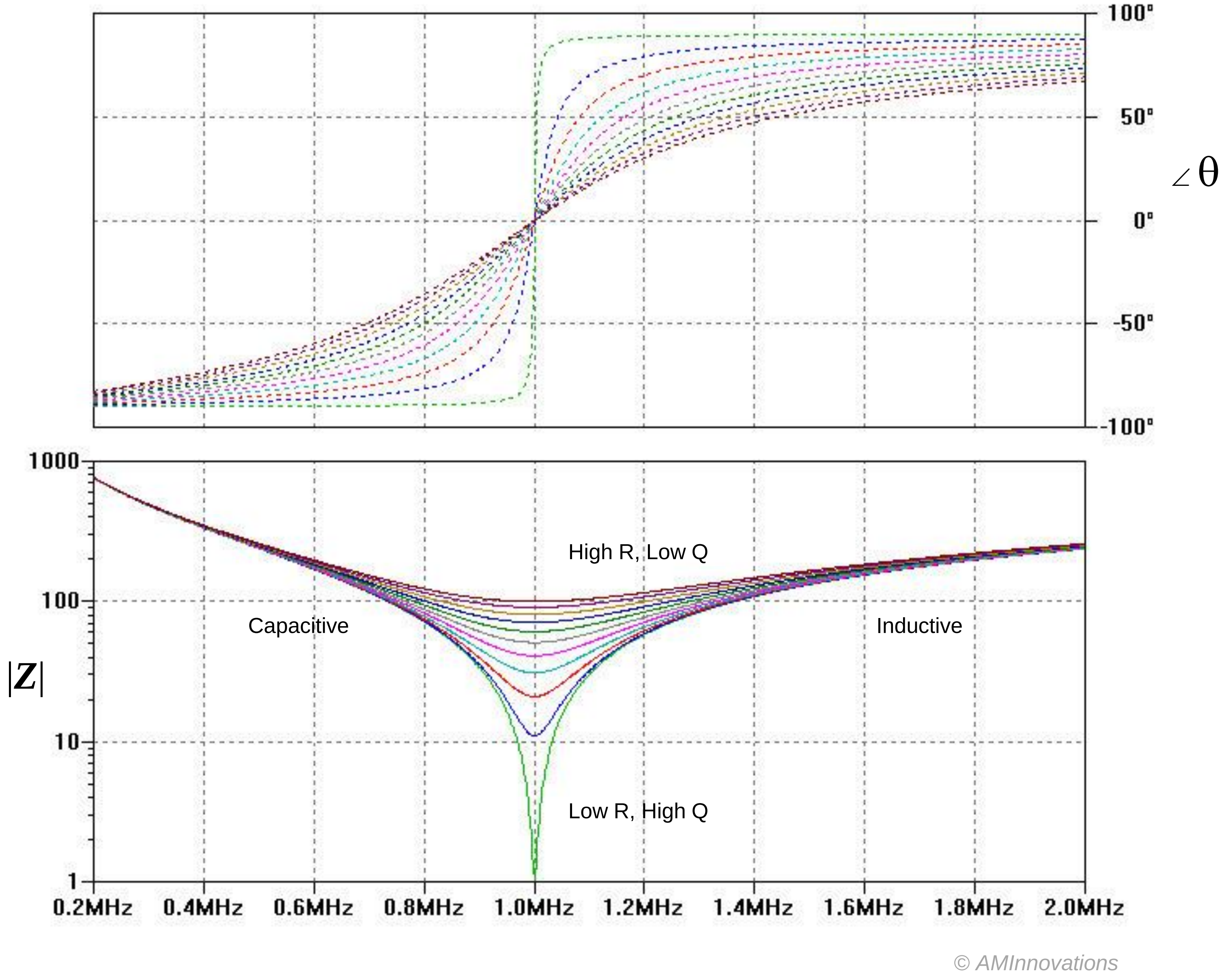


Series Resonance

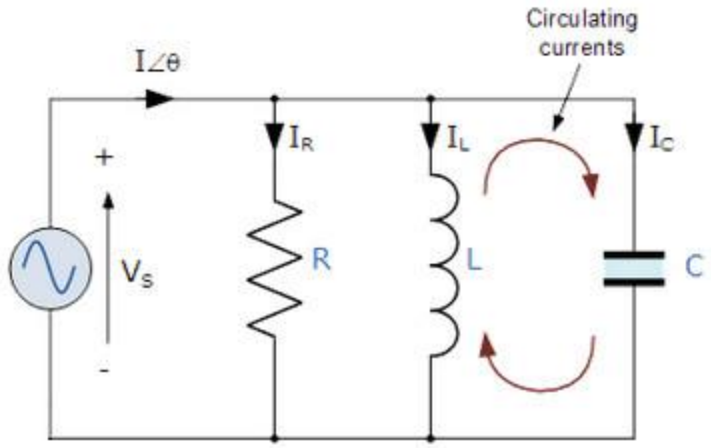




Series Resonance Component Impedance



Parallel Resonance



At resonance the reactive current is zero

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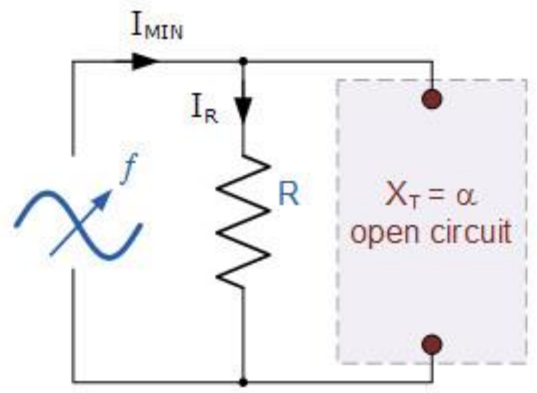
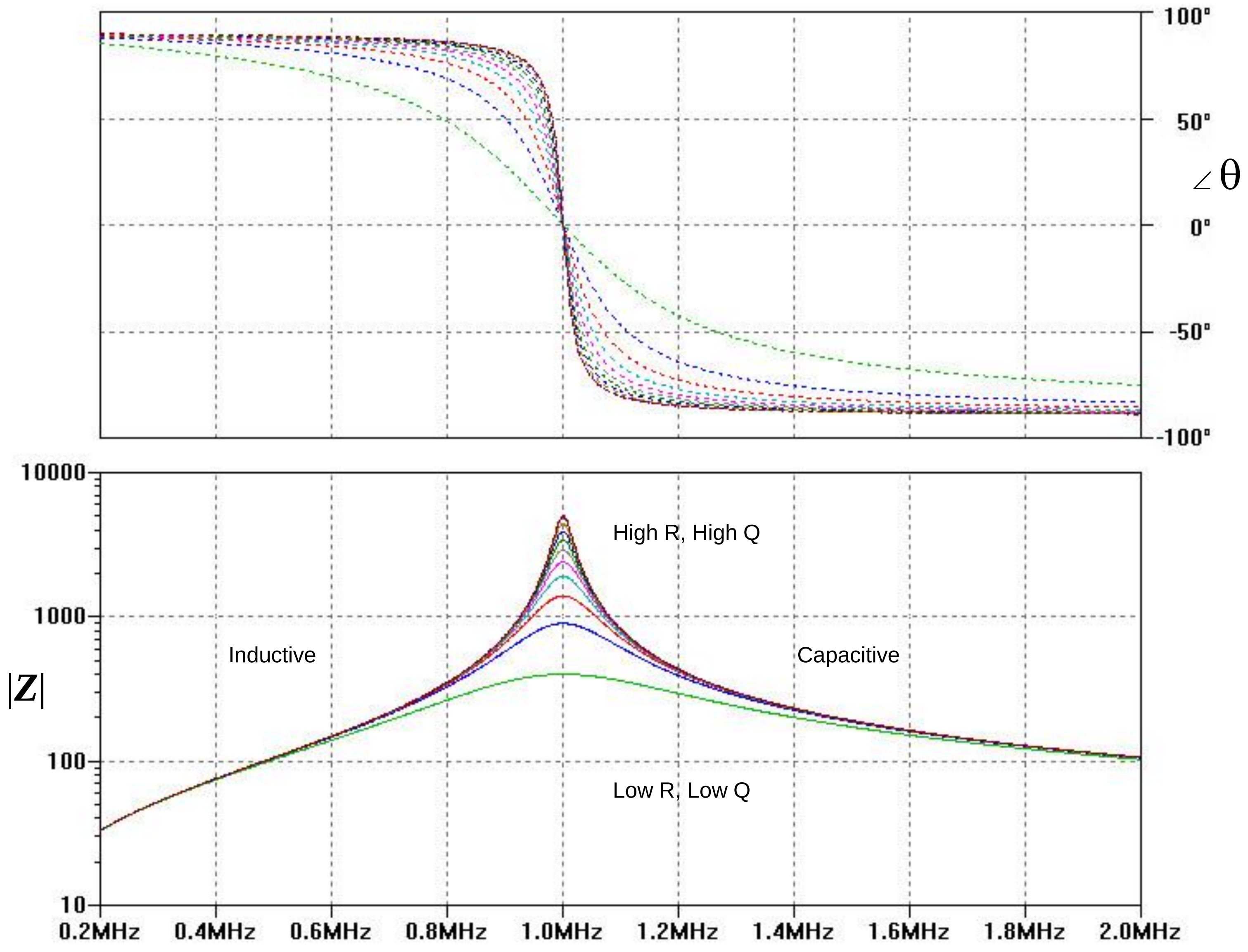


Parallel Resonance Component Impedance



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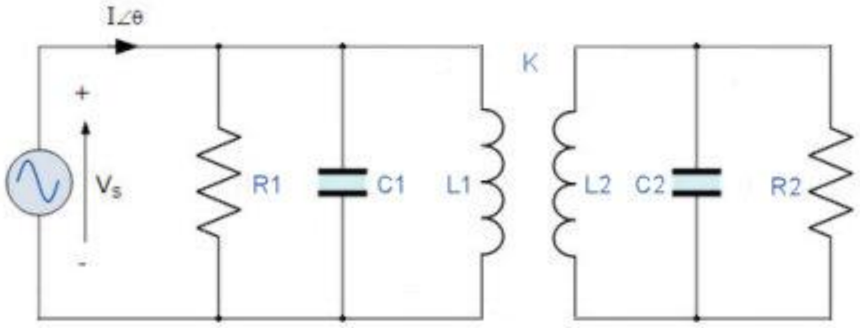
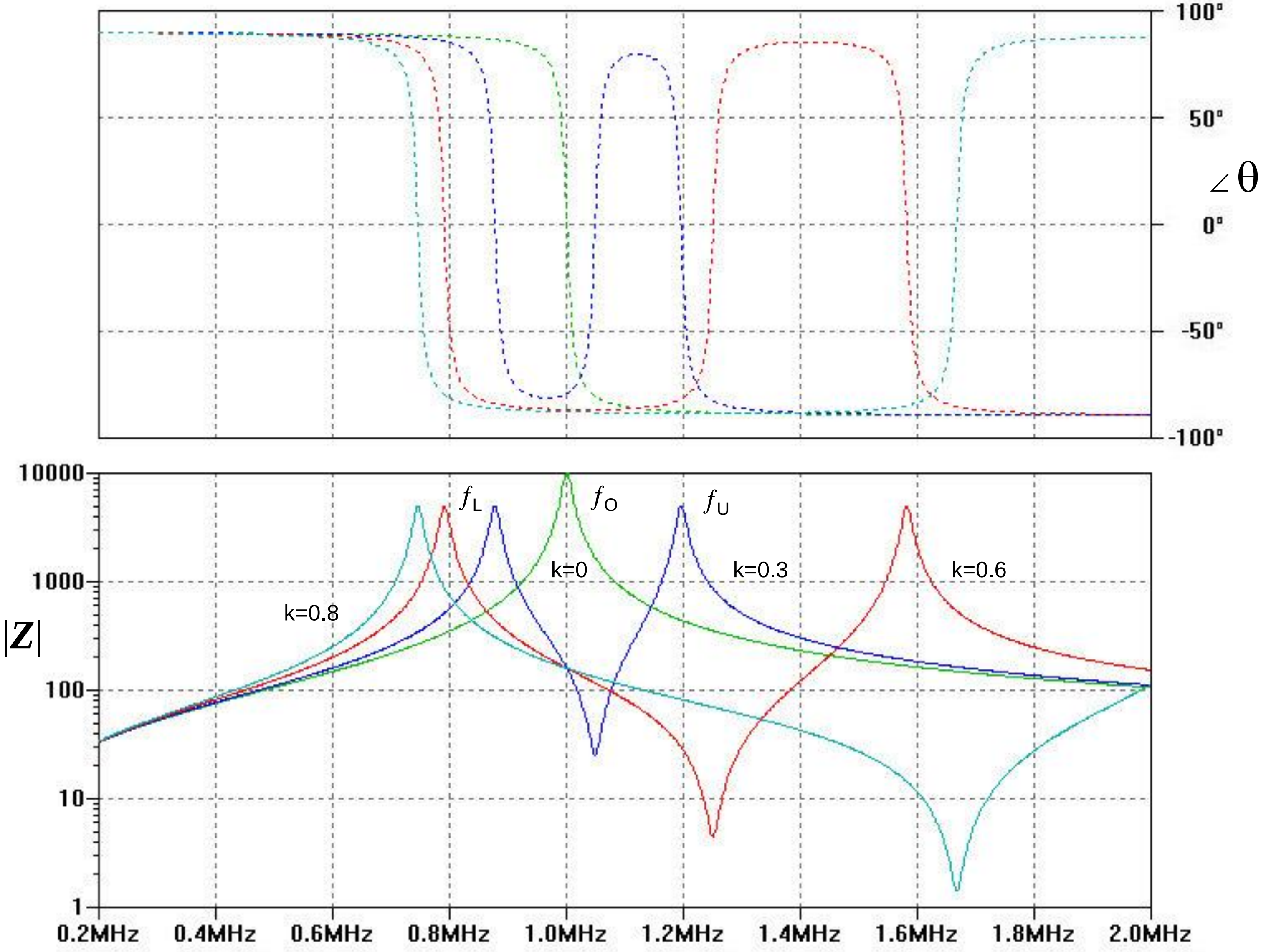
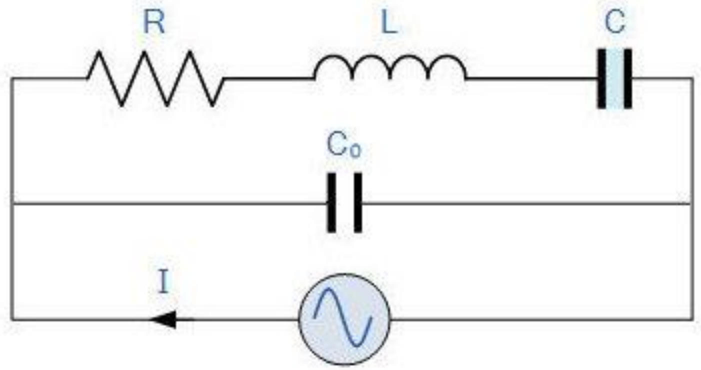
Coupled Resonant Circuits



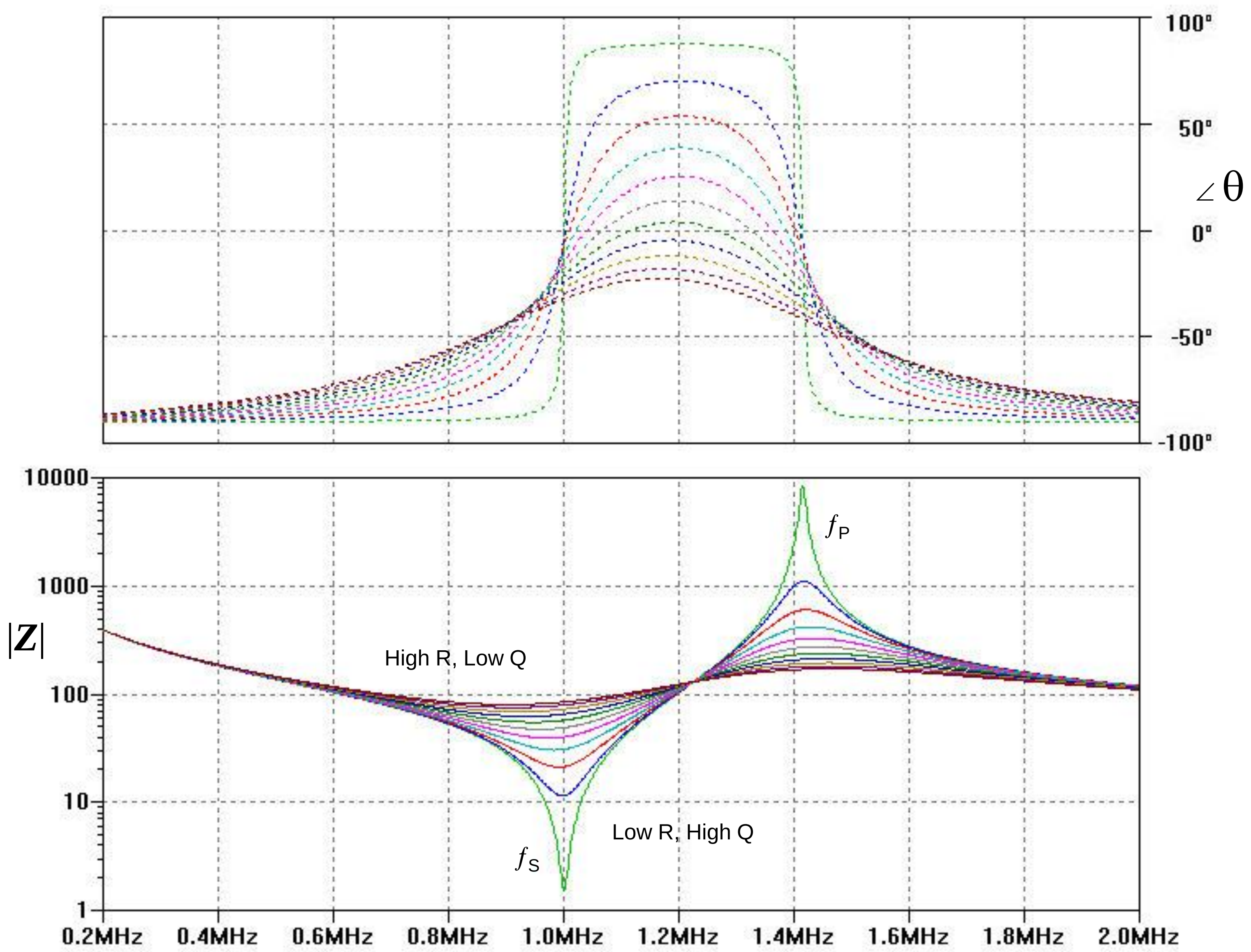
- Coupled resonant circuits interact.
- When both fundamentals f_O are close frequency splitting or "beating" occurs.
- $f_O \rightarrow f_U$ and f_L, (upper and lower).
- Non-coupled the two circuits may have the same resonant frequency.
- As magnetic coupling coefficient *k* increases, f_U and f_L move further apart.
- Tesla coils have coupled primary and secondary coils, typically *k* ~ 0.1 - 0.3



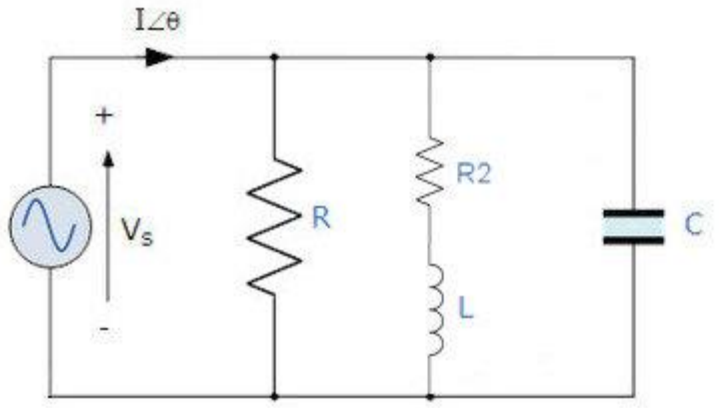
Multiple Resonant Modes



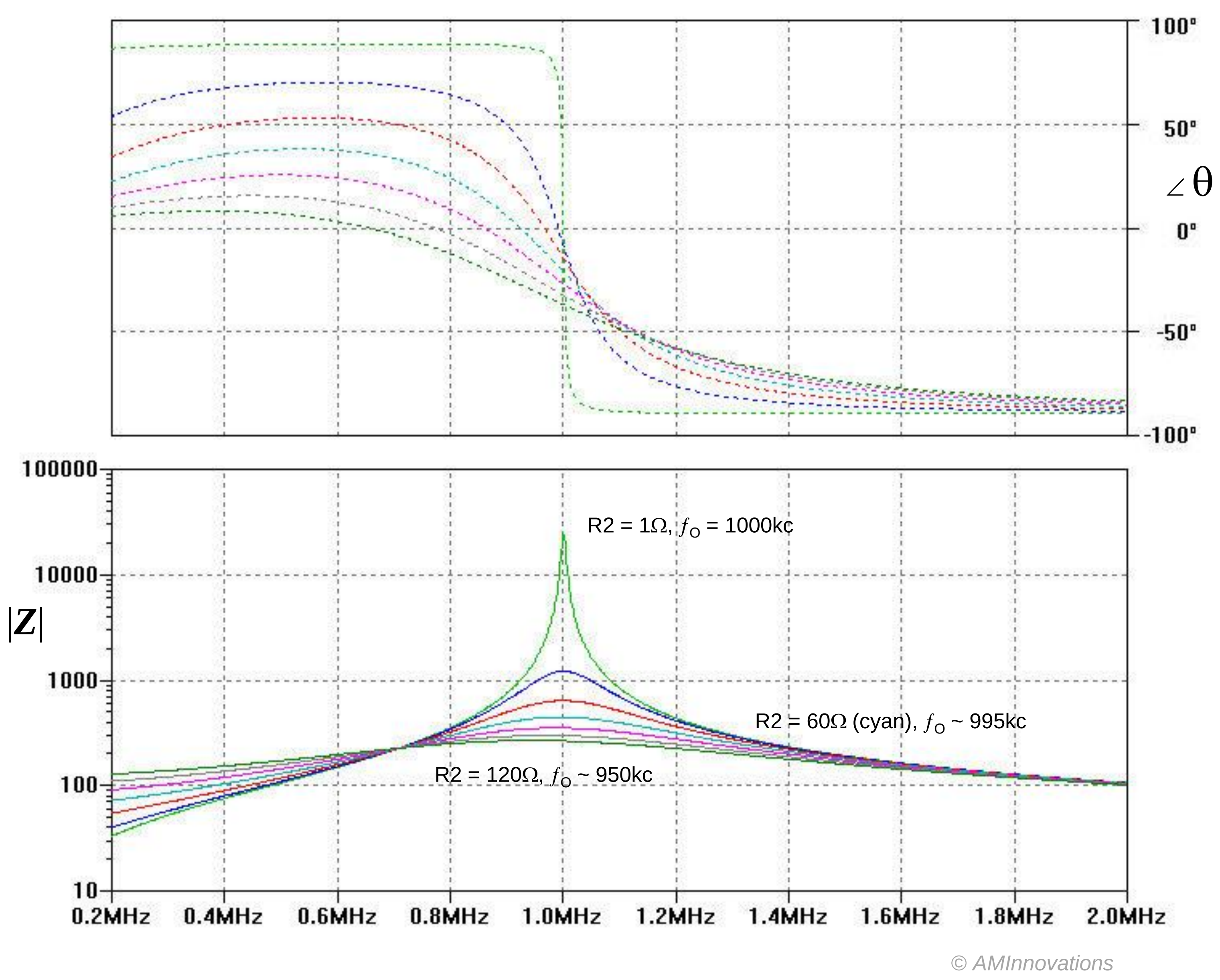
- Crystals and piezo-electric materials exhibit multiple resonant modes, both a series f_S, and parallel f_P, resonance.
- The equivalent circuit has both parallel and series resonant circuits.
- A Tesla coil secondary is a complex distributed resonator and can also exhibit f_S and f_P resonant modes.
- The combination of multiple resonant modes and frequency splitting in a TMT system represents a significant tuning and generator matching challenge.



