A Test-bed Validation of Electromagnetic Surface Wave Propagation Along a Dielectric-Coated Metal Pipe

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Abstract — **This paper provides a summary of the results of an attempt at experimental verification of the propagation of electromagnetic surface waves at microwaves frequencies, in and along the uniform dielectric coating of a circular cylindrical metal pipe, based on the previously stablished theoretical investigation. These experimental results are of value for the diagnostic of anomalies on the surface of tar-coated pipes used in protecting the underground power transmission cables (feeder pipes). A test-bed was designed and implemented using an aluminum tubes (10" diameter) with an acrylic tube coating (0.25" thickness). Two identical wave launcher/receiver arrays, each of 32 elements around the tube for relatively uniform radiation/reception, were designed and fabricated at the frequency of interest (~6 GHz). This arrangement was put in a specially designed small anechoic chamber and attached to a network analyzer. A variety of tests were performed to stablish the launch efficiency, prove surface wave propagation along, and reflection from different types of anomalies on the coating. In the paper, a number of test results and supporting graphs will be provided and future work for improving the performance of the launch array and the test-bed arrangement for better results will be outlined.**

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1. INTRODUCTION

The primary motivation for this work the investigation of the possibility of the use of electromagnetic (EM) surface wave technology in the microwave band for detecting defects (damage or disbonding) in the coating of the underground electric pipes. (Although, the basic technology has potential applications in multi-frequency waveguide systems for ground and space communication systems, as well.) This method would not require any information about the current-carrying cables and their configuration inside the pipe unlike other proposed methods involving low frequency EM waves or acoustics waves.

In this method, the only parameters of interest are the diameter, thickness, and composition of the metal (carbon steel pipe, the composition, thickness and dielectric properties (dielectric constant and loss tangent) of the coating material. The applicability and feasibility of this method has been studied both theoretically and experimentally. The continuing experimental study and verification is the subject of this paper.

The method takes advantage of a launched RF surface wave supported by and travelling along the coating of the metal pipe. Upon hitting a significant discontinuity such as damaged, torn, or disbonded coating, a reflected wave is generated which travels back toward the launch point. If this reflected wave is strong enough, it can be detected. The use of Time-Domain Reflectometry (TDR) or radar techniques can provide the location of the defect by measuring the round trip time of the launched pulse. A schematic of the procedure is shown in Figure 1.

The pulse would be centered at a frequency related to the pipe diameter, coating thickness and composition, etc. The launch method and mechanism is critical and is investigated.

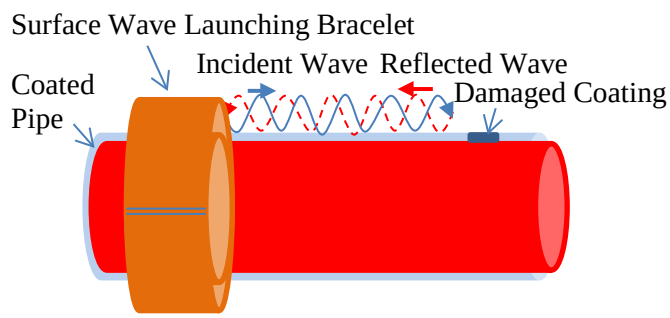

Figure 1. Schematic of error detection technology

2. THEORETICAL SUMMARY

Previously, It has been shown theoretically, that electromagnetic (EM) surface waves can propagate outside and along a circularly cylindrical metal objects with dielectric coating (and without coating if the metal conductor is lossy) [1-3]. Some details of this theoretical investigation are provided in [3] but the full details will be provided in a future paper.

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To summarize briefly, the fields can be expanded in a circular cylindrical coordinate system. They involve hybrid modes which are in general a combination of TEM (electric and magnetic field vectors transverse to the direction of propagation), TE (transverse electric field vectors) and TM (transverse magnetic field vectors) modes. For a uniform field around the circular cylindrical pipe, only TM and TE modes exist, while for sinusoidal variation around the cylinder only HEM (hybrid electric and magnetic modes with both transverse and longitudinal field vectors) modes exist.

The first and dominant mode of propagation is a TM mode designated as TM0, which is uniform around the circular cross-section of the pipe and can exist and propagate along the pipe regardless of decreasing thickness of the coating layer. This mode, therefore, has no cutoff. The next mode is TE1 followed by TM1 and then TE2 and so-on. The number of modes increases with frequency. As opposed to the modes inside a waveguide in which as frequency is decreased to a cutoff frequency at which the mode becomes evanescent or non-propagating, the cutoff outside is reached when the mode completely radiates and does not stick to the pipe, except, as mentioned for the TM0 which does not have a non-zero cutoff frequency.

3. EXPERIMENT SET-UP

From our initial theoretical investigation and its application to a coal-tar clad pipe of approximately 10” in diameter and 0.25” in dielectric thickness we selected the range of 6-7 Hz as our baseline frequency range. For our test-bed arrangement the following components were developed.

- We used a rolled aluminum sheet to form a pipe and then covered it with an acrylic cylinder of approximately the same dielectric constant than the coal tar cladding of an actual pipe. Assorted acrylic cylinders of different lengths were fabricated to be concatenated and used for test purposes.

- Two circular array antennas to be used as a wave launcher/receiver are designed, developed, fabricated, and tested.

- A small anechoic chamber was set-up to house the pipe and launcher combination.

- An Agilent (now known as Keysight) vector network analyzer is used for the tests.

The two launchers were wrapped tightly around the pipe, one used as a wave transmitter port and one as a receiver port as needed.

Launcher Array

Several ideas and options for the design of a device to launch an electromagnetic wave in the 6-7 GHz frequency range were considered. Basically the design has to provide a fairly uniform power distribution around the circular cylinder, and excite only the dominant TM0 mode and to the extent possible, prevent the generation of assorted leaky and creeping waves around the cylinder. We did not require the most efficient or final design for a launcher; rather, we needed one that would prove the concepts. To that end we conceived of a launcher that could be easily constructed in a short time.

In summary, the selected launcher consists of two array strips. Each involves flexible copper-clad dielectric (a micro-strip design) etched with 16 antenna elements/probes spaced approximately half a wavelength apart at 6 GHz which can cover half the perimeter of the cylinder. The two strips are connected together via a power divider/combiner and wrap around the pipe, thus providing a 32-element launcher array. The radiating elements are short micro-strip line segments along the length of the cylinder, designed such that primarily the single dominant TM0 mode is launched on the pipe.

Figure 2 below show the design layout of this flexible launcher array. Figure 3 is a picture of the launcher as it looks on the test-bed system (described below). This launcher is a reciprocal device, meaning that it is capable of both launching and receiving an electromagnetic wave on the pipe in its design frequency range.

Test-bed

our test-bed for laboratory experiments uses an aluminum pipe segment which matches that of the nominal 10”-diameter coal-tar coated pipe. However, the selected dielectric material is acrylic with a similar permittivity, but has much lower loss than coal-tar. This will allow us to use lower power laboratory instrumentation as well as a better a more predictable total system performance during testing.

For our system the test-bed was specifically created to provide validation for the developed theory of the behavior of electromagnetic waves and that the prototype launcher performs as expected. For this we were interested in answering several questions: Is an EM wave launched? Is there power flow along the dielectric? And does the power flow and attenuation in the dielectric match predictions? And finally can we determine and observe the various examples of artificially created damage in the acrylic coating.

The test-bed consists of a 4’ long by 10” diameter thin walled rolled aluminum tube over which a series of ¼” thick acrylic tubes are placed. A schematic for the placement of various dielectric coating anomalies on the pipe is shown in Figure 3. These acrylic tubes include a base tube of 2’ with the remaining 2’ made up of multiple 4” sections. Doing this allows us to replace any of the smaller sections with similar length sections that might include a reflective short, or some examples of damaged areas. Figures 4 show a 2’ long acrylic tube segment. Figure 5 shows a 5” spacer segment used to change the location of other sections along the length of the aluminum tube. Figure 6 show a 4’ segment with copper short created at one end. Figure 7

shows an acrylic end segment which includes some absorbing material used to simulate a pipe that continues indefinitely (no reflection). Figure 8 illustrates an acrylic segment surrounded by an aluminum sheet used to cause a complete reflection of the electromagnetic (a short). This piece is used for locating the total reflection position along the pipe.

Finally, in order to demonstrate the EM field propagation along the pipe and concentrated in and near the dielectric material (instead of radiating out into space, see [3]), Copper- or aluminum- covered foam-board plates were used. These are completely reflective with a hole cut in the center that is slightly larger than the pipes dielectric-clad outer diameter. Plates with different size hole/aperture were made (0.25” or 0.5” larger than the clad pipe). A typical one is shown in figure 9.