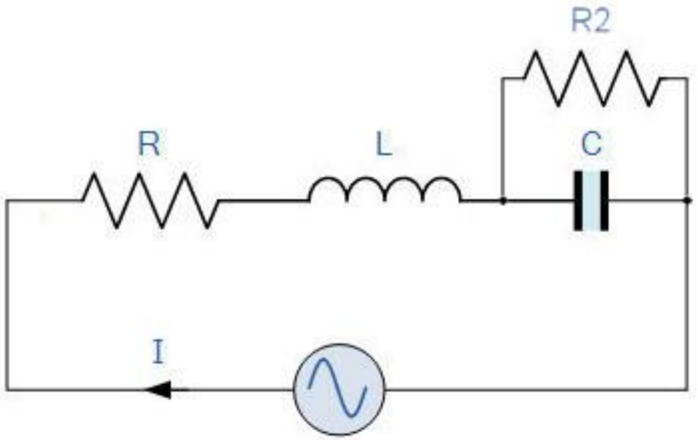
Parallel Resonance Offset with Series Resistance



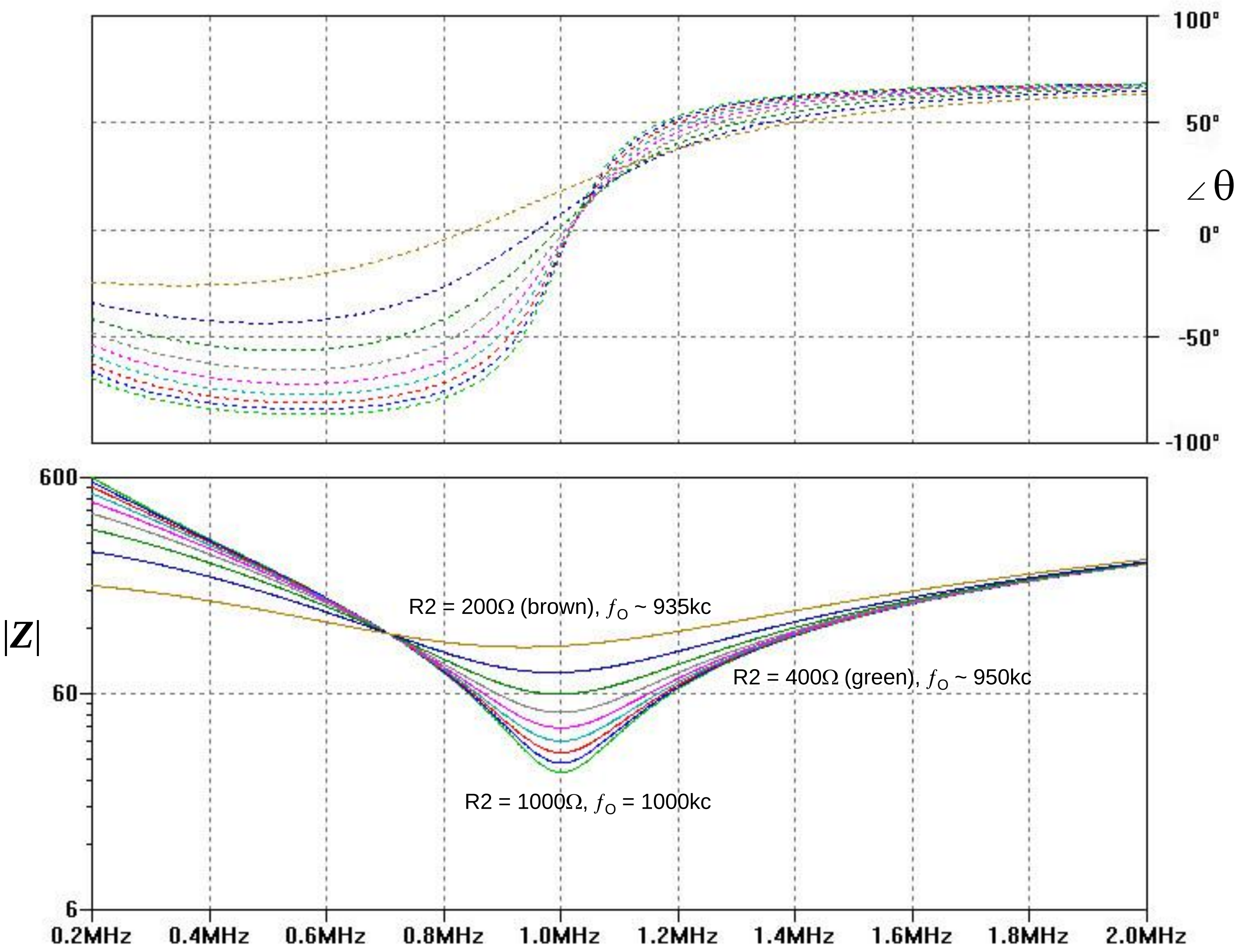
- Resistance R2 in series with the inductor L will cause resonant frequency offsets.
- Tesla coils can have significant series resistance in the secondary coil.
- When R2 $\rightarrow X_L$, f_O starts to shift downwards.
- Large offsets can occur in Tesla coils, which impacts generator drive frequency and matching.

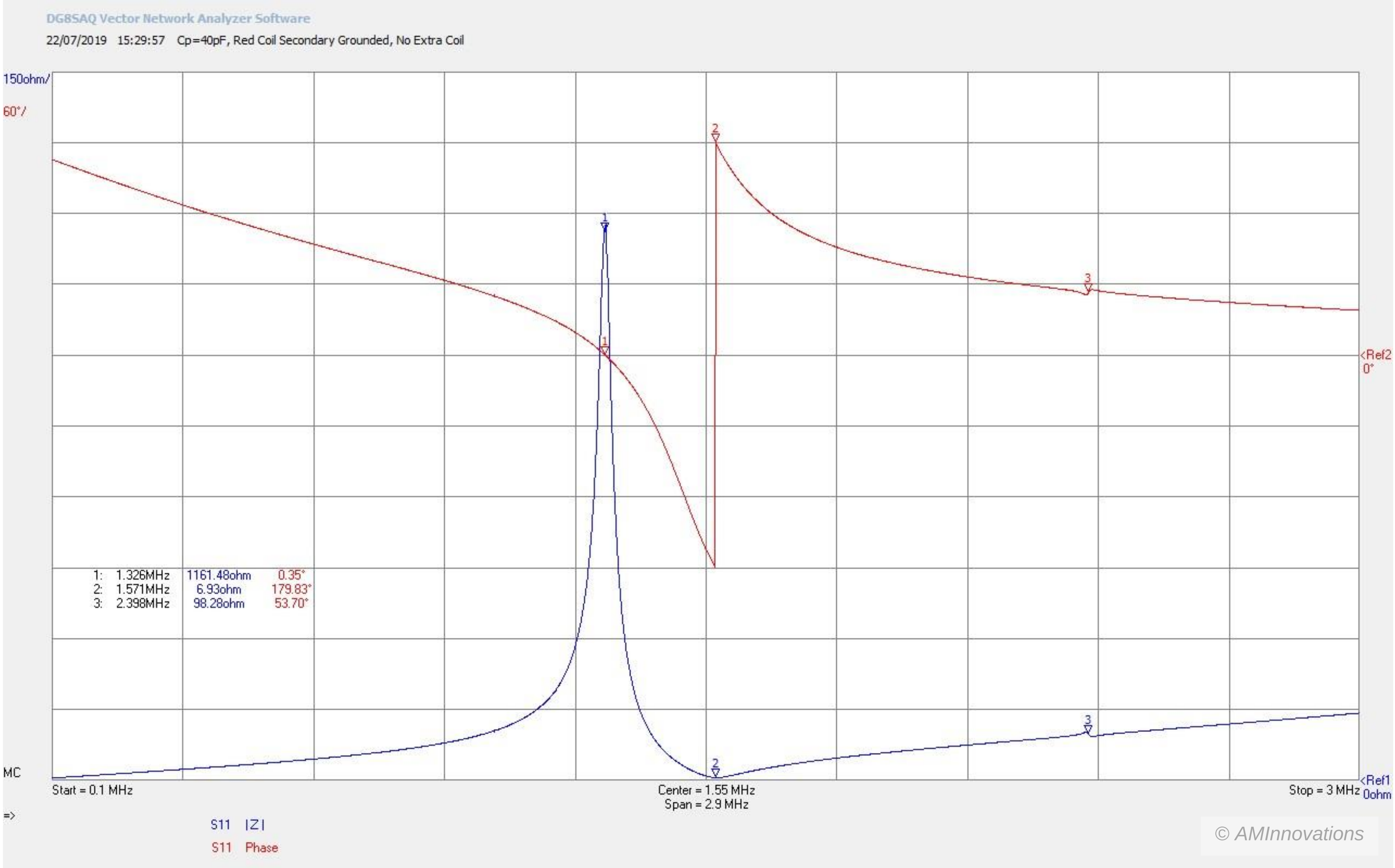


Series Resonance Offset with Parallel Resistance

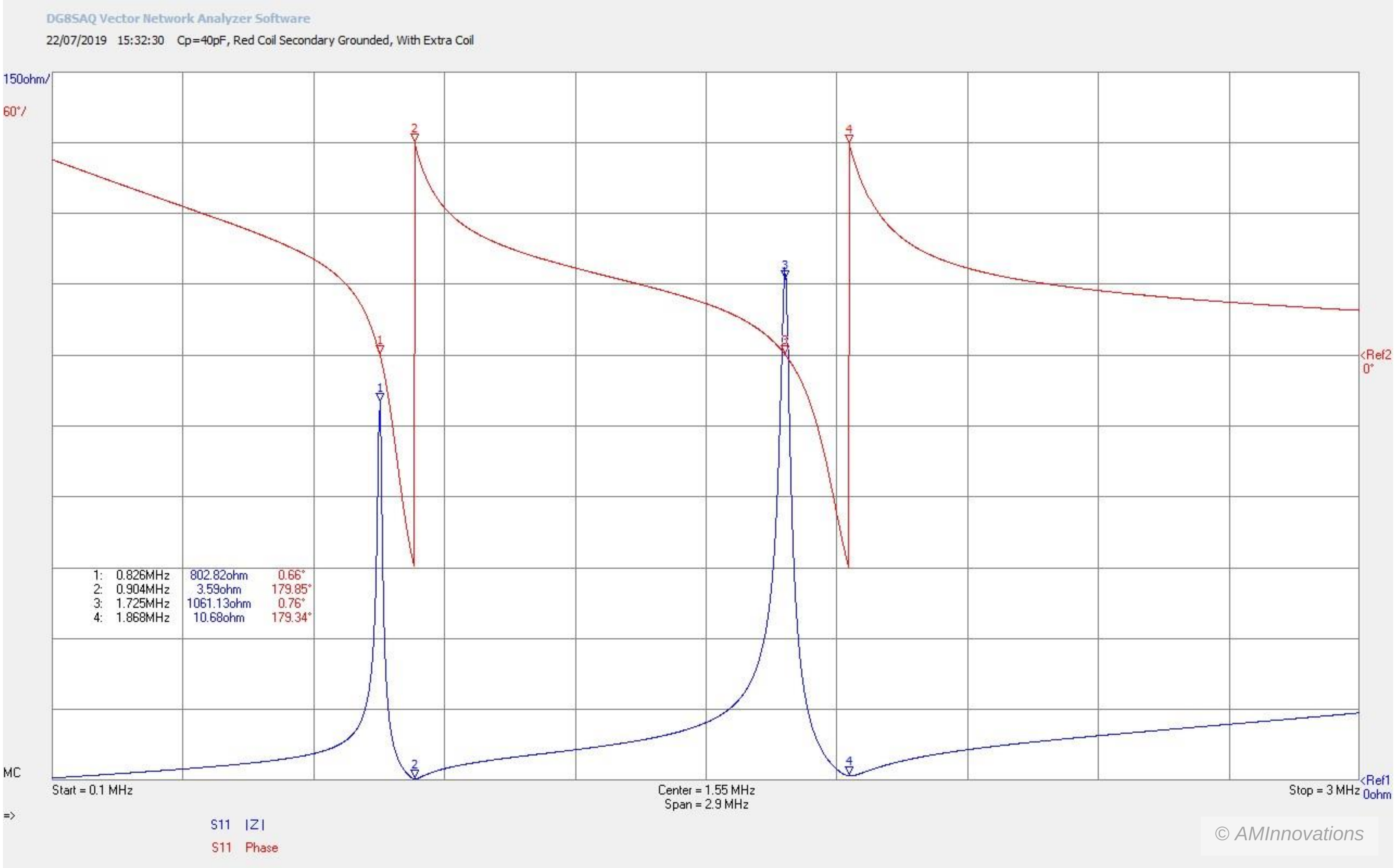


- Leakage resistance R2 in parallel with the capacitor C will cause resonant frequency offsets.
- When R2 $\rightarrow X_C$, f_O starts to shift downwards.
- Leakage in the primary circuit tank capacitors of a Tesla coil or TMT system, can cause frequency offsets and generator to primary mismatches.

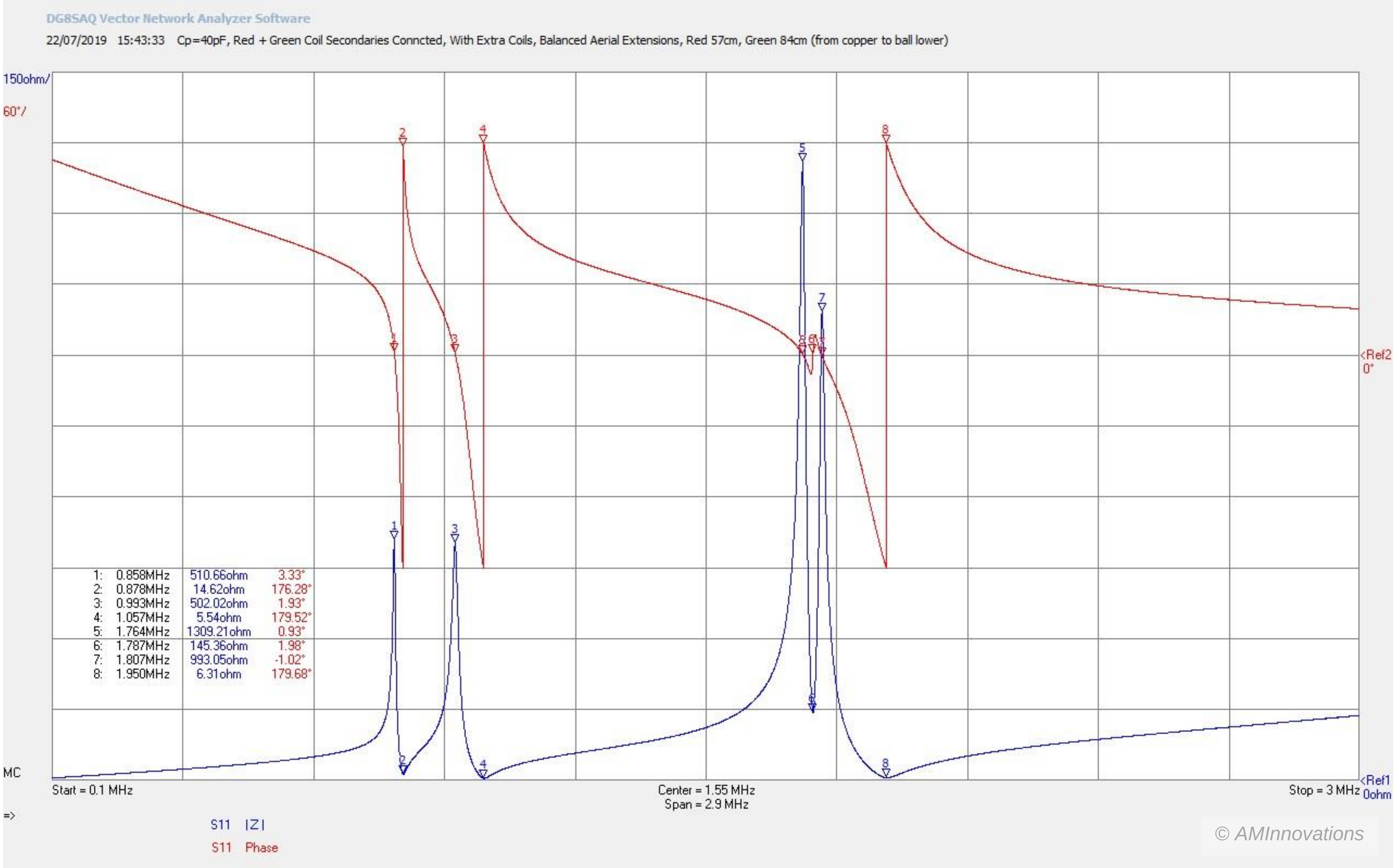




Red Primary and Secondary Coil Input Impedance $\boldsymbol{Z_{11}}$: ESTC 2019 Eric Dollard's Colorado Springs Experiment



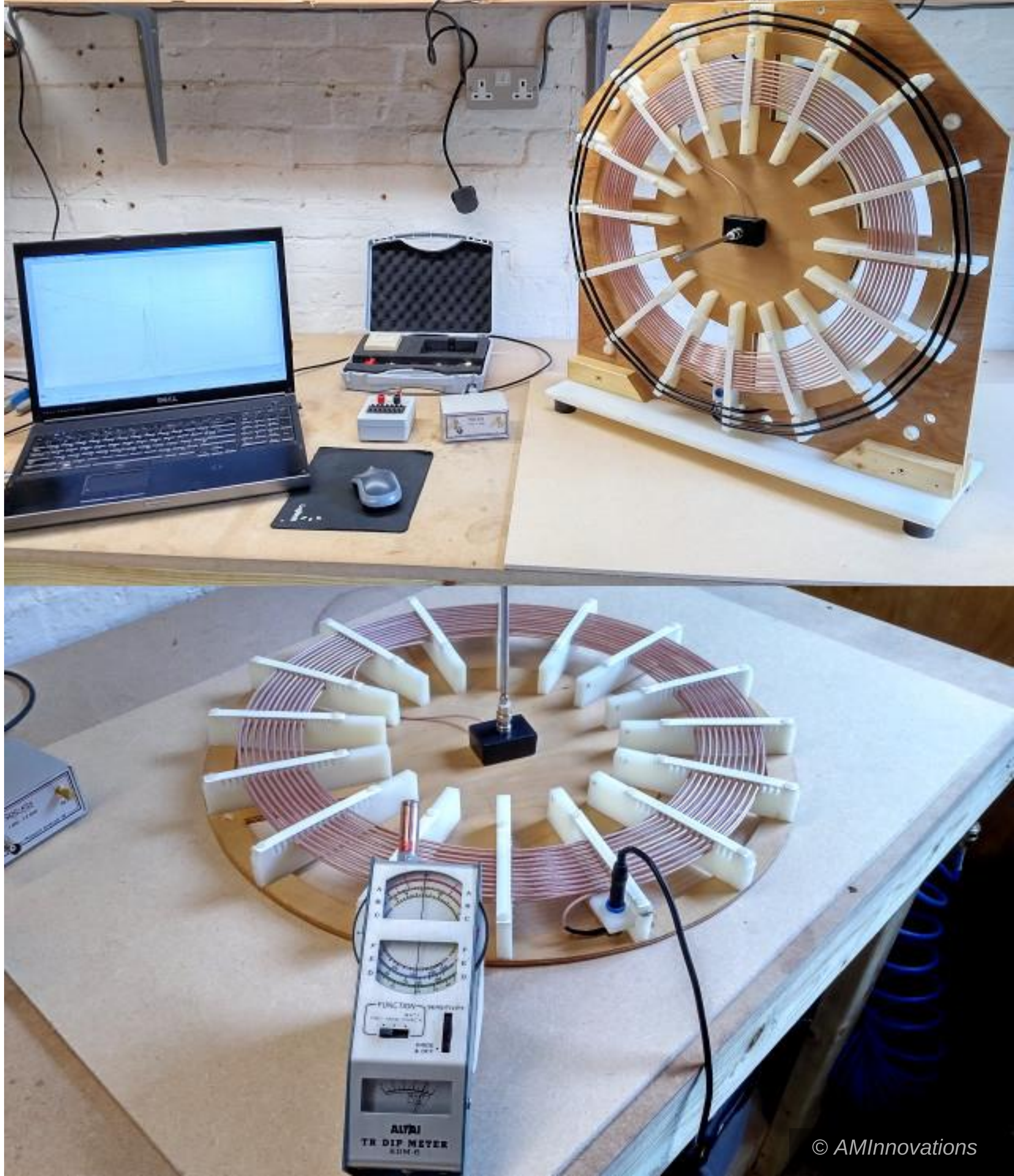
Red Primary and Secondary with Extra Coil Z_{11} : ESTC 2019 Eric Dollard's Colorado Springs Experiment



Complete TMT System with Single Wire Connection Z_{11} : ESTC 2019 Eric Dollard's Colorado Springs Experiment

Vector Network Measurements

- A Tesla coil is a very sensitive, high-Q, high-selectivity, air-cored free resonator.
- Accurate measurements on a Tesla coil require a careful and disciplined approach.
- Measurement safety must be observed at all times.
- Cables and connections between the VNA and the Tesla coil need to be carefully arranged.
- The measurement environment must be carefully considered to reduce stray effects e.g. metal proximity.
- Ambient radiation, signals, and electrical noise need to be minimised to prevent pickup and errors.
- If possible measurements should be cross-checked by another means e.g. dip meter, spectrum analyzer etc.
- Series-fed VNA connection allows accurate measurement of the free resonator properties.
- Primary-fed VNA connection allows complete system characterisation from the perspective of the generator.



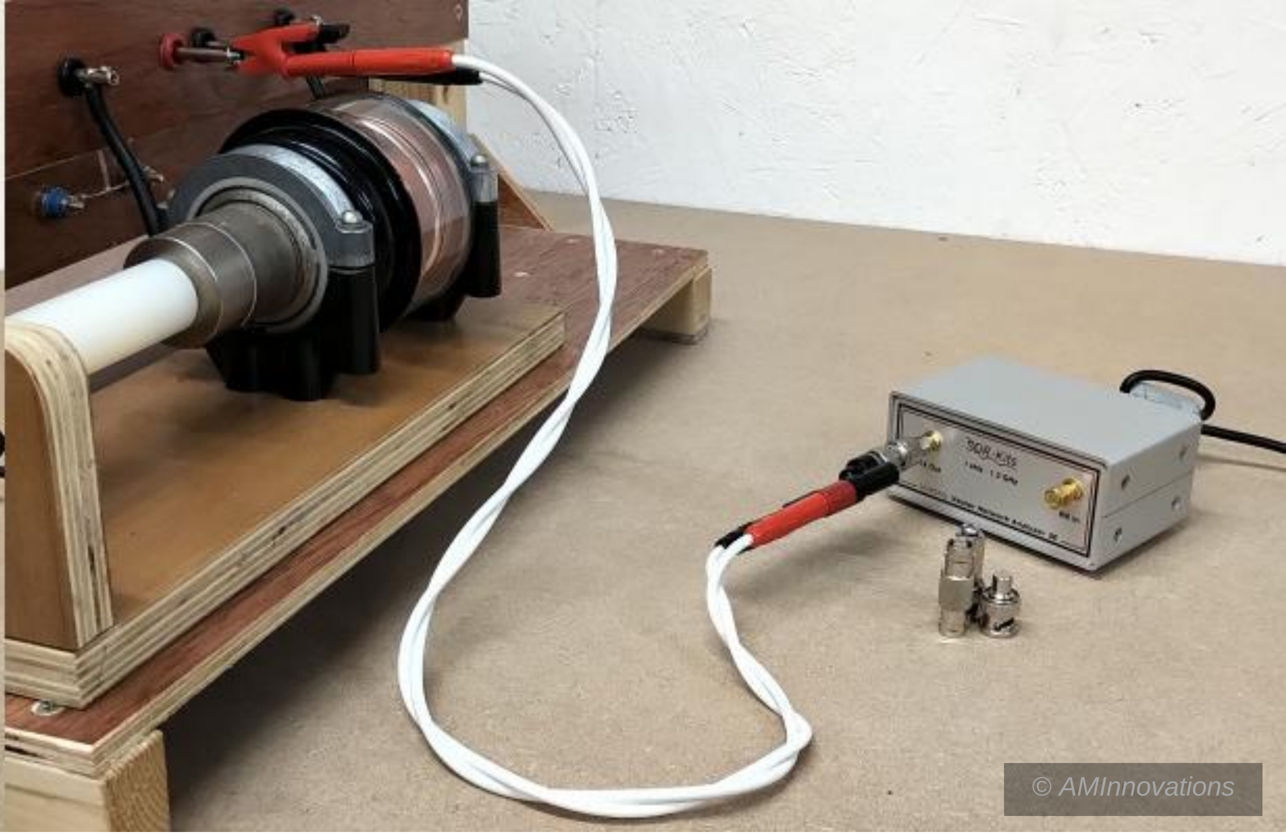
Measurement Safety

- Tesla coils (TC) run at high power, with high voltages and currents:
  - Output powers < 1W - 10kW and beyond.
  - Secondary coil voltage magnification from a few 100's of volts, to 10MV and beyond.
  - Primary coil drive currents from a few amps up to 10kA, and much more in pulsed supplies.
  - Large radiated field strengths possible, both dielectric and magnetic.
  - Operating TCs at high power requires experience, extreme caution, and common sense!
- Vector network analysers are sensitive small signal ac measurement instruments:
  - Maximum input power usually limited to 0-20dBm (1mW – 100mW) – Power attenuators not sufficient for TCs.
  - Often input ports are AC only, no DC components or offsets at any port – DC blockers required.
  - Easily over-loaded by large ambient fields – ports need screening during TC operation.
  - TCs often have high voltage gain between primary and secondary. Measurements of S_{21} may require an attenuator.

Tesla coils and VNAs should not be operated connected at the same time!

Arrange experimental method and equipment connections to minimise the chance for mistakes in the measurement and operating procedures.

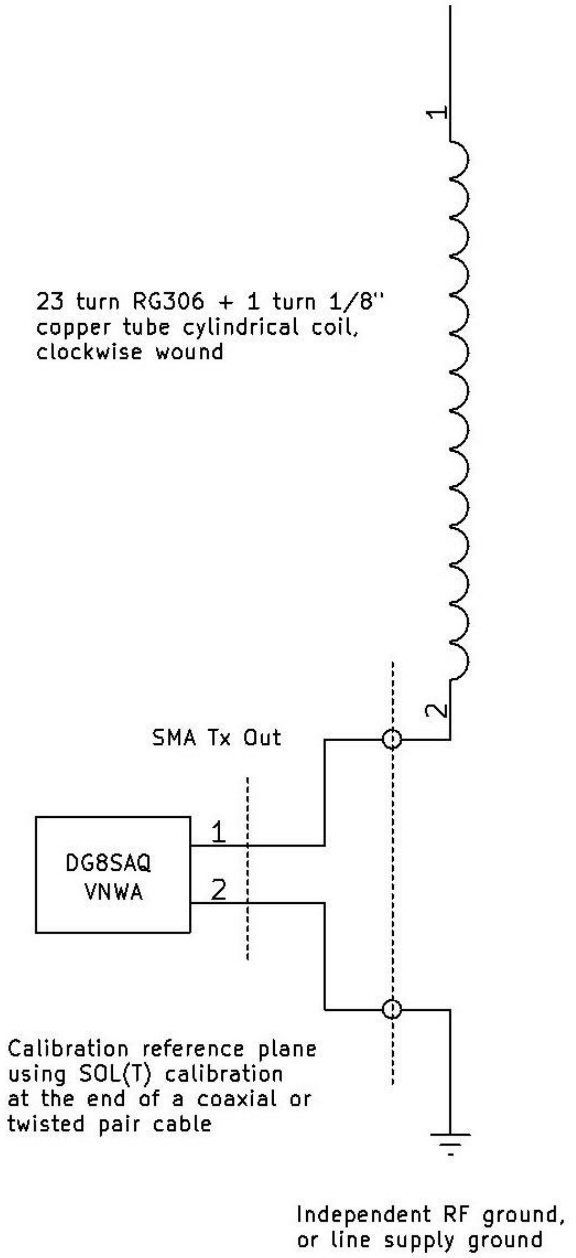
An Alternative Use for the Vector Network Analyzer!



- Where possible use short coaxial connections (BNC or SMA) with matching connectors.
- Where non-coaxial cable and connections are required use fine-stranded (low inductance) twisted pair cable (16awg), with insulated crocodile clips. Arrange SOLT elements to match the cable terminations.
- Calibrate as close as possible to the generator inputs to the TC, and using the SOLT procedure.
- The reference plane should be arranged according to the type of measurement e.g. series or primary-fed.

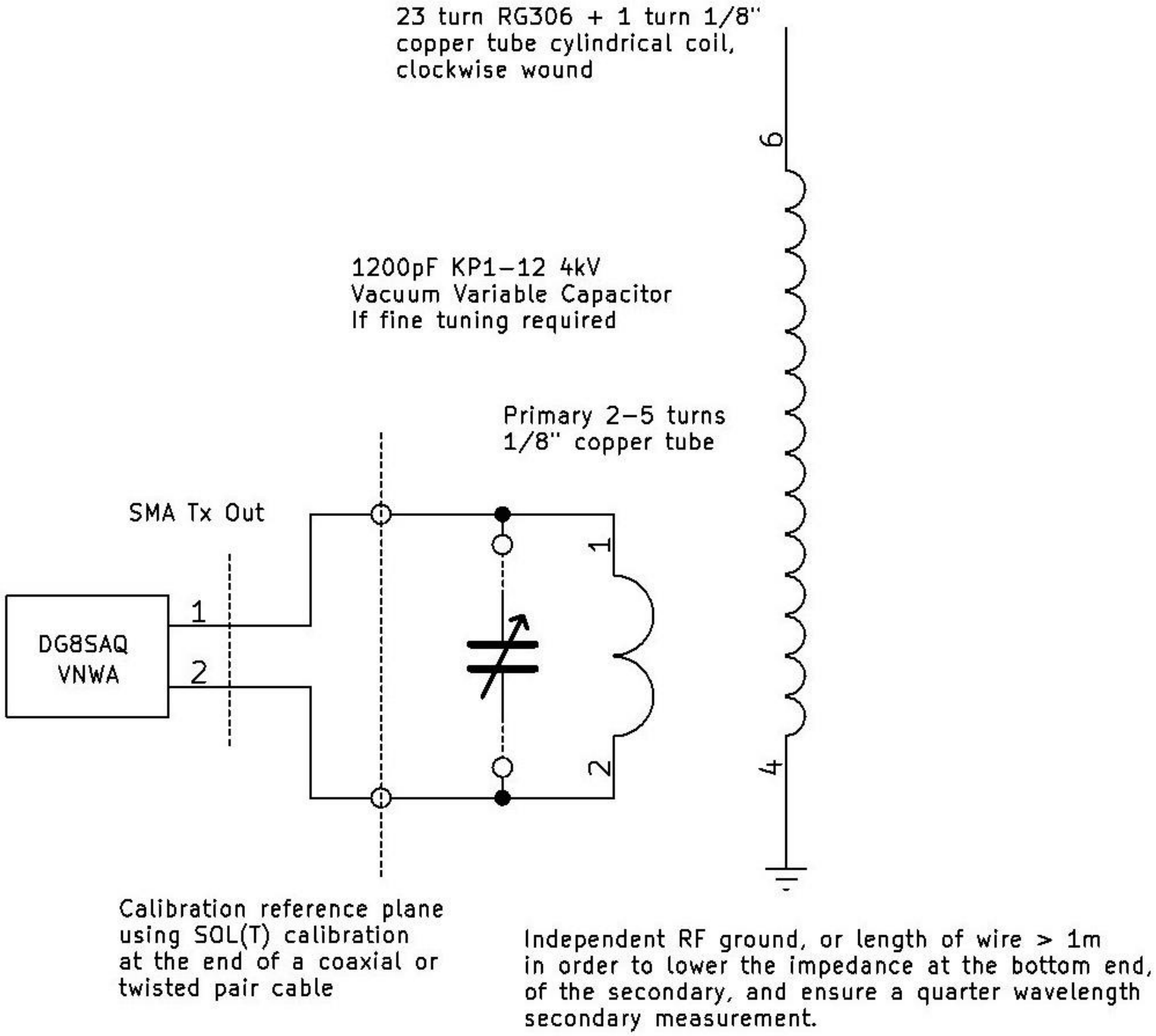
Series-Fed Measurements

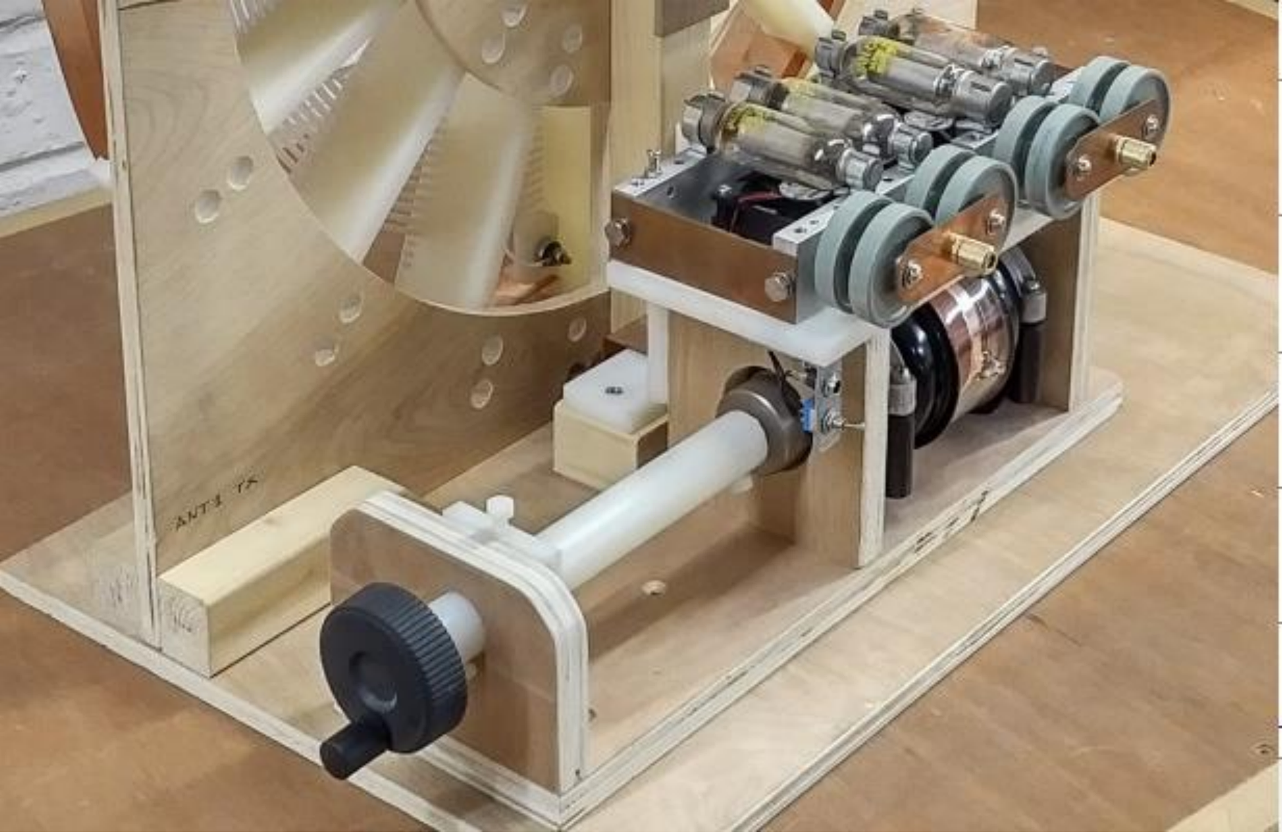
- Suitable for direct impedance measurement of a single coil, or connected coils, with minimal distortion of the free resonance. e.g. a Tesla secondary and/or extra coil,
- This arrangement is effectively like an antenna placed directly in series with the positive terminal of the VNA output port.
- The negative terminal of the VNA port is connected down to an independent RF ground, or the line supply ground.
- A Z_{11} single port measurement represents a good measure of the coil characteristics.
- SOLT calibration used to set the reference plane as close to the secondary coil terminal and ground terminal as possible.
- The free resonance of the coil is easily effected by the presence of other coils e.g. a primary or extra coil.
- The free resonance of the high-Q secondary coil is minimally disturbed by connection to the VNA by this method.

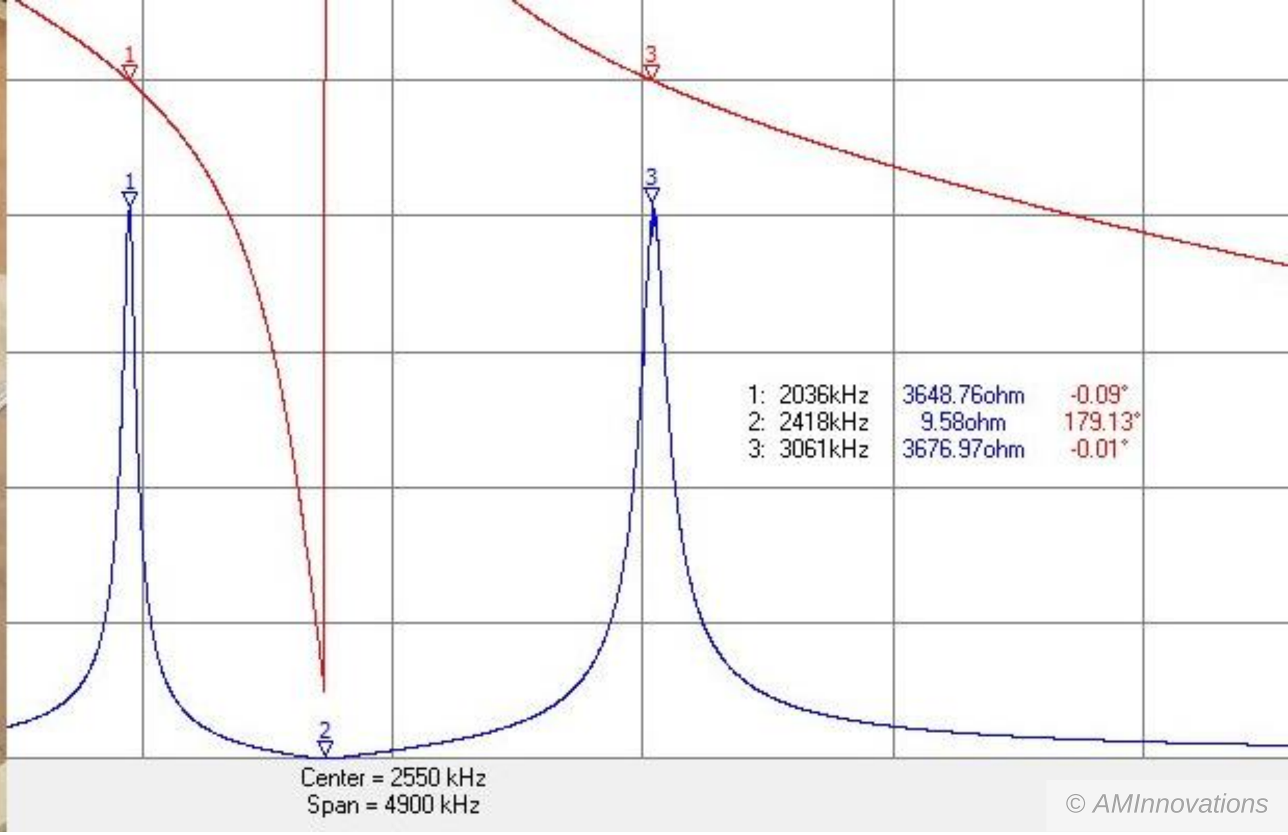


Primary-Fed Measurements

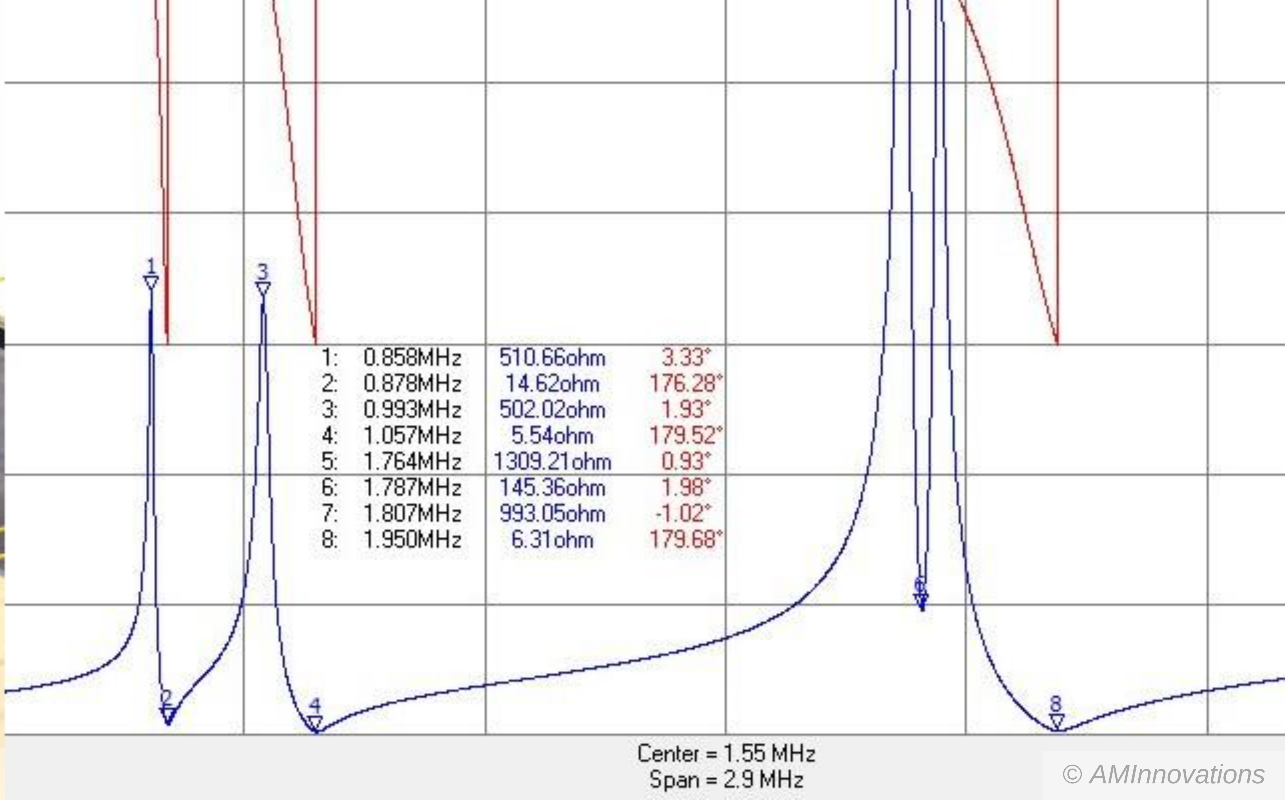
- A Tesla coil is operated by electrically driving the primary from a suitable generator.
- A primary-fed measurement looks at the impedance of the complete TC, TMT, and whatever is connected as loads etc.
- A Z_{11} single port measurement will characterise the frequency response of the complete system from the perspective of the generator.
- The Z_{11} measurement is useful for matching the impedance of the generator, and identifying key operating points of interest.
- A Z_{21} two port measurement will characterise the transfer response, from the generator through to the load, of the complete system.
- Tuning of the complete system can be adjusted and measured dynamically.



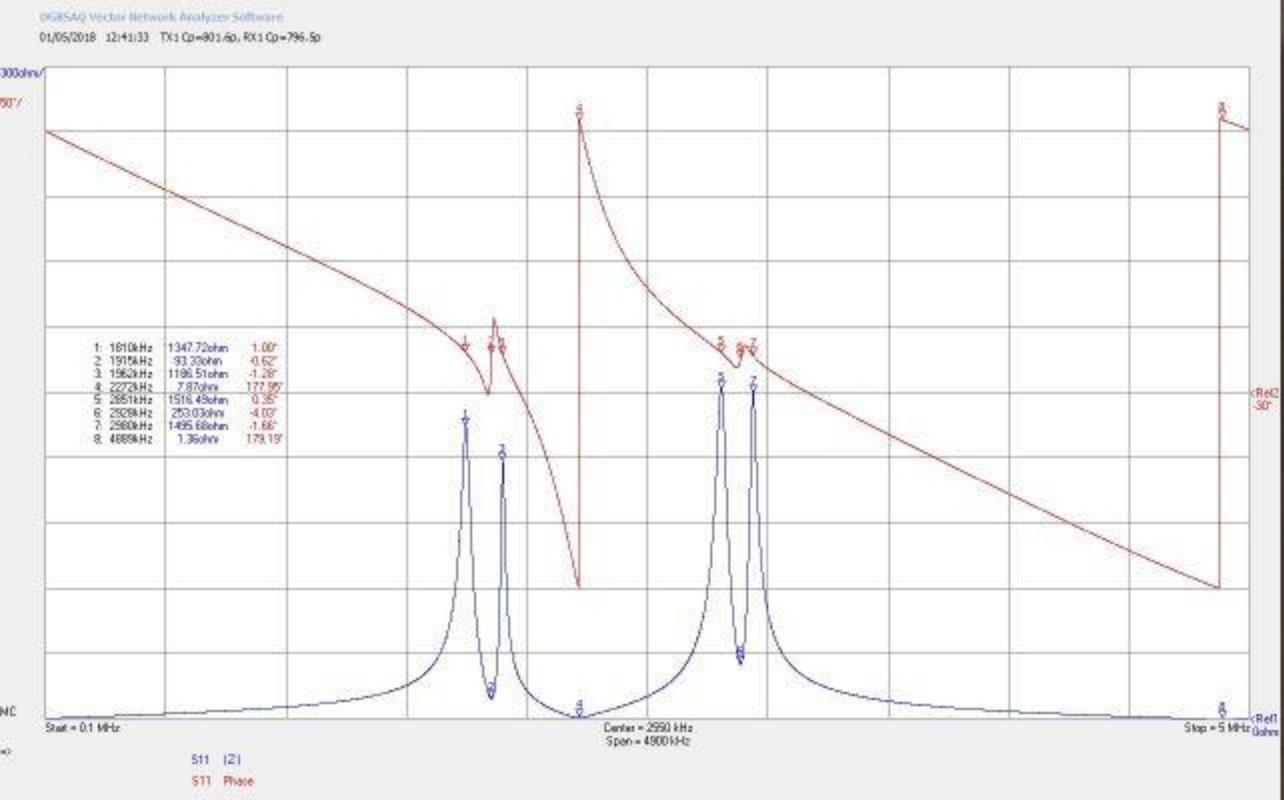


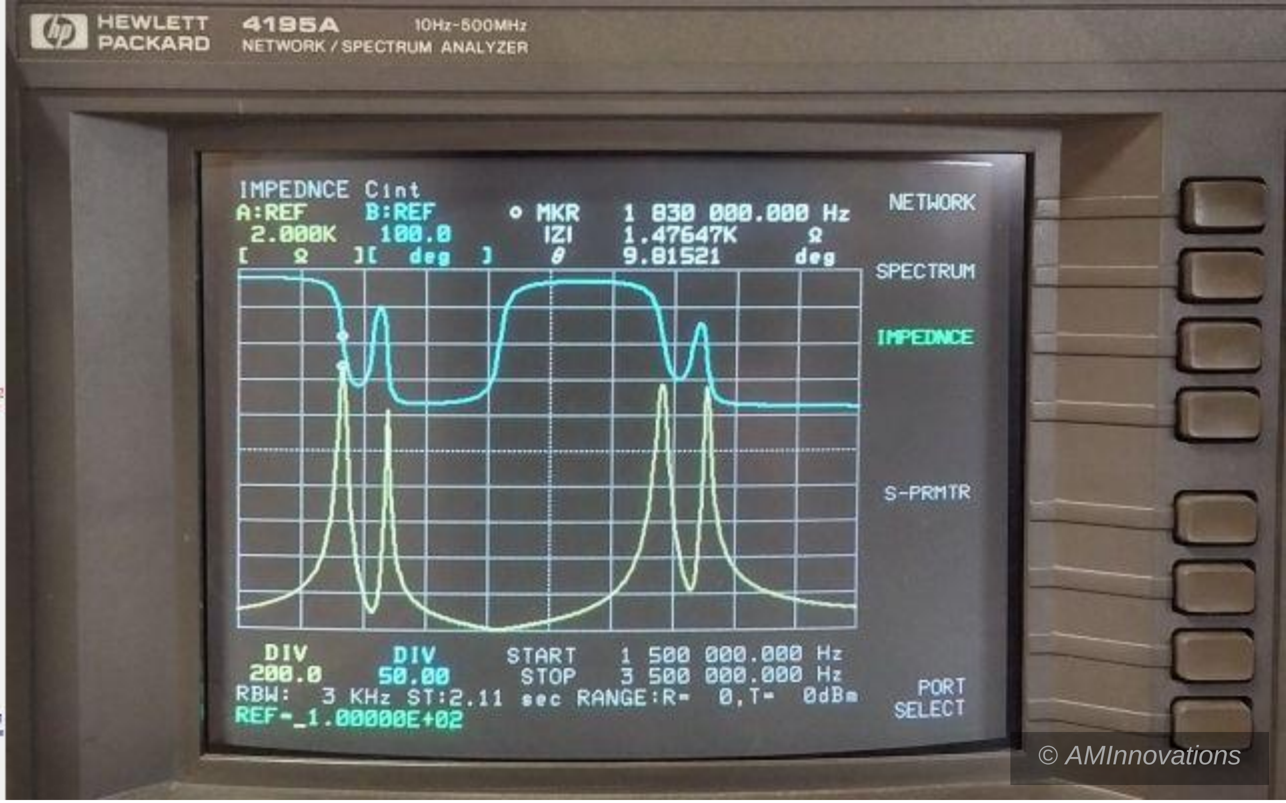


- Fine tuning of a TMT system suitable for experiments in the displacement and transference of electric power can be accomplished by adjusting a parallel capacitance in the primary resonant circuit.
- The upper resonant frequency of this system comes from the primary and the lower from the secondary, tuning the primary shifts these resonant points, adjusting accurately the frequencies and the impedance.
- The VNA impedance scan reveals the characteristics of the key points (1-3), showing both $|\boldsymbol{Z}|$ and $\angle\,\theta$, and their balance.
- Matching the impedance of the generator type to these key points will ensure maximum power transfer during operation.



- ESTC 2019 Eric Dollard's Colorado Springs Experiment – swing-link matching unit connecting the vacuum tube linear amplifier to the primary of the red (Tx) coil, and ideally tuned to marker 2 (878kc) or 4 (1057kc), the two lowest series resonant modes of the TMT system.
- The system was demonstrated at 848kc, effectively marker 2 in the large-signal characteristics.
- A spark gap generator (Vril MWO) was also subsequently used to drive this experiment, and was tuned to marker 2 at 878kc where the input impedance of the TMT system is very low, (marker 4 could also be used with this generator).
- The most suitable matching point for optimum TC or TMT drive is dependent on the type of generator being used.





- Measurement comparison between the DG8SAQ, and a calibrated Hewlett Packard 4195A, shows good correlation in the feature characteristics, and $|Z|$ key point accuracy of ~ ± 2%. Here both measuring the same flat coil TMT system.
- Phase accuracy corresponds well at the key point frequencies and is ~ ± 5% of the HP.
- The general form of the phase measurement appears somewhat different as the DG8SAQ is displaying wrapped phase $-\pi \rightarrow \pi$, and the HP unwrapped phase ($-\pi_{/2} \rightarrow \pi_{/2}$). The feature correlation in the phase plots is accurate.
- Useful dynamic range of the DG8SAQ is less than that of the HP, and has been found to be ~ 75dB up to 500Mc, which is more than adequate for measurements of Tesla coils, and other expert amateur applications.

VNA Measurements for Tesla Coils - Conclusions

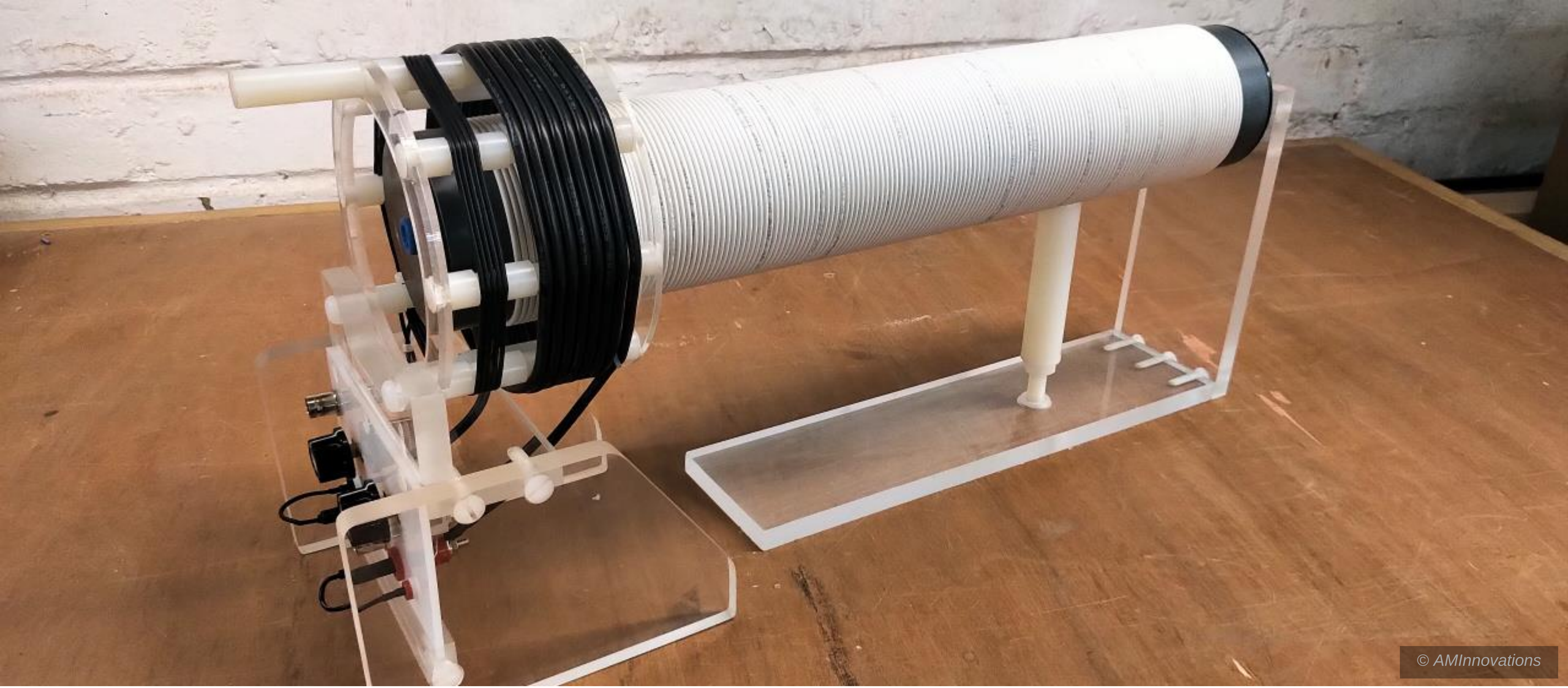
- VNA Measurements of Tesla coils and TMT systems provide a considerable insight into their electrical characteristics, properties, and modes of operation.
- The DG8SAQ USB VNA is an accurate and cost effective advanced measurement technique for the enthusiast or expert amateur.
- Accuracy of measurement is very good in the frequency band of TC operation, when compared with professional VNA equipment, and at a small fraction of the cost.
- Good correspondence is obtained between the small signal ac impedance analysis using the DG8SAQ VNA, and large signal Tesla coil and TMT performance running at high output powers.
- The DG8SAQ has a range of other generator measurement features such as spectrum analysis, signal generator, and frequency meter.
- The DG8SAQ has sophisticated PC software for setup, calibration, measurement, and graphing the results. Easy to learn and use, and well supported with regular updates.

References and Further Reading

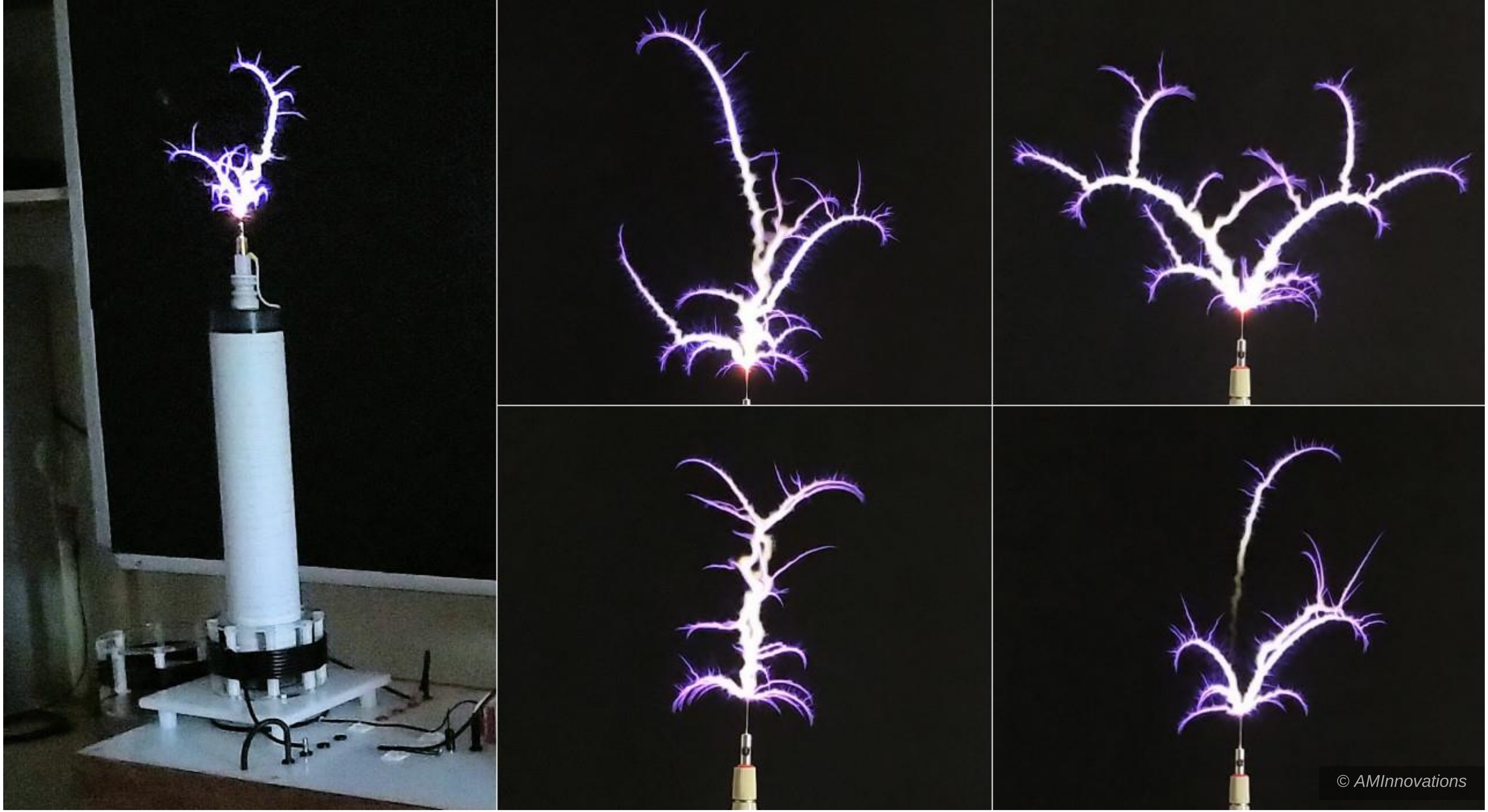
- *Introduction to Network Analyzer Measurements*, National Instruments.
- *Understanding the Fundamental Principles of Vector Network Analysis*, Keysight Technologies.
- *HP4195A Combined Network/Spectrum Analysis*, Agilent (formerly Hewlett Packard).
- *Experiments with the DG8SAQ VNWA and the SDR-Kits Test Board*, Baier T., SDR-Kits.
- *A Small, Simple, USB-Powered Vector Network Analyzer Covering 1kHz to 1.3GHz,* Baier T.
- *A Low Budget Vector Network Analyzer for AF to UHF*, Baier T.

Appendix 1 - The Wheelwork of Nature
Cylindrical Tesla Coil Analysis

- Secondary designed to resonate at ~ 3.5Mc in the 80m amateur band, 3.5-3.8Mc (UK).
- Secondary 155 turns 1mm^2 silicone coated wire, (2.45mm outer, 1.1mm dia. conductor).
- 5:1 Aspect ratio, tightly wound for maximum dielectric induction field magnification.
- Primary 7.5 turns 12AWG silicone coated micro-stranded cable.
- Primary tuned by KP1-12 20pF – 1200pF 4kV vacuum variable capacitor.
- Adjustable frequency drive in lower and upper parallel modes f_U and f_L, from ~ 2.5Mc – 3.7Mc.
- Magnetic coupling between primary and secondary variable by coil spacing.



The Wheelwork of Nature – Fractal “Fern” Discharges – Standard Cylindrical Tesla Coil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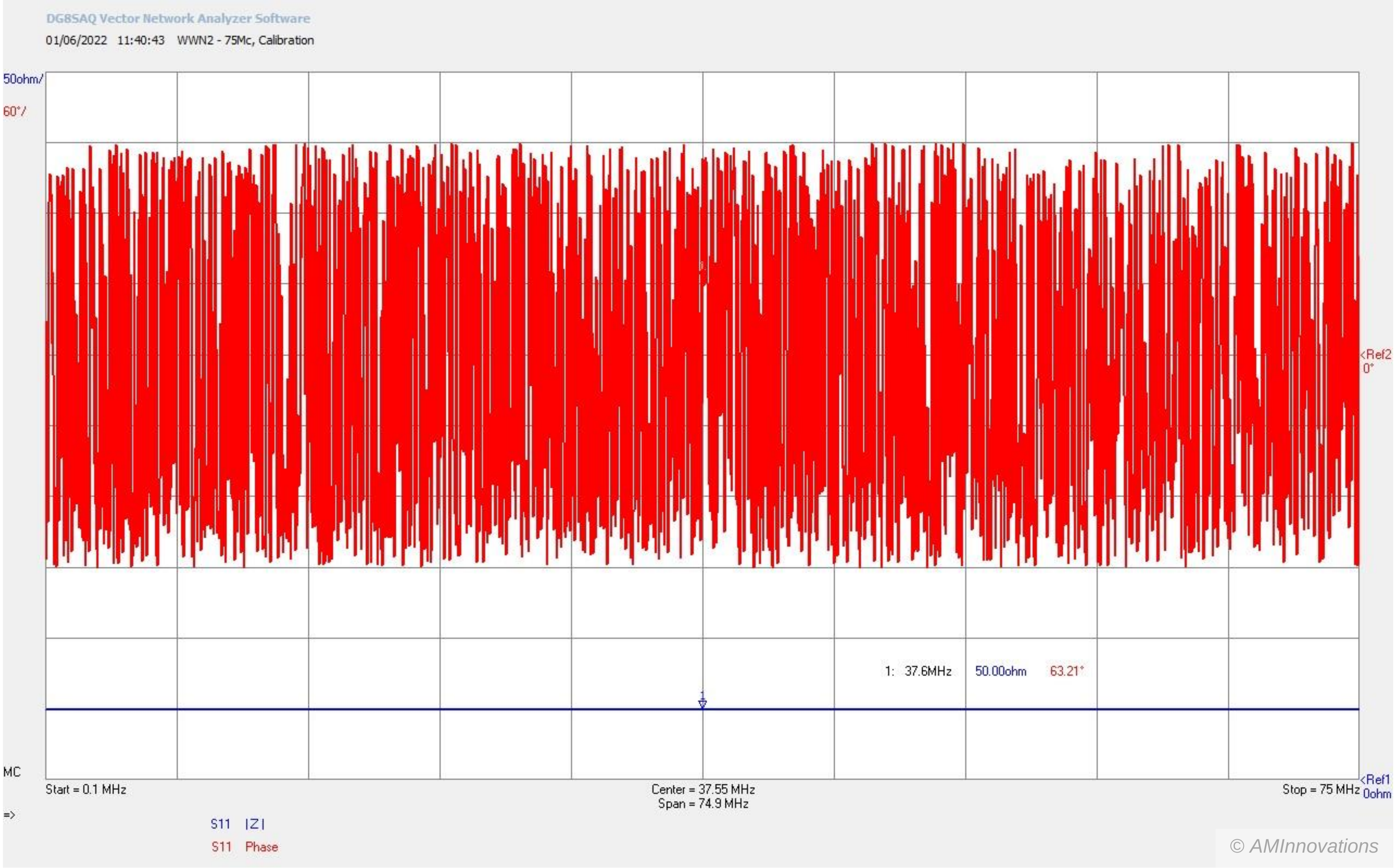
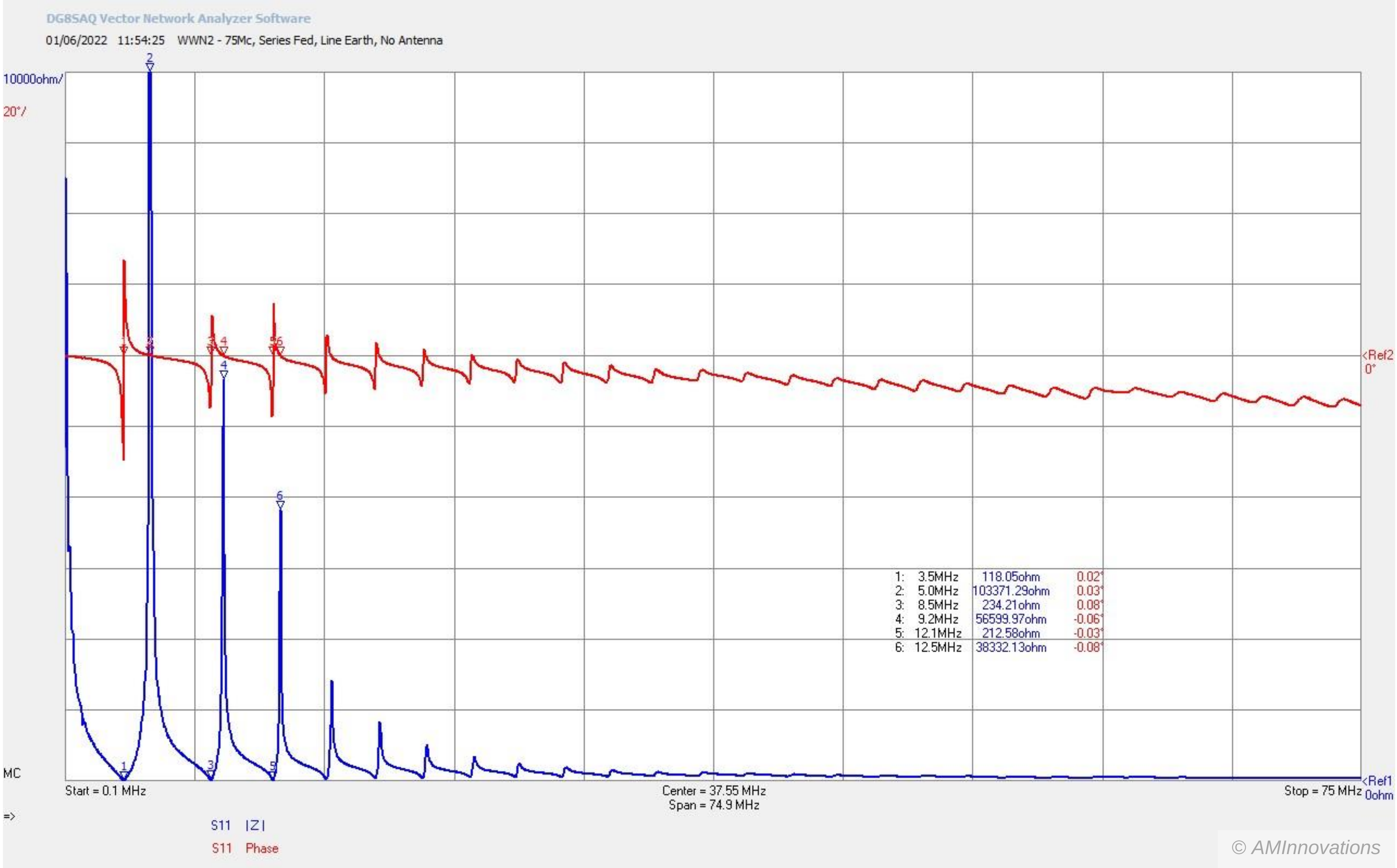
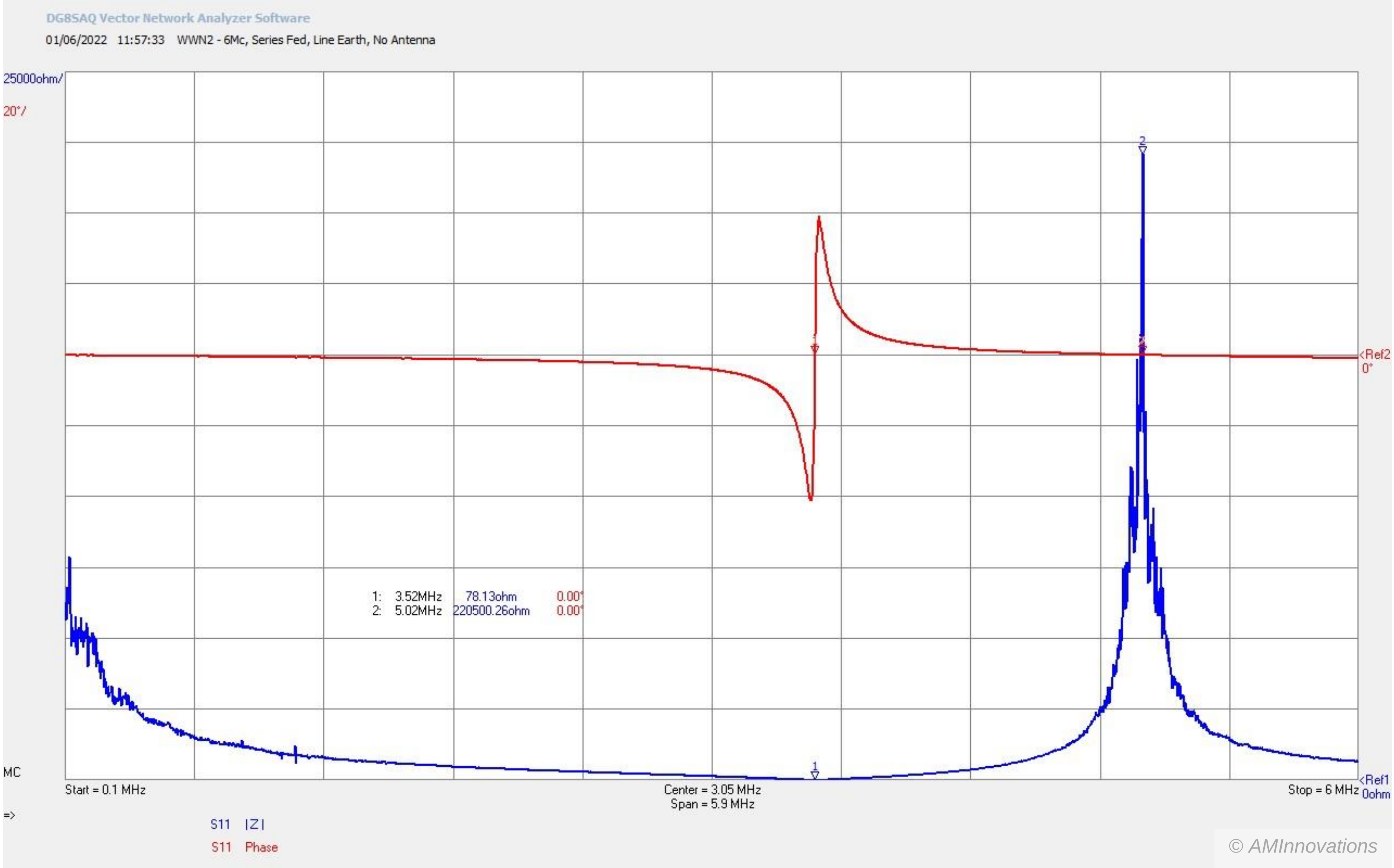


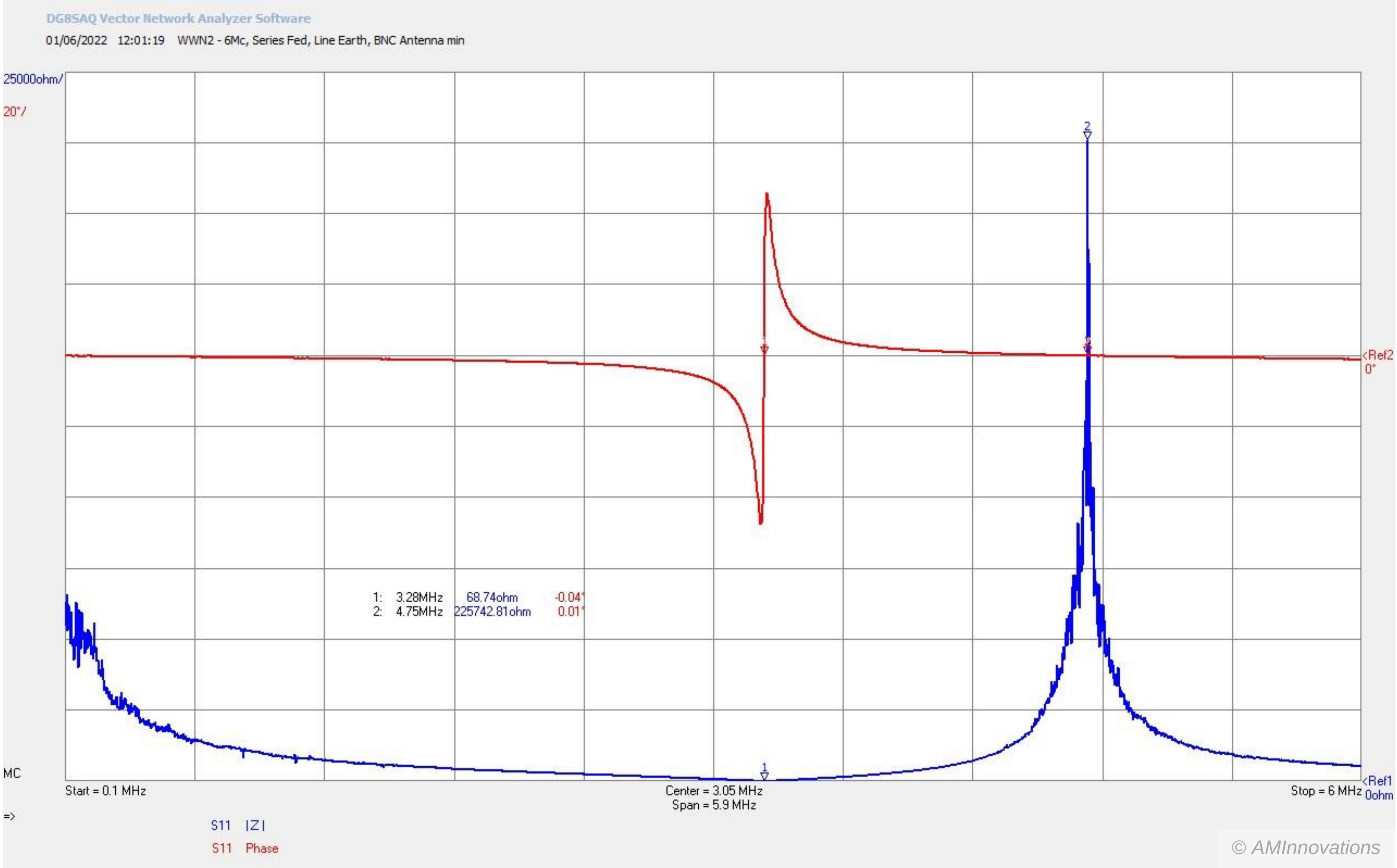
Calibration DG8SAQ VNWA : 15cm BNC cable, 0.1-5 MHz, 50Ω termination



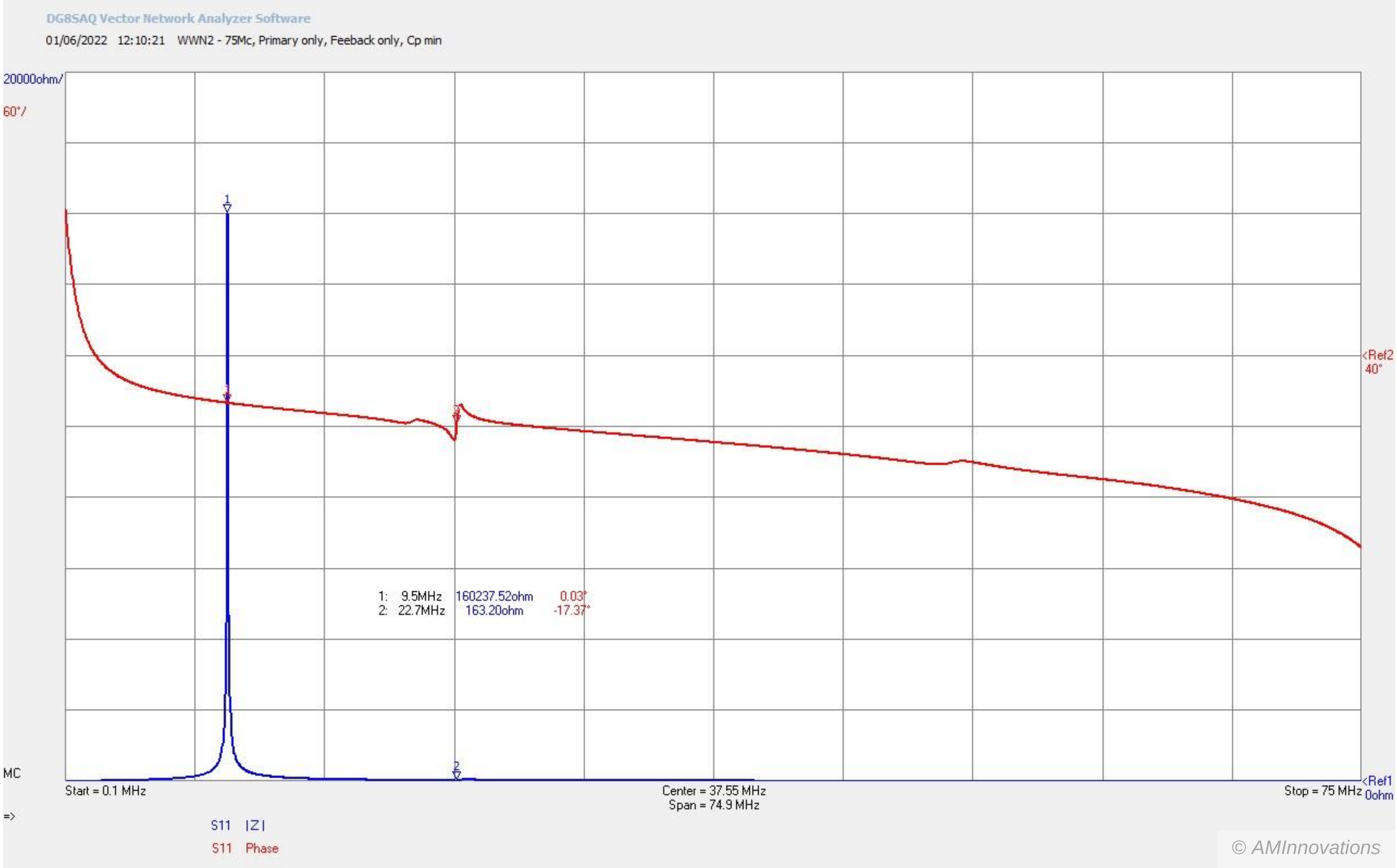
Series-Fed Secondary Coil Only – Wideband 75Mc Scan



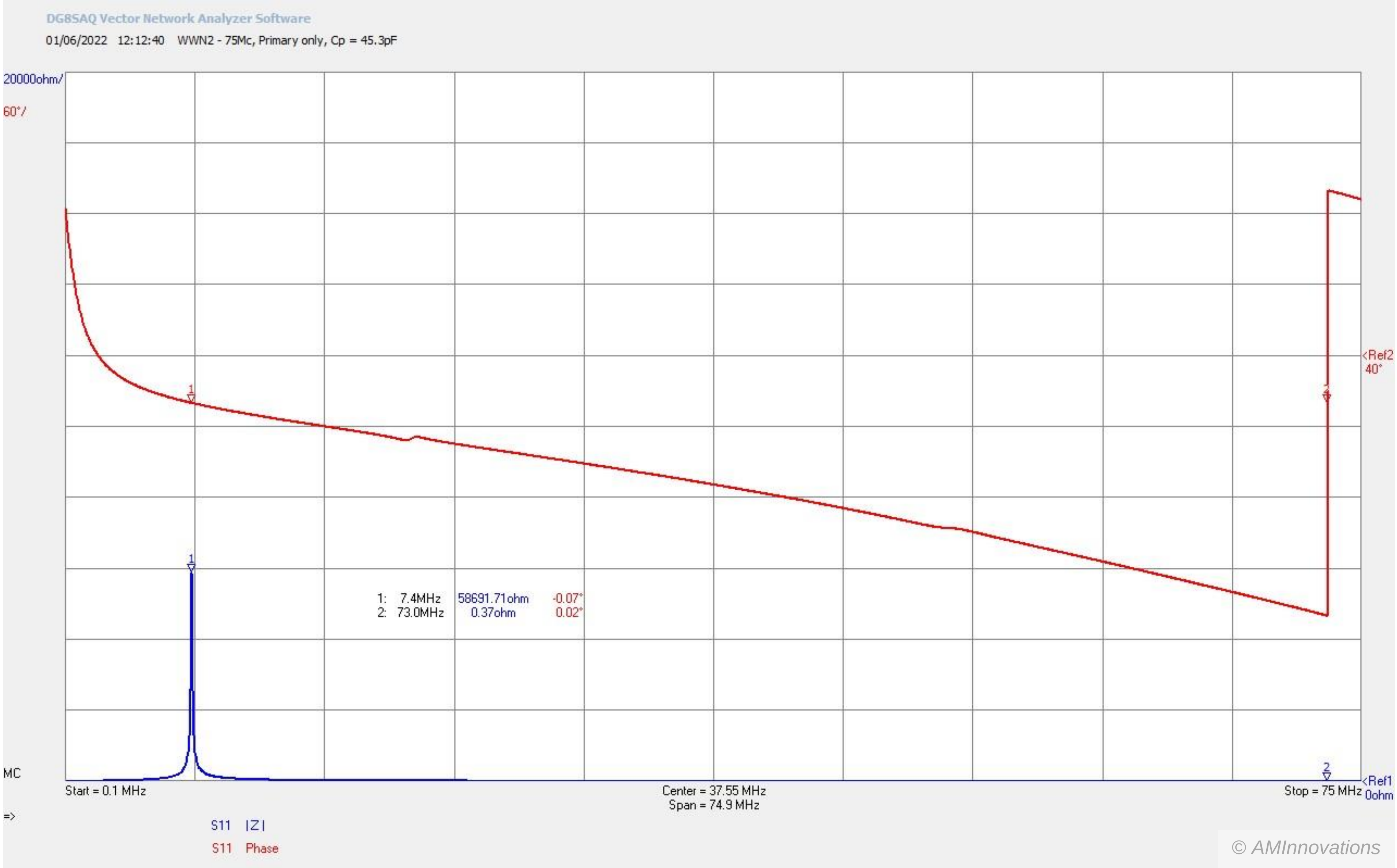
Series-Fed Secondary Coil Only – Fundamental Series and Parallel Resonant Modes



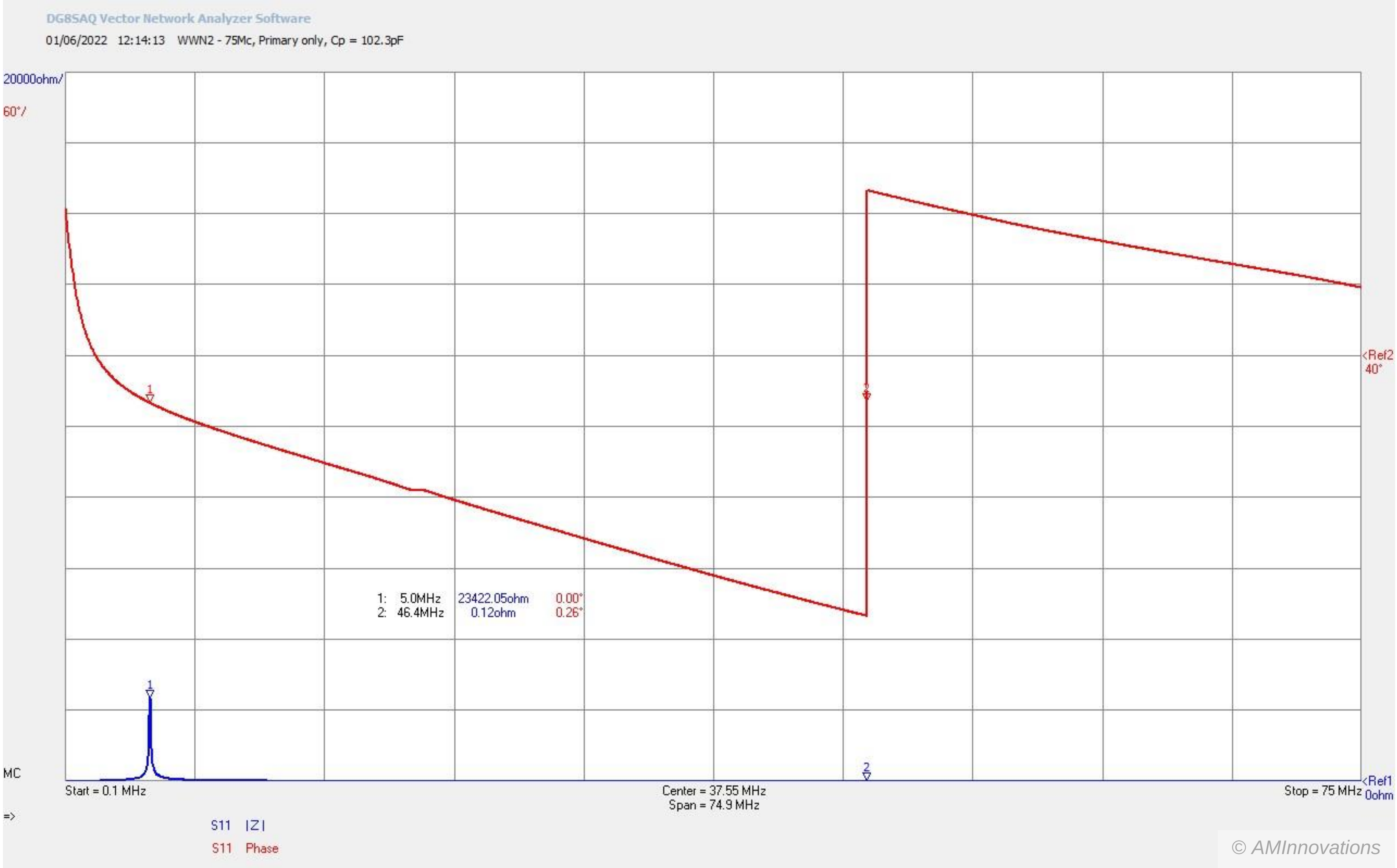
Series-Fed Secondary Coil Only – With Top-end BNC Antenna Minimum Extension



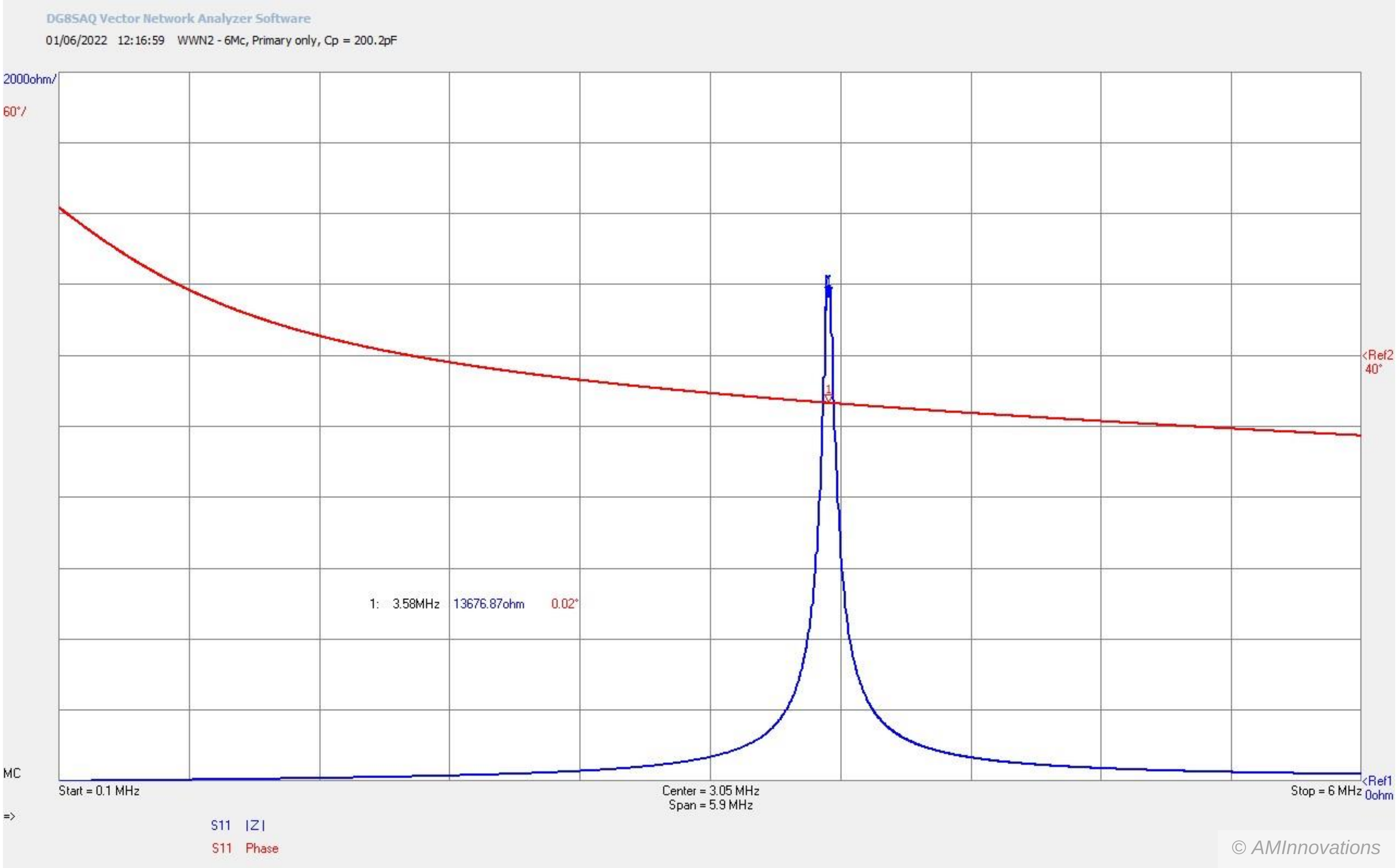
Primary Coil with Feedback Coil Only – Wideband 75Mc Scan, Self Primary Capacitance Only



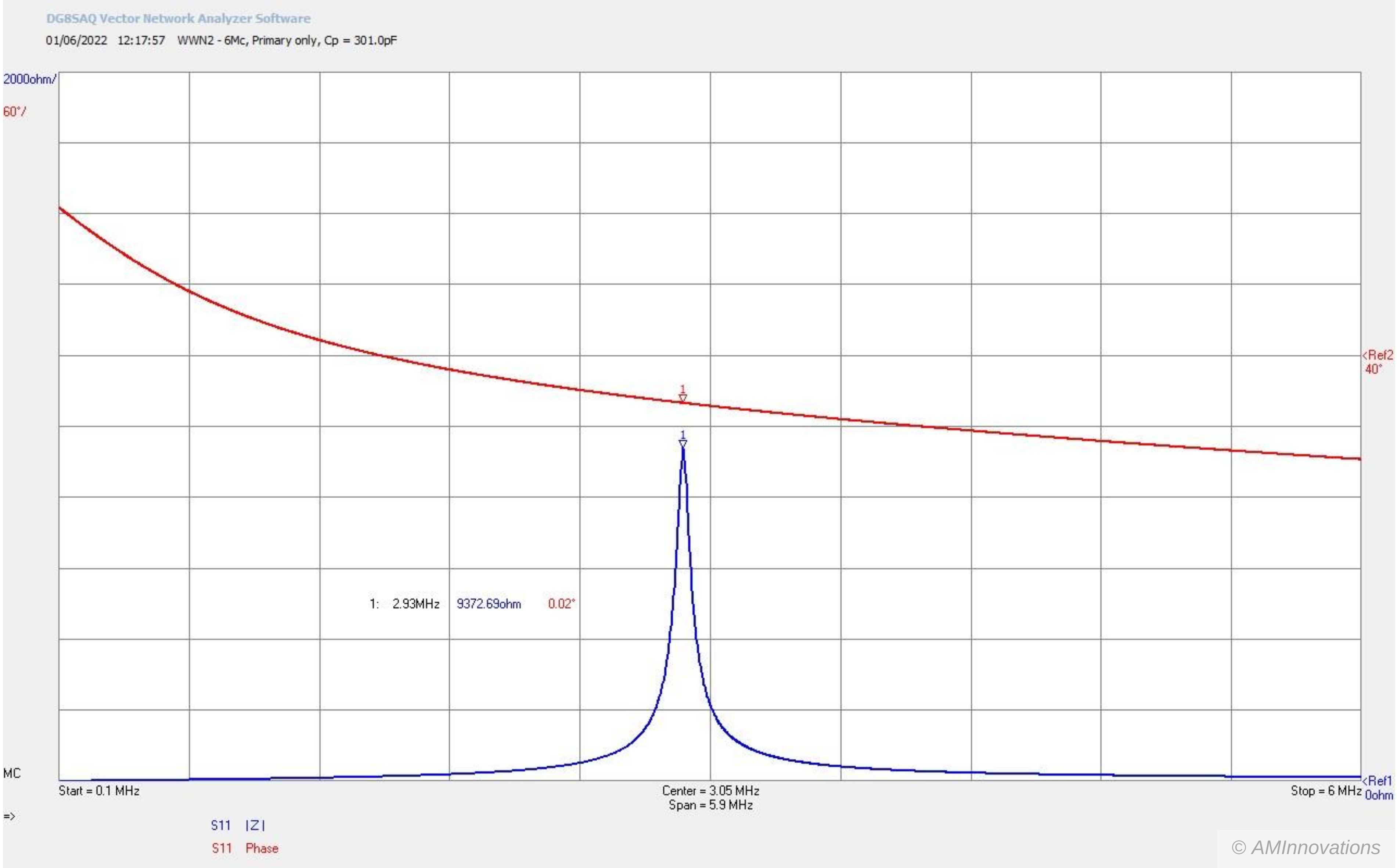
Primary Coil with Feedback Coil Shorted – Primary Capacitance Cp = 45.3pF, Series and Parallel Resonant Modes



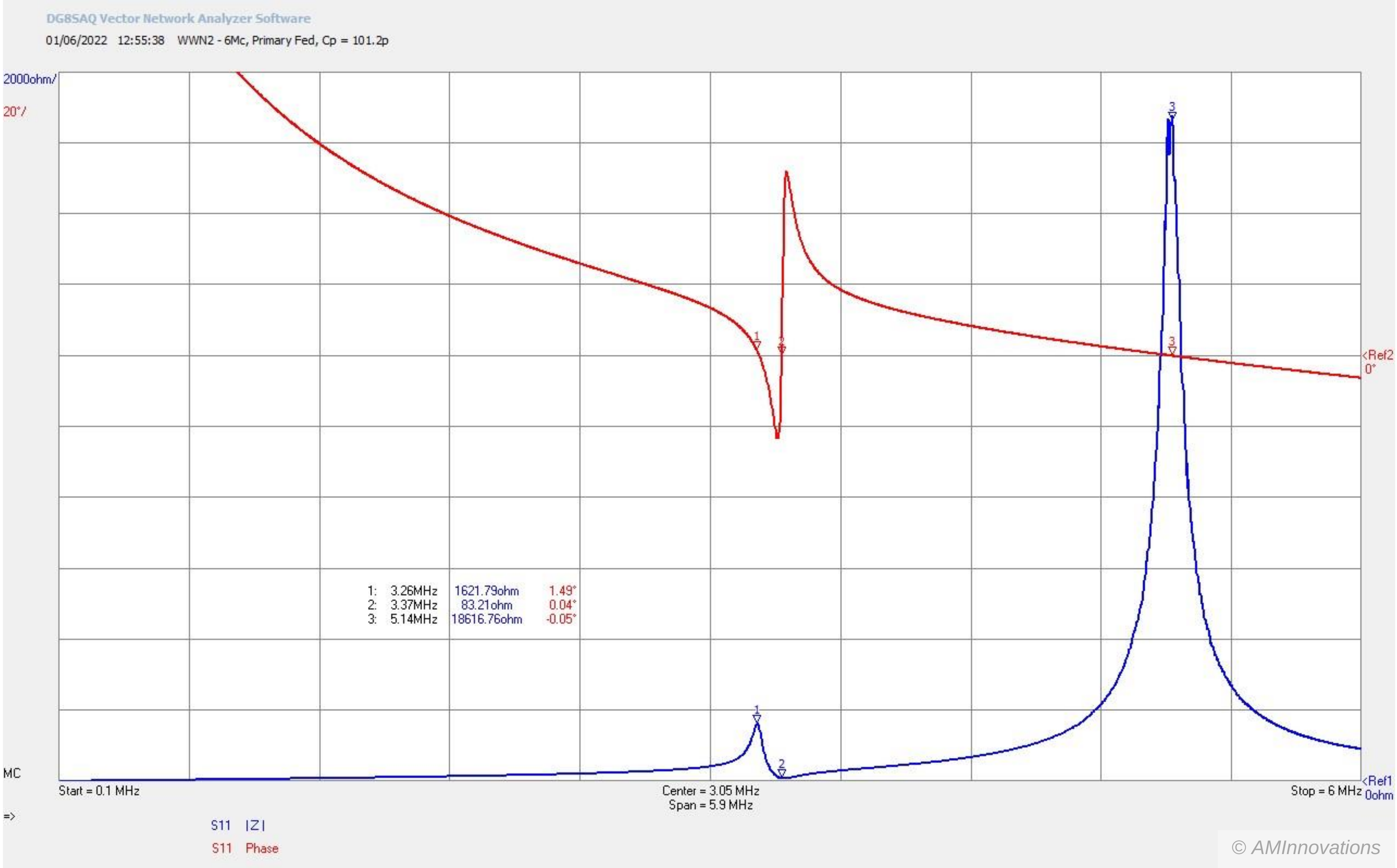
Primary Coil with Feedback Coil Shorted – Primary Capacitance Cp = 102.3pF



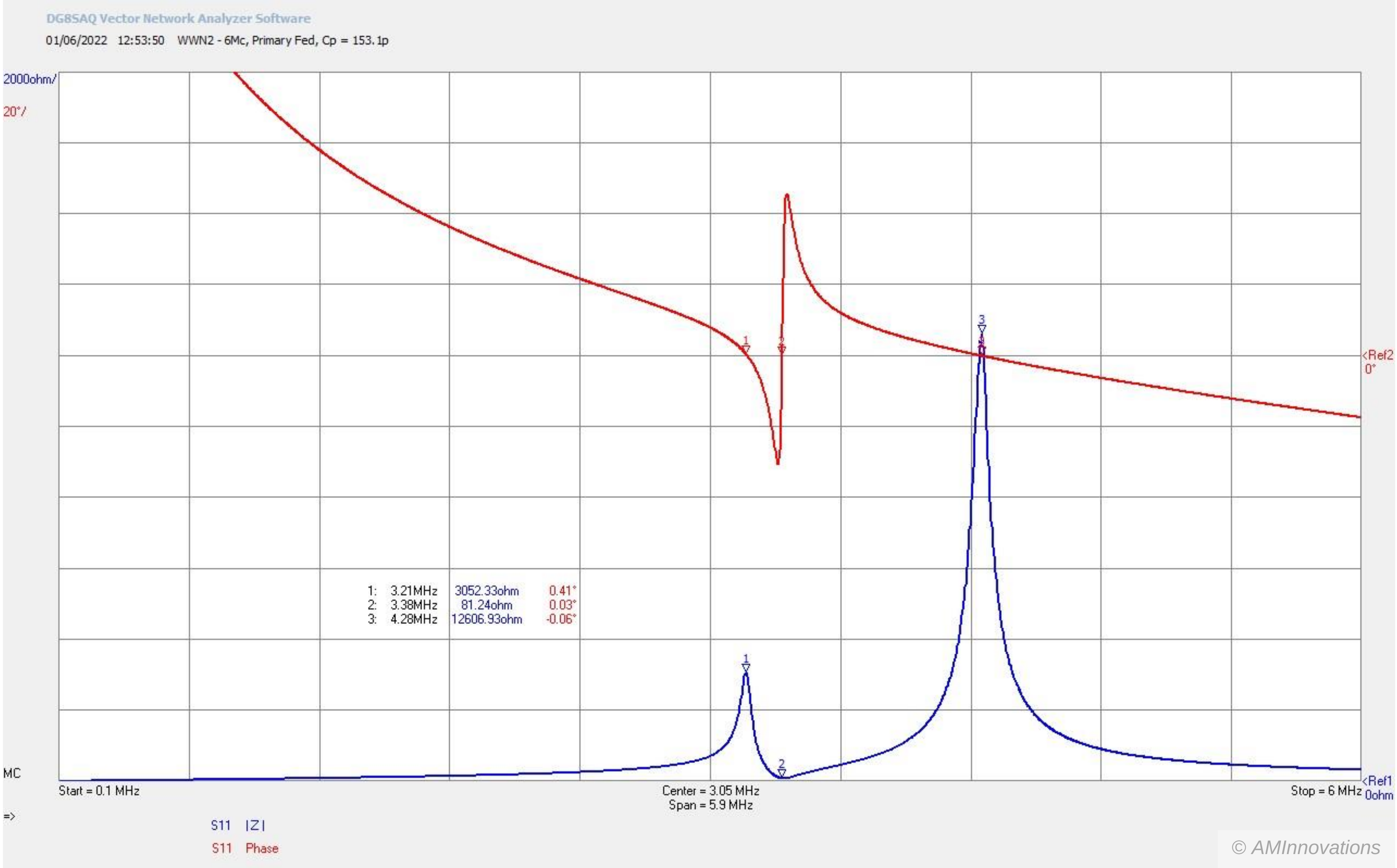
Primary Coil Only – Primary Capacitance Cp = 200.2pF



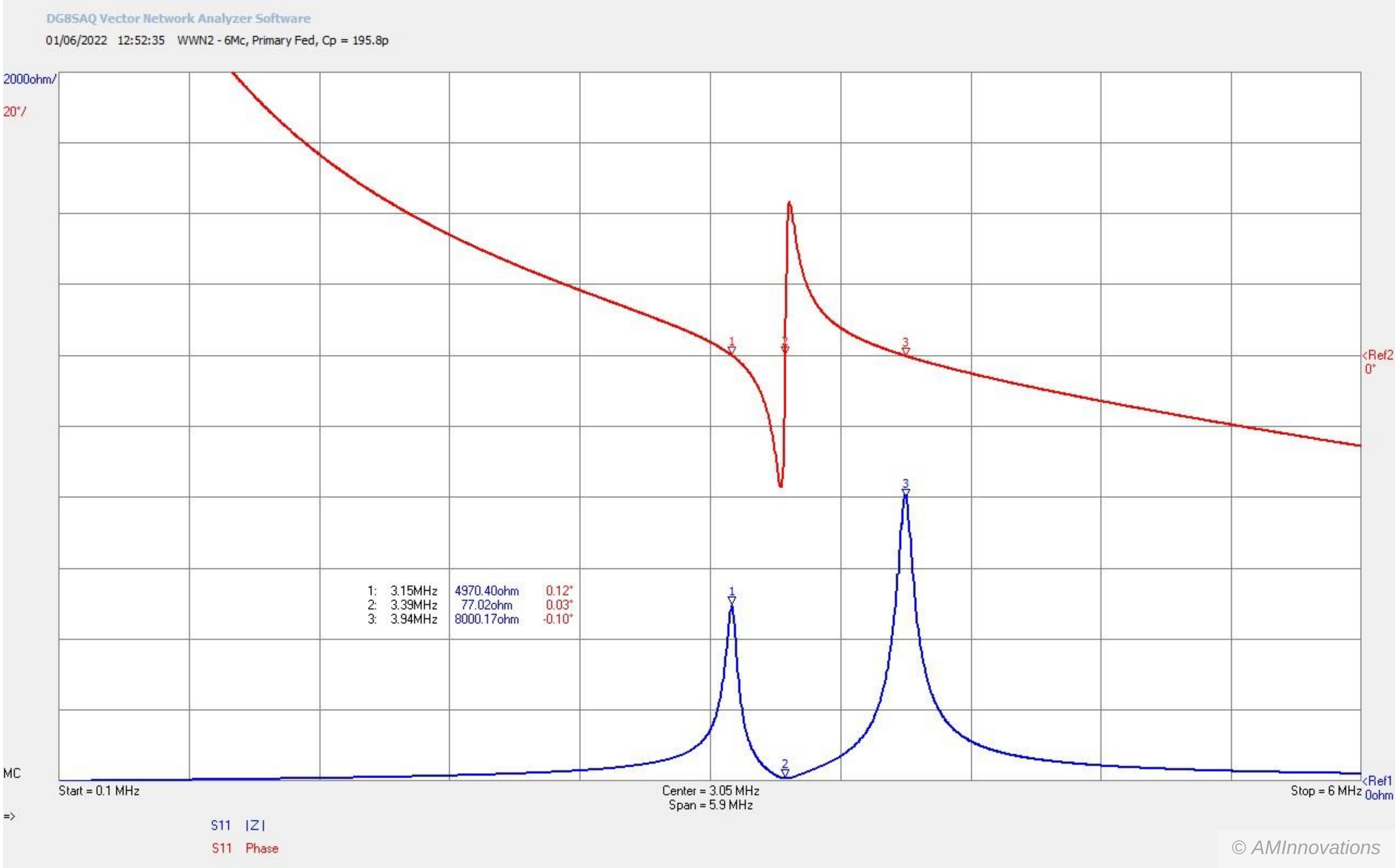
Primary Coil Only – Primary Capacitance Cp = 301.0pF



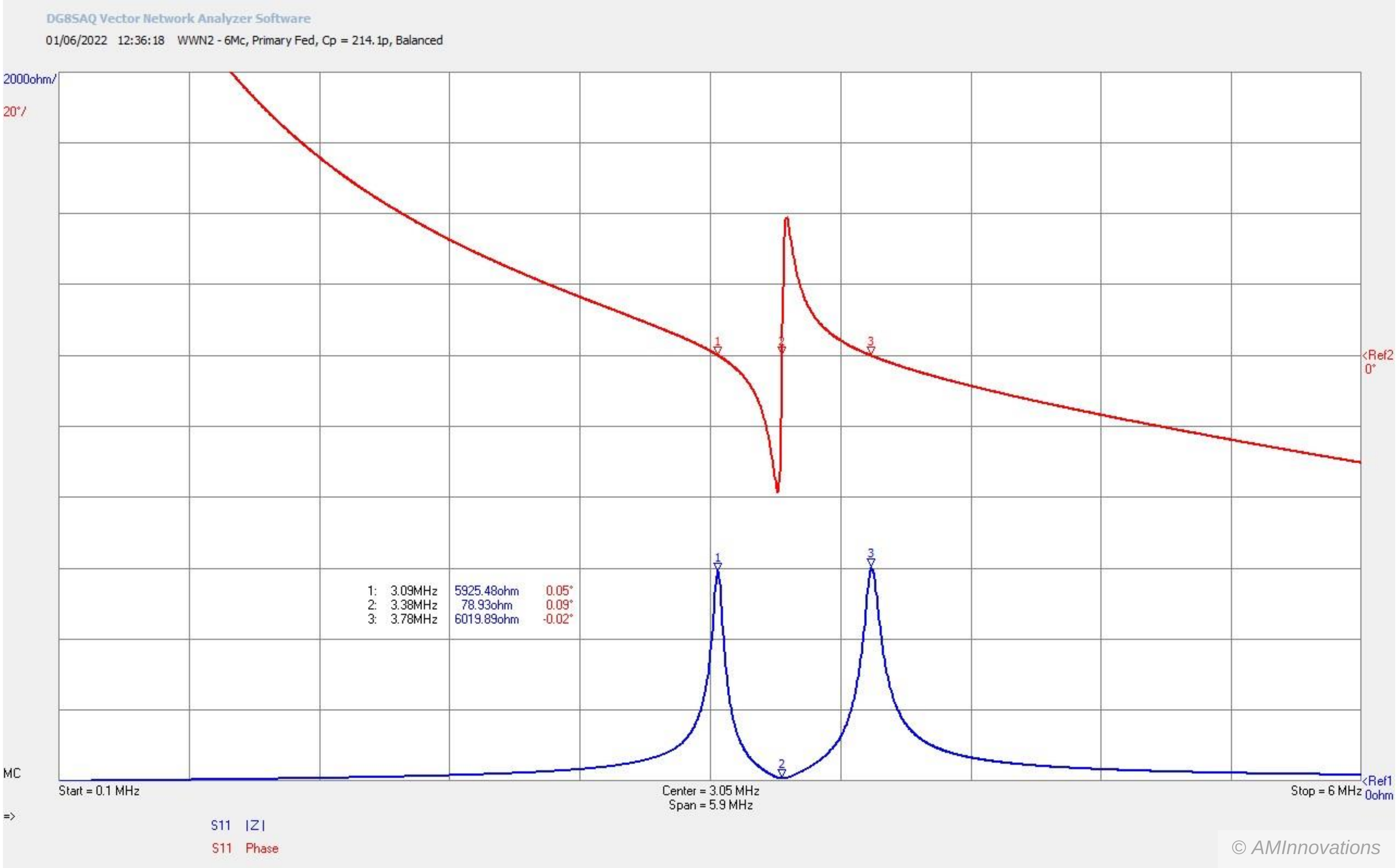
Primary Fed Secondary Coil – Cp = 101.2pF, Series, Upper Parallel, and Lower Parallel Resonant Modes



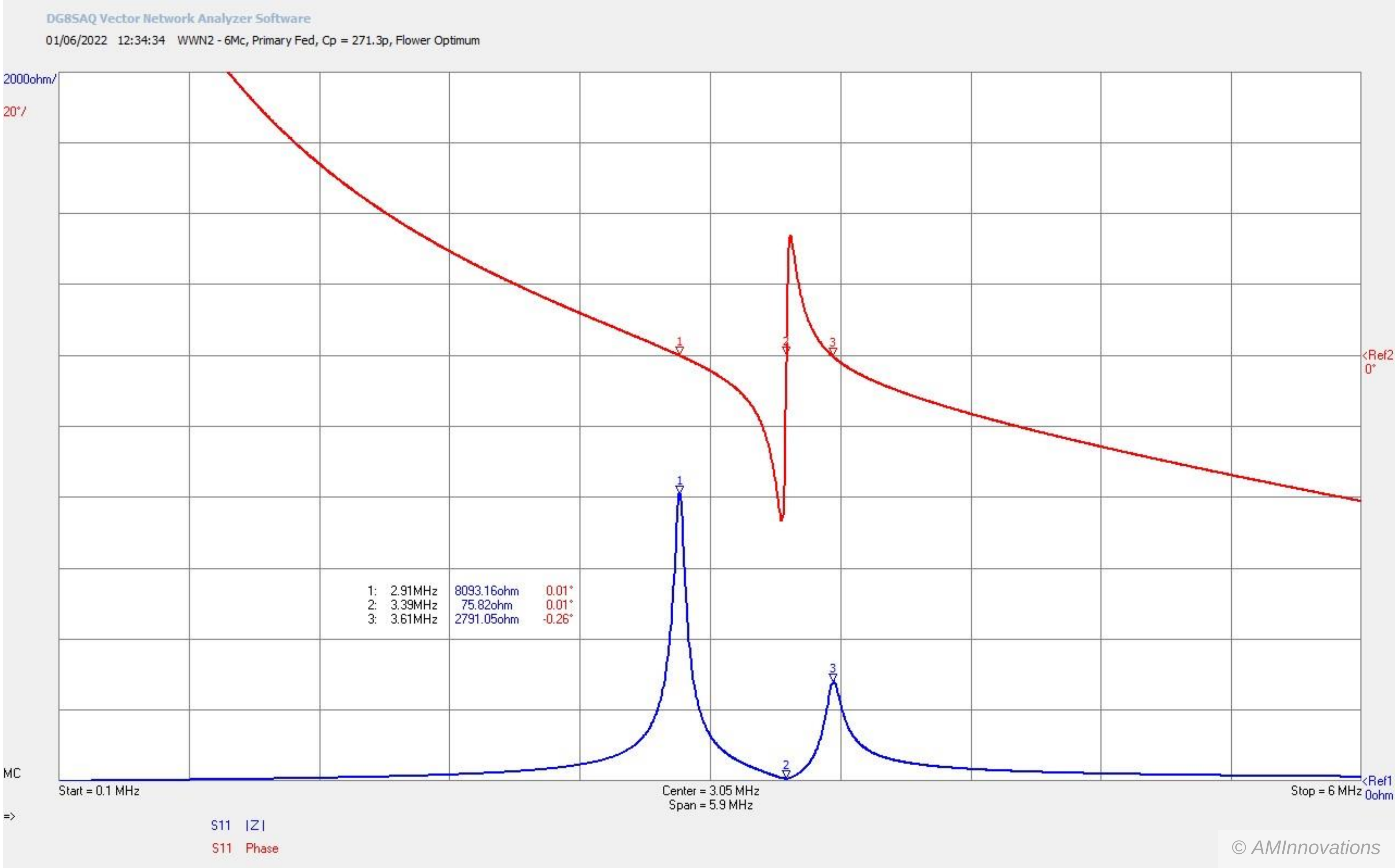
Primary Fed Secondary Coil – Cp = 153.1pF, Series, Upper Parallel, and Lower Parallel Resonant Modes



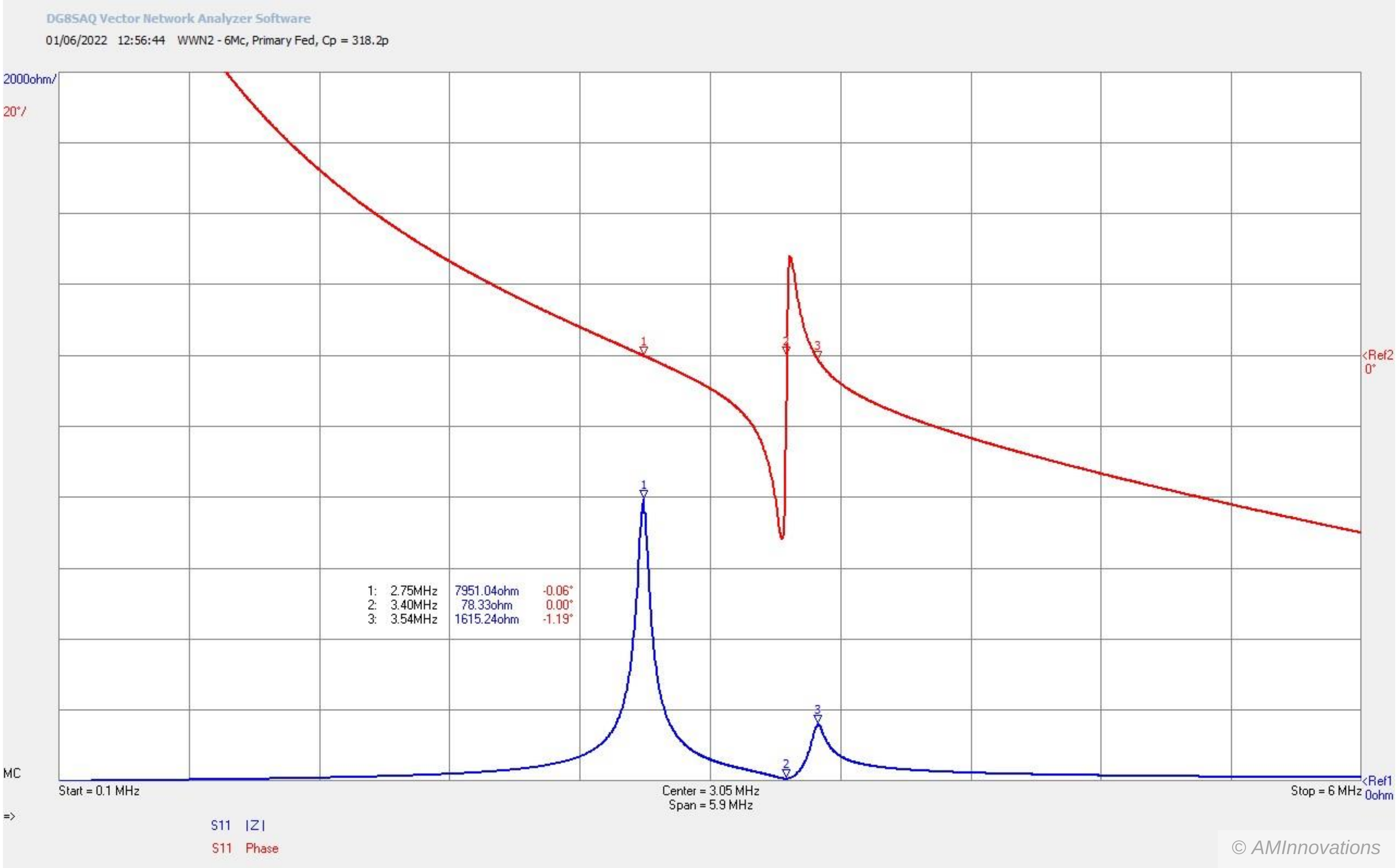
Primary Fed Secondary Coil – Cp = 195.8pF, Empirical Optimum Upper Parallel Mode



Primary Fed Secondary Coil – Cp = 214.1pF, Balanced Parallel Modes



Primary Fed Secondary Coil – Cp = 271.3pF, Empirical Optimum Lower Parallel Mode



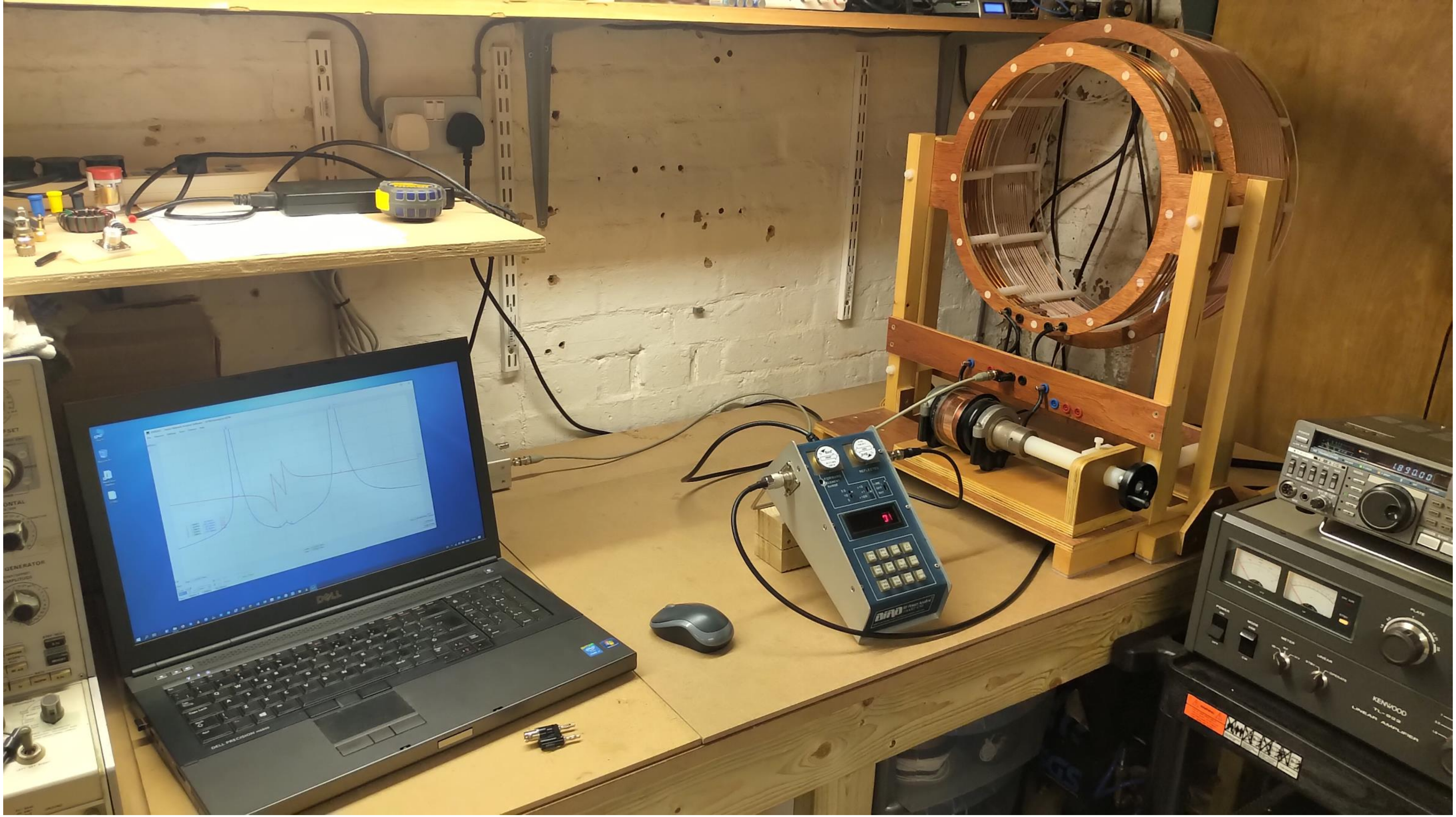
Primary Fed Secondary Coil – Cp = 318.2pF

Appendix 2 - Telluric Transference of Electric Power

TMT Cylindrical Tesla Coil Analysis

- Secondary designed to resonate in the 160m HF band for both a single Tesla coil and a complete TMT system, 1.8-2.0Mc (UK).
- Secondary is 23 turns RG306 shield + 1 turn $^{1}/_{8}$” copper tube, 24 turns total to 3 in primary, 8:1 voltage magnification ratio.
- Primary has adjustable turns and is tuneable, made from $^{3}/_{16}$” annealed copper tube.
- Equal weights of copper in the secondary and primary used to match the boundary conditions when f_o < ~3Mc.
- Primary tuned by KP1-12 20pF – 1200pF 4kV vacuum variable capacitor.
- Coupling between primary and secondary can be varied continuously by spacing between the coils.


MFJ
MFJ IntelliTuner
AT5K
ANTENNA TUNER
INPUT
OUTPUT
DIRECT
TUNED
INDUCTOR
KENWOOD
TL-922
LINEAR AMPLIFIER
PLATE
LOAD
BAND
POWER
METER
LINEAR
BIRD
© AMInnovations

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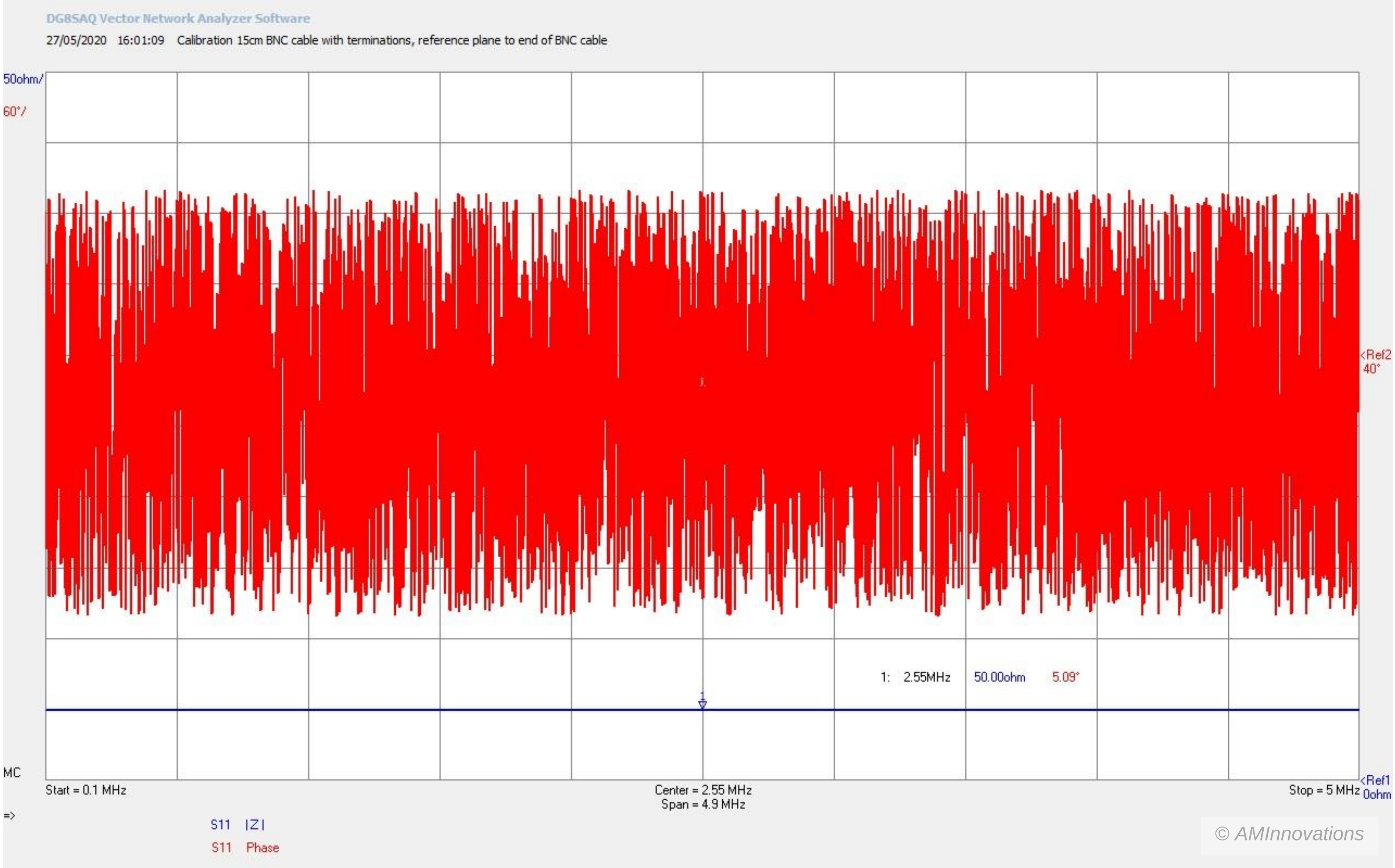
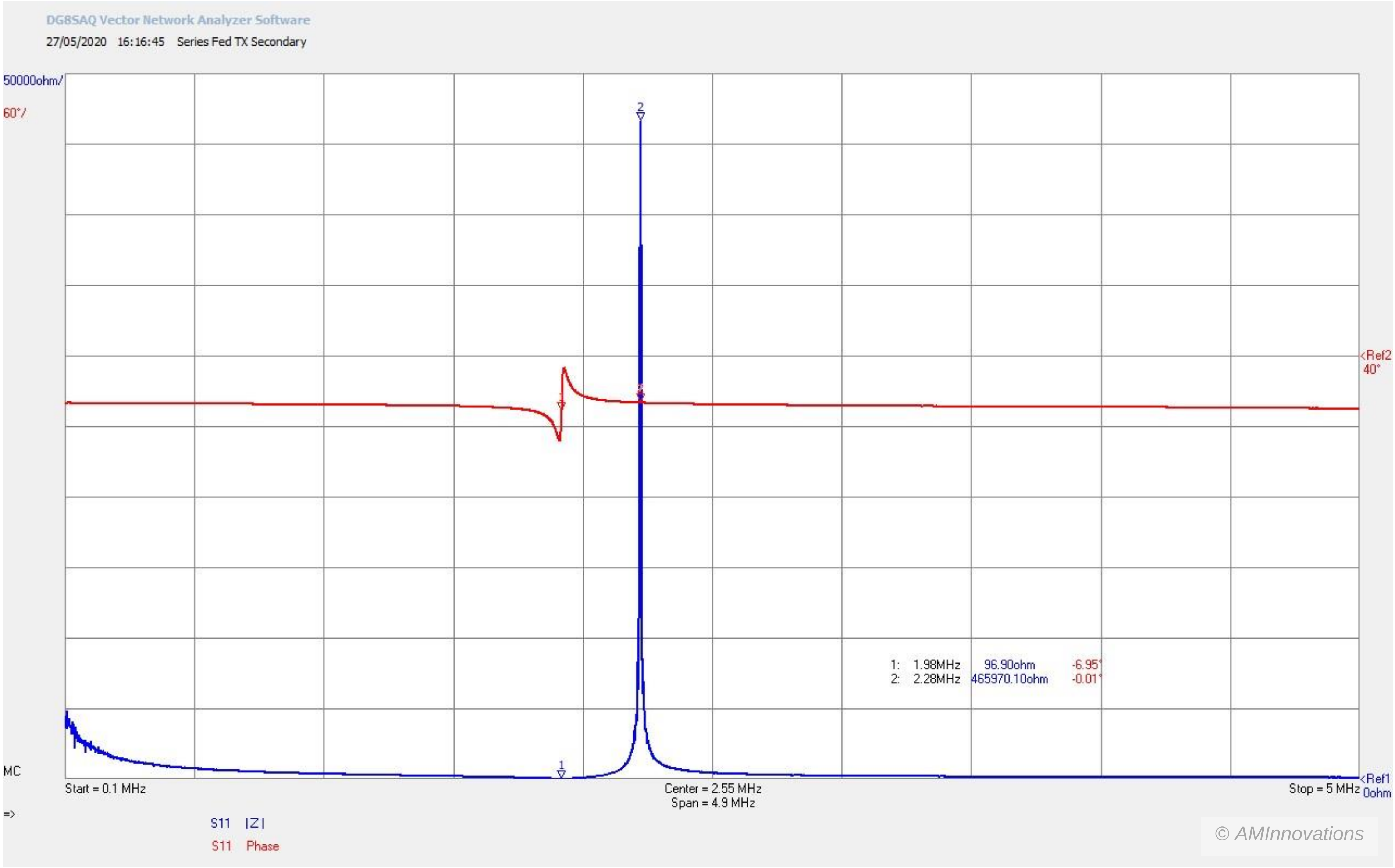
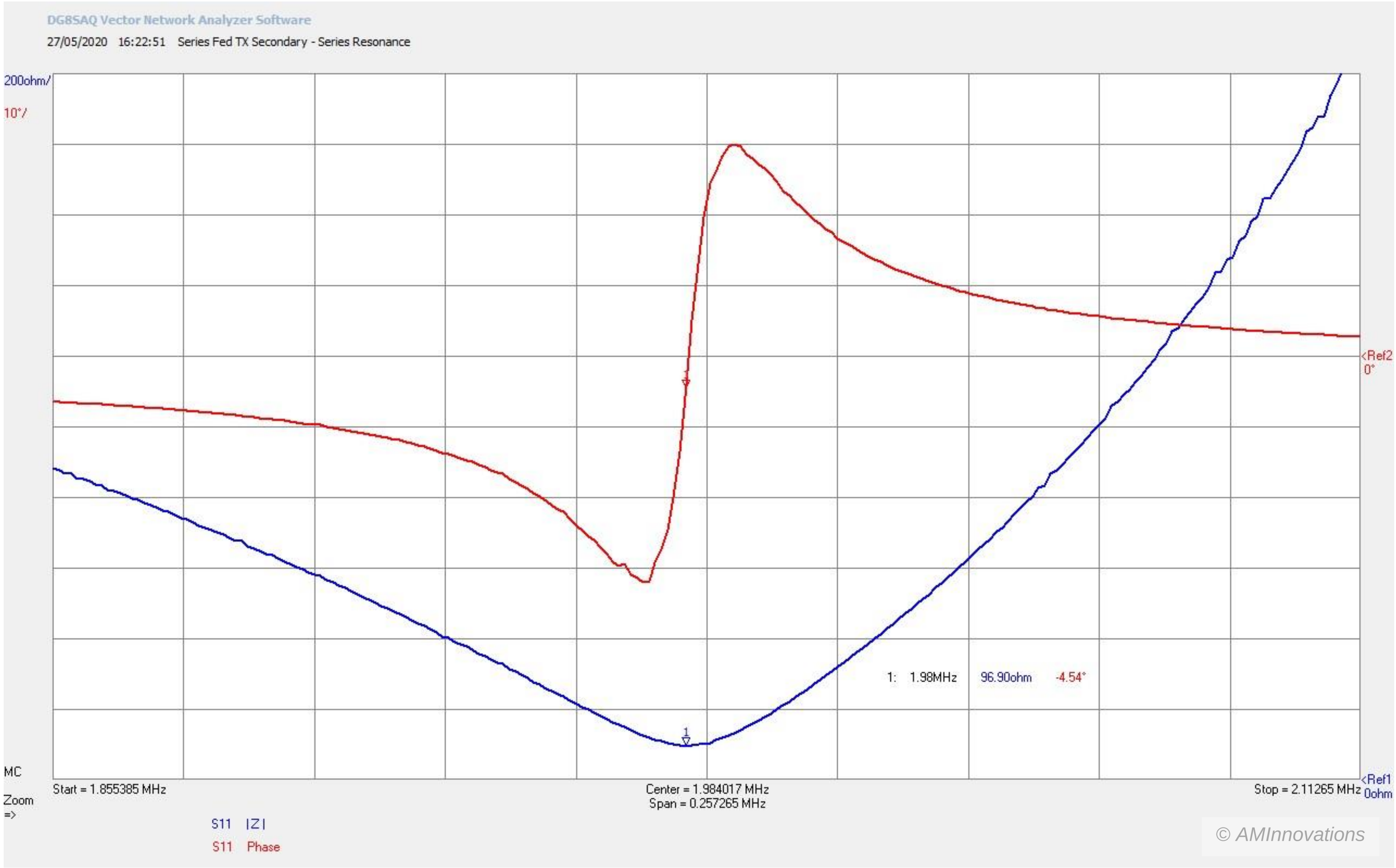


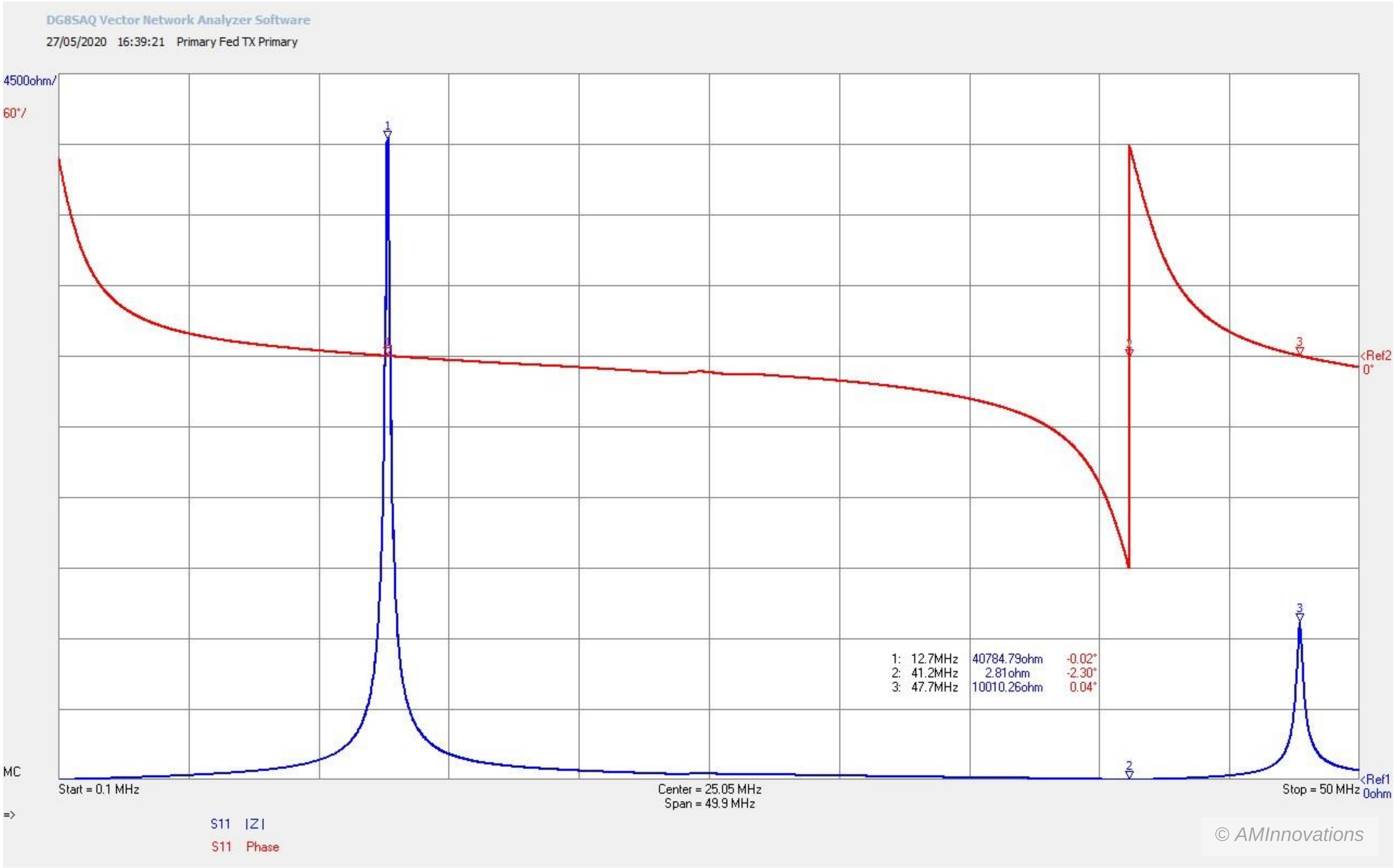
Calibration DG8SAQ VNWA : 15cm BNC cable, 0.1-5 MHz, 50Ω termination



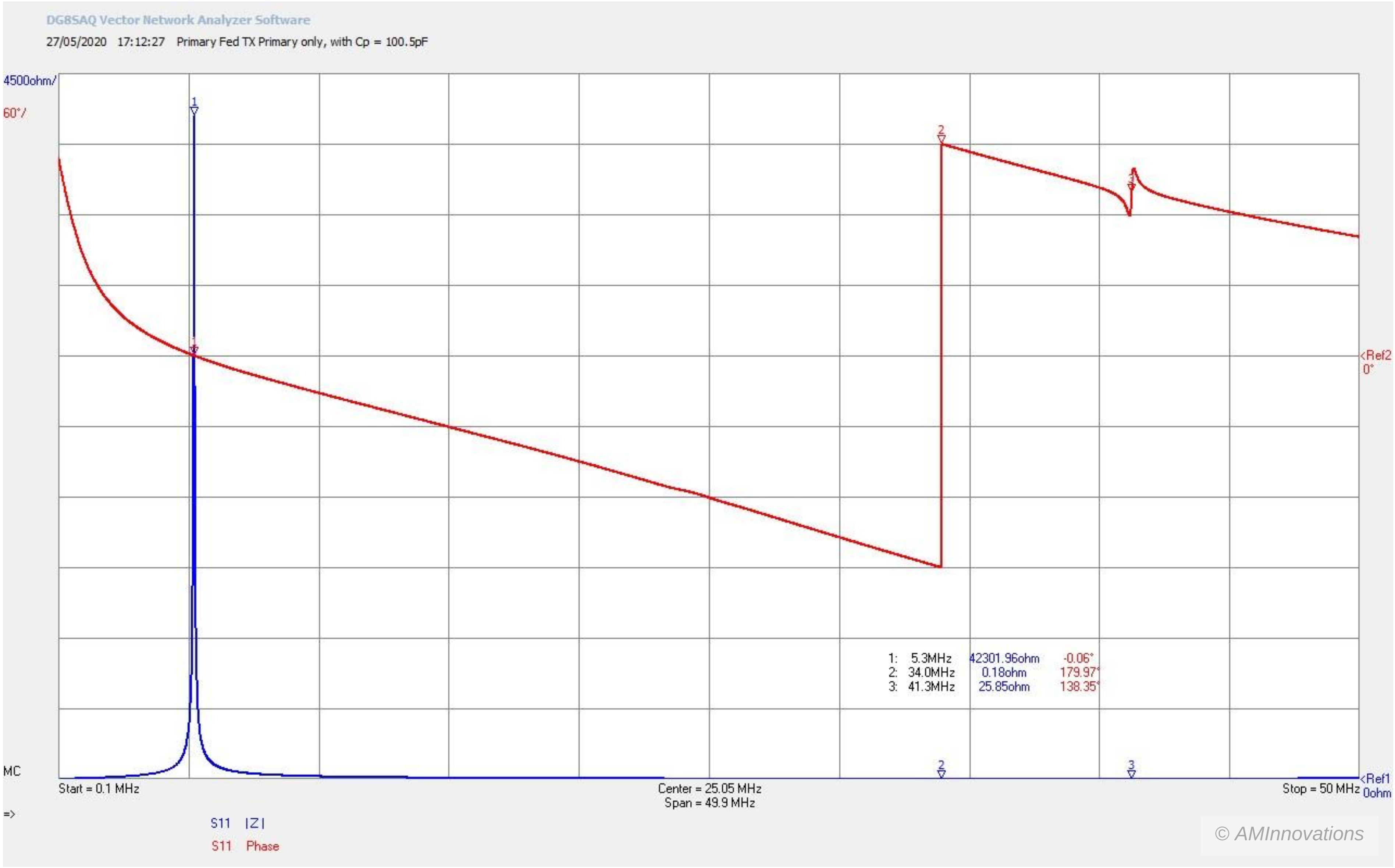
Series Fed Secondary Coil only – Series and Parallel Points



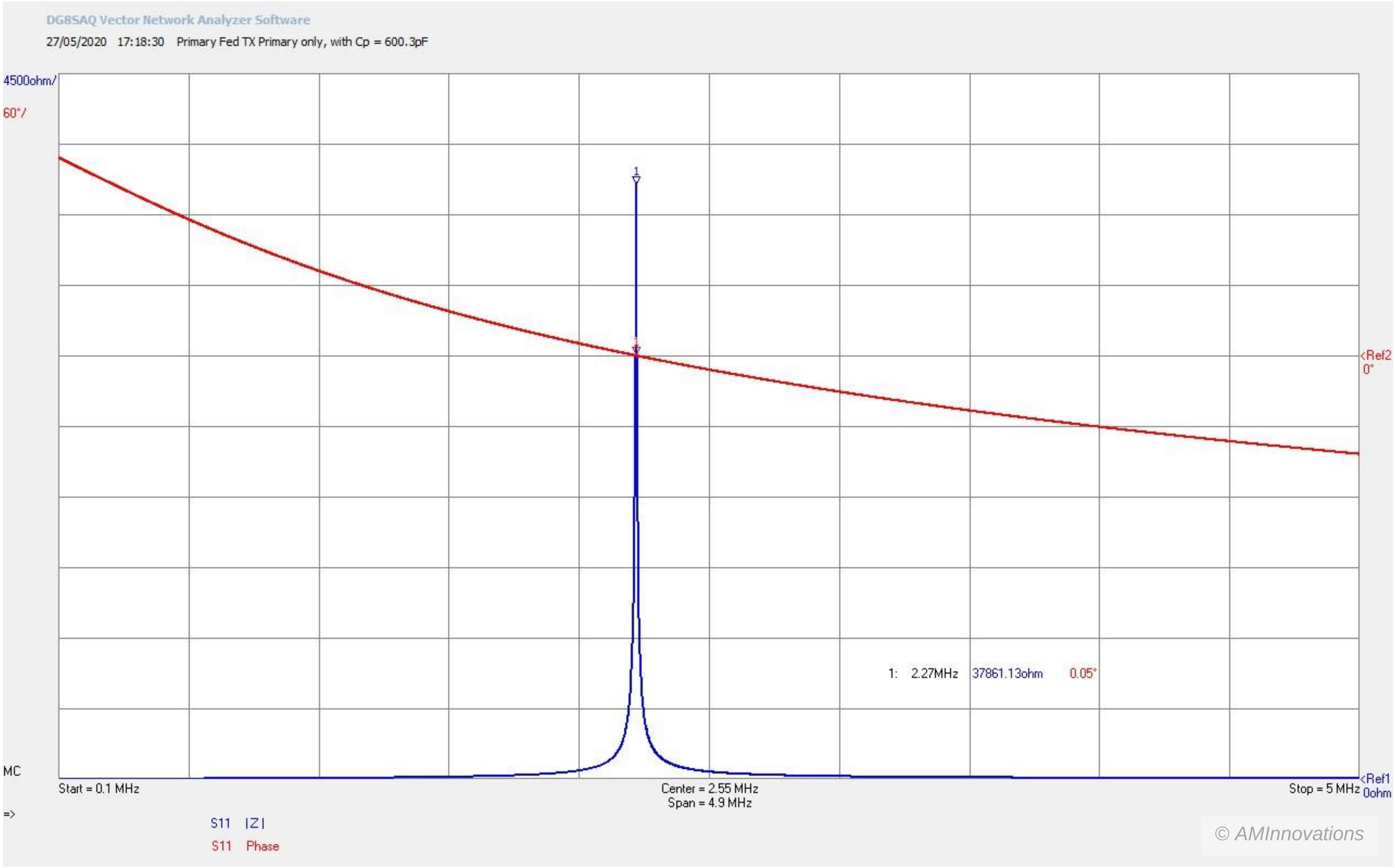
Secondary Coil only – Series Resonance (zoomed)



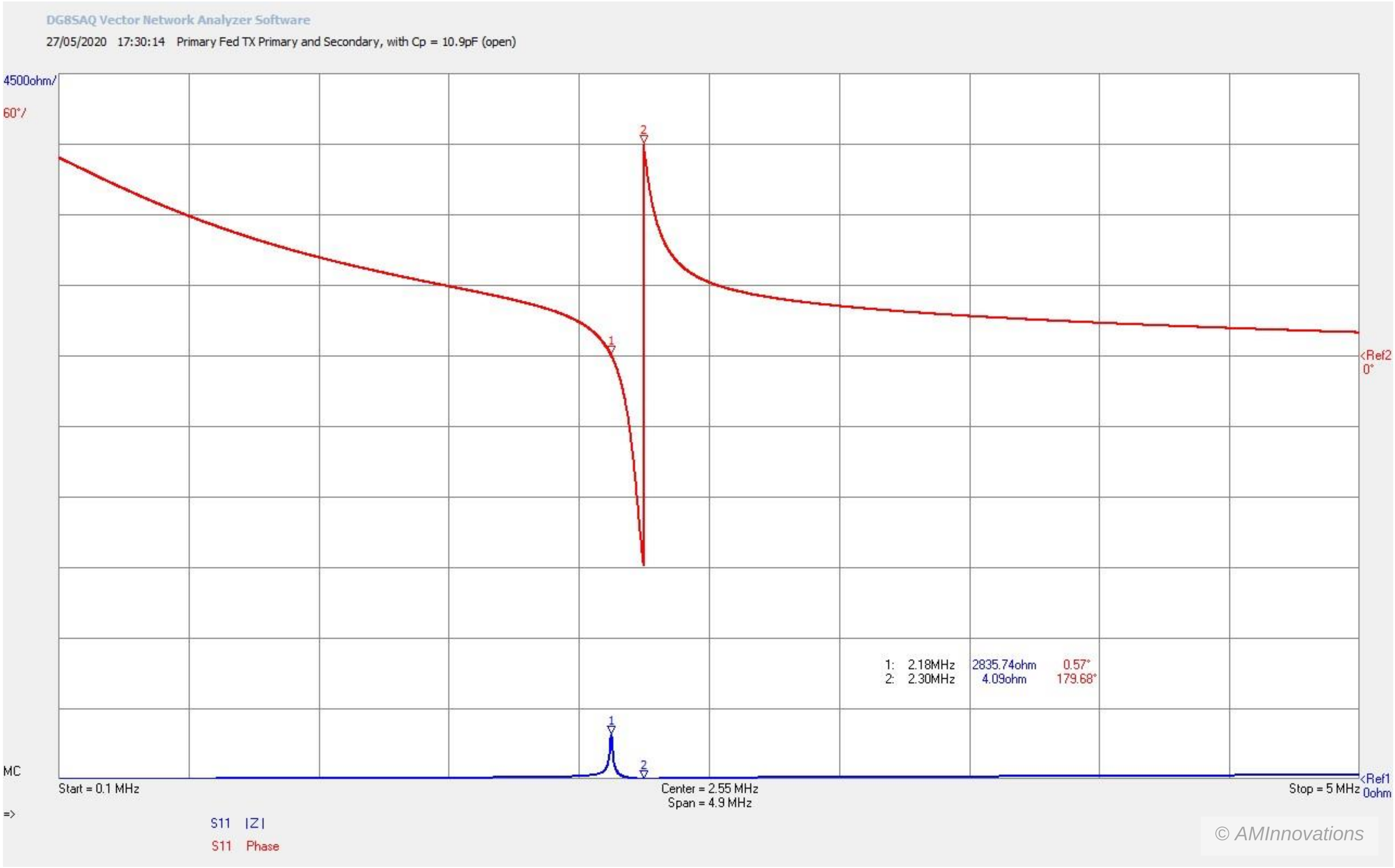
Primary Feed of the Primary Coil Only, with no Tuning Capacitor, Wide-band 50MHz showing self-resonance



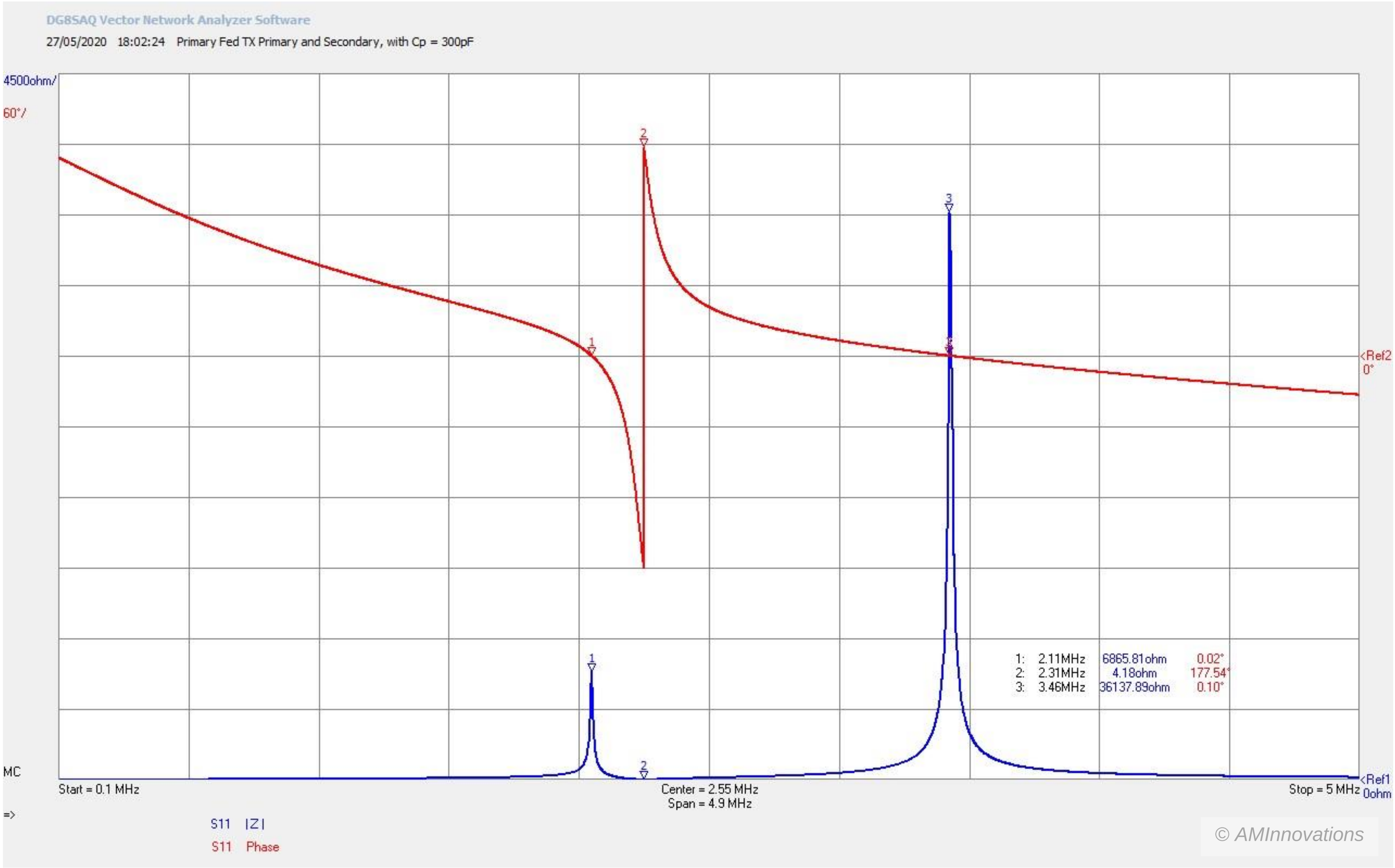
Primary Coil Only, C_P = 100.5pF, Wide-band 50MHz scan



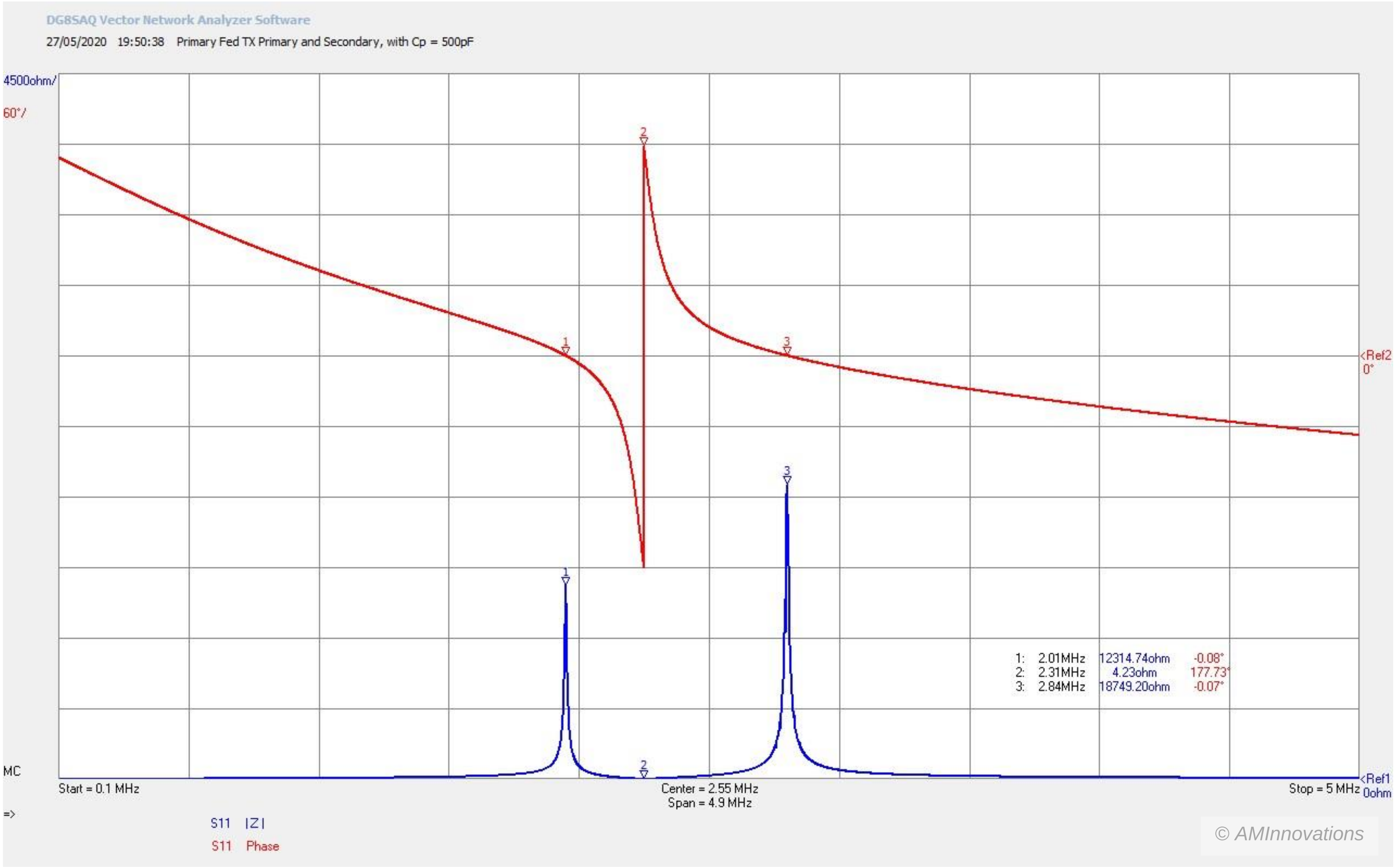
Primary Coil Only, C_P = 600.3pF, Standard 5MHz scan



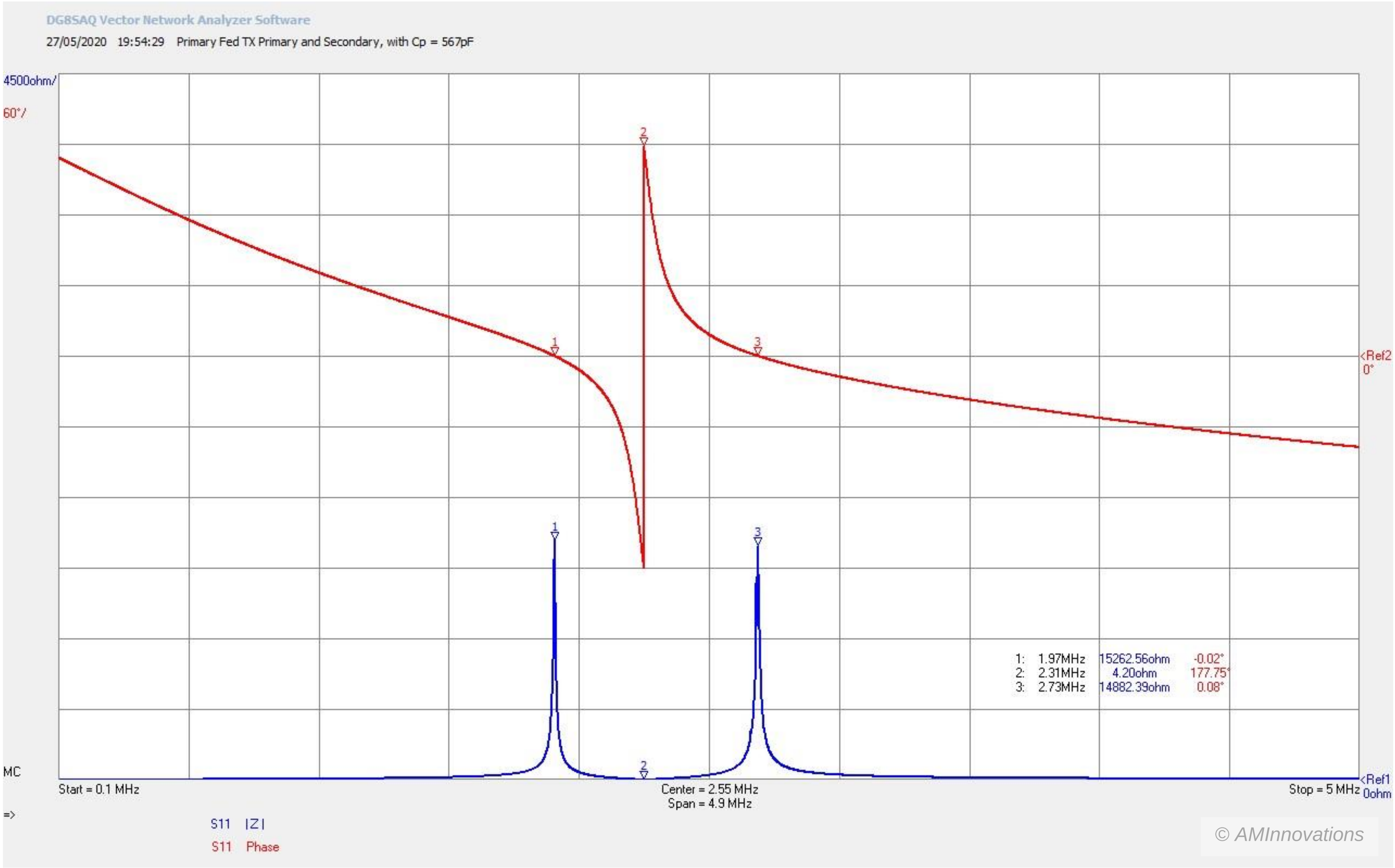
Primary and Secondary Coil, k ~ 0.2, C_P open (10.9pF), same $|Z|$ and $\angle\theta$ vertical scales



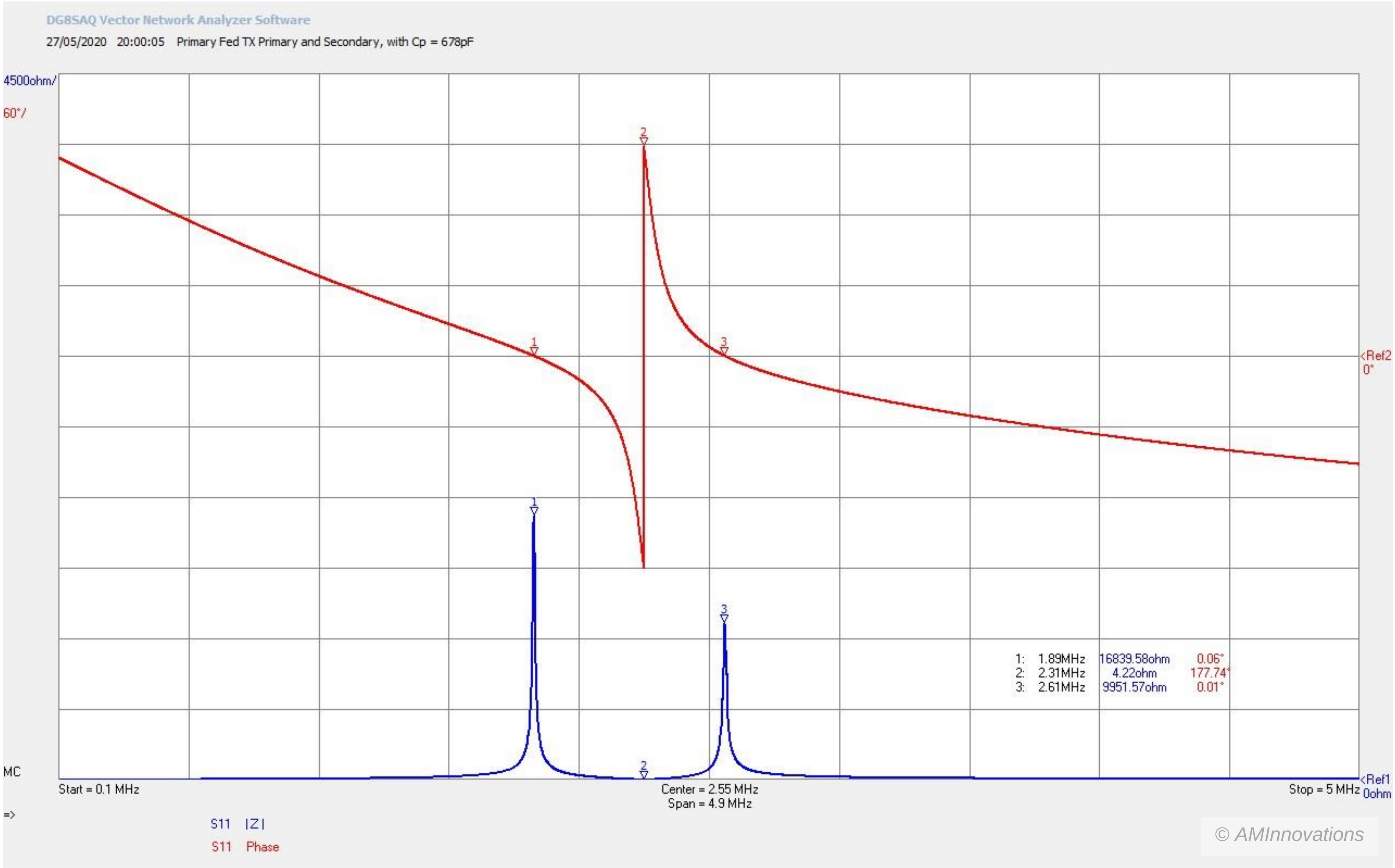
Primary and Secondary Coil, C_P = 300pF, Primary impedance peak approaching Secondary resonance



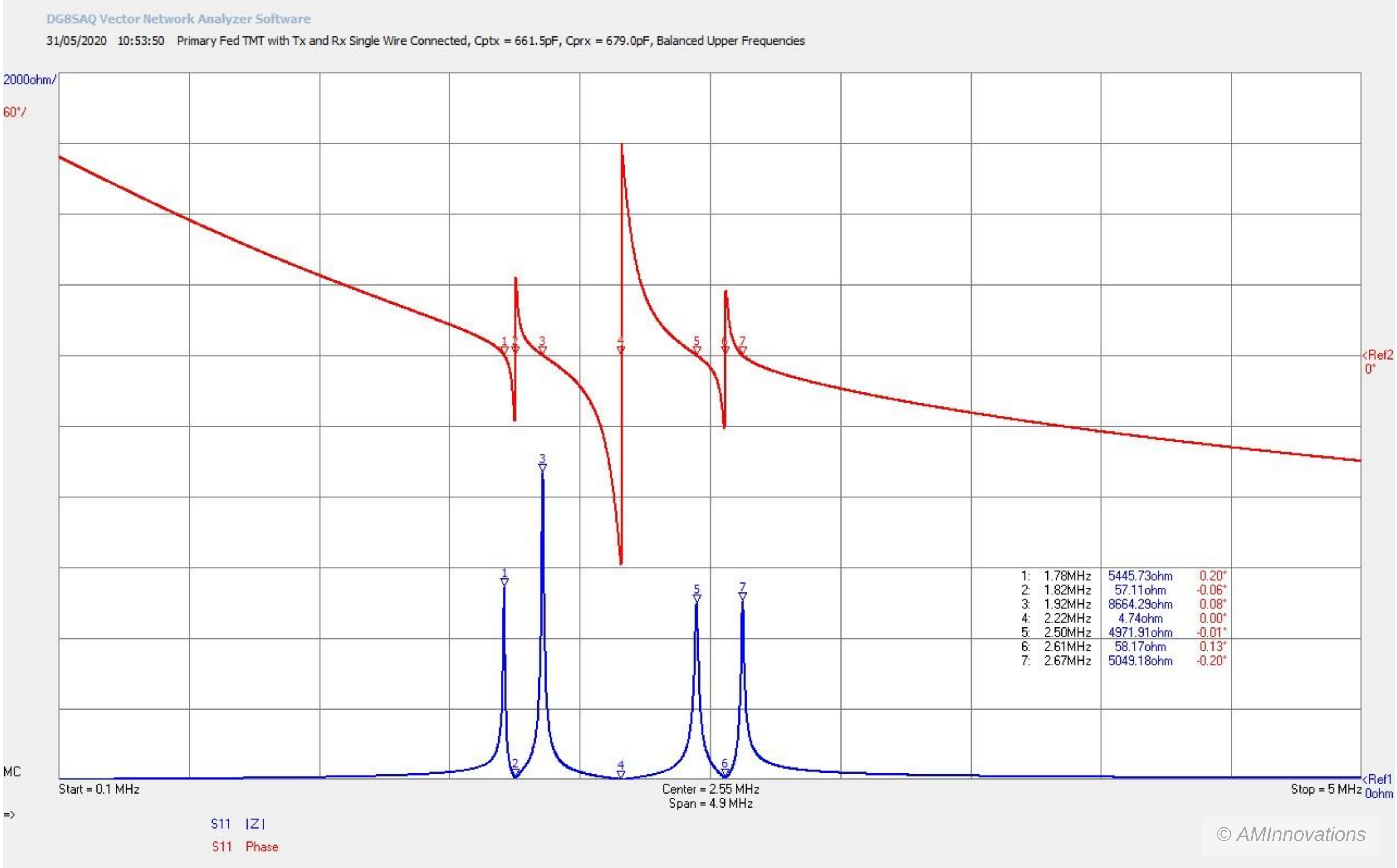
Primary and Secondary Coil, C_P = 500pF, Primary peak dominates at the Upper Resonant Frequency f_U



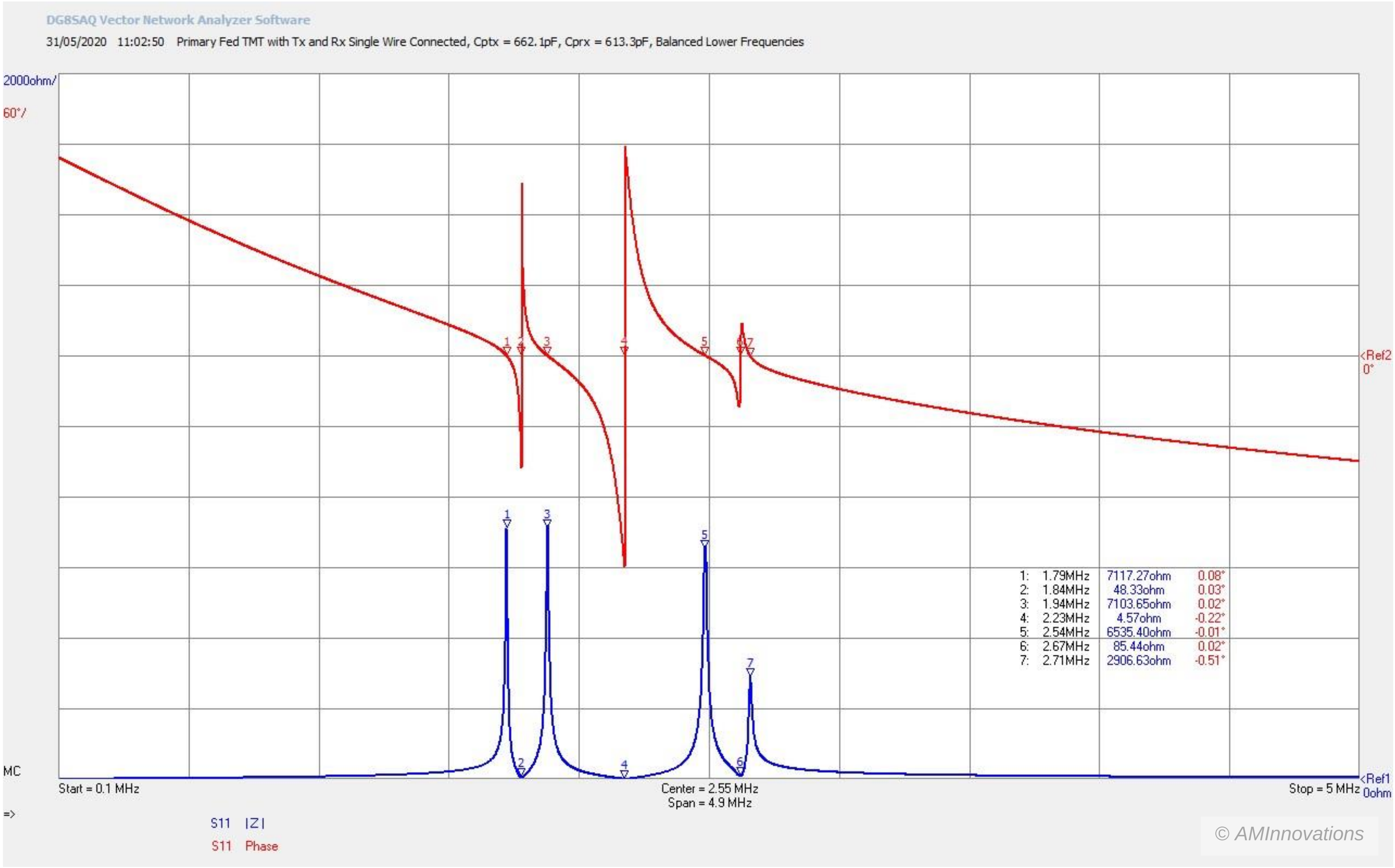
Primary and Secondary Coil, C_P = 567pF, Balanced point where $\boldsymbol{Z}$ is equal for f_U and f_L



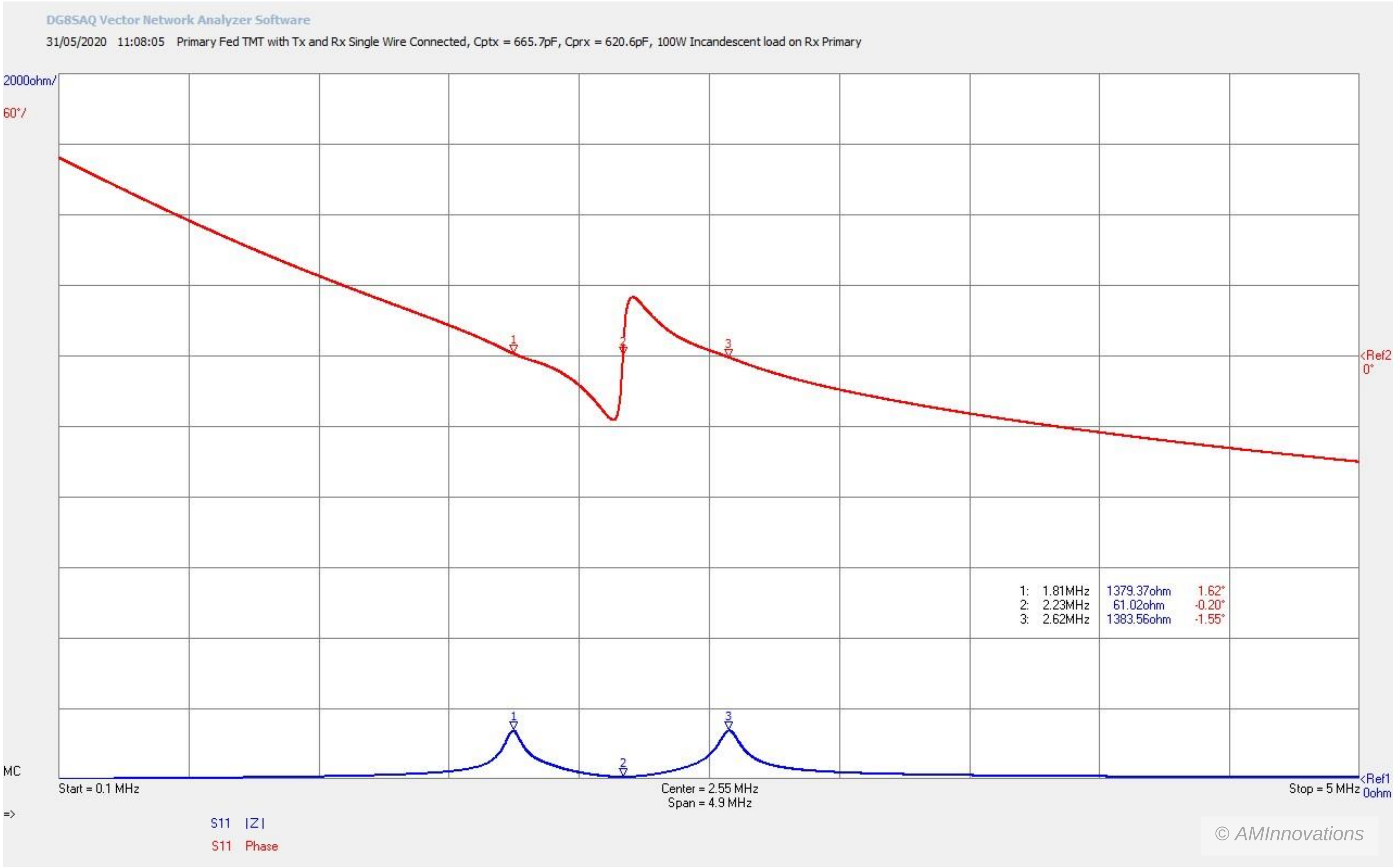
Primary and Secondary Coil, C_P = 678pF, Secondary peak dominates at the Lower Resonant Frequency f_L



TMT Single Wire Connected, Balanced Upper Resonant Frequencies f_U, C_{PTX} = 661.5pF, C_{PRX} = 679.0pF



TMT Single Wire Connected, Balanced Lower Resonant Frequencies f_L, C_{PTX} = 662.1pF, C_{PRX} = 613.3pF



TMT Single Wire Connected,100W Incandescent Lamp Load on Rx Primary, C_{PTX} = 665.7pF, C_{PRX} = 620.6pF