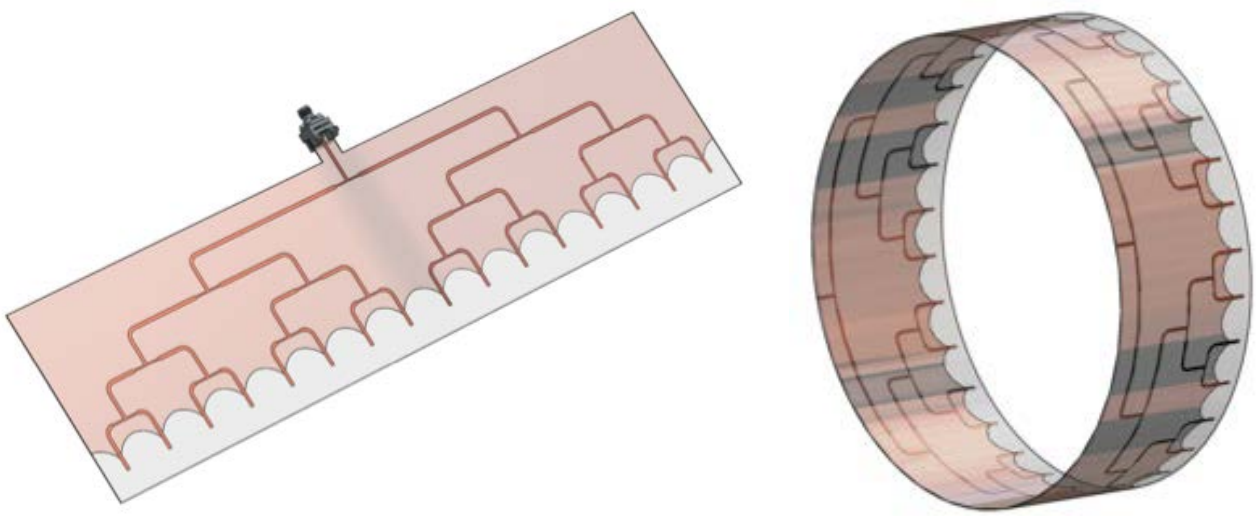

Figure 2. Layout of Wave Launcher: An array 16 corporate-fed RF microstrip radiating elements from one half of the launcher. Two such arrays are corporate-fed and wrapped around the metallic cylinder to form the launcher.

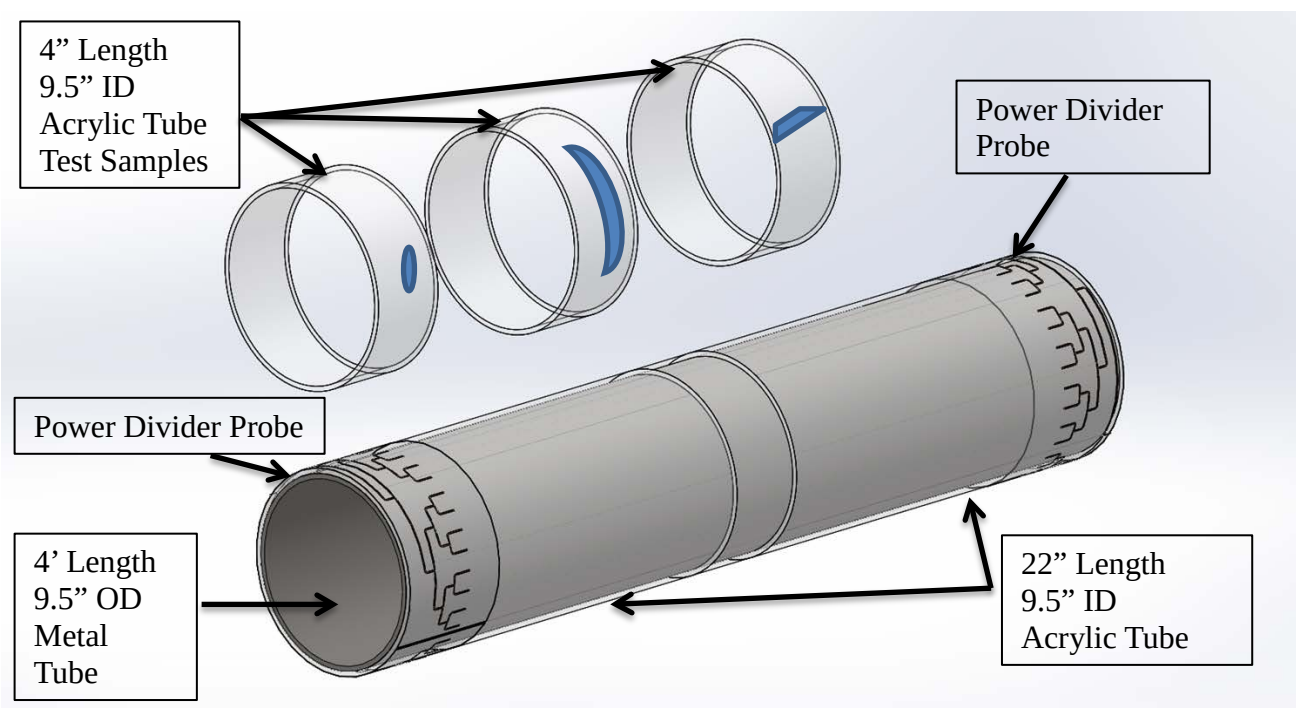

Figure 3. Schematic for the placement of various dielectric coating anomalies on the pipe.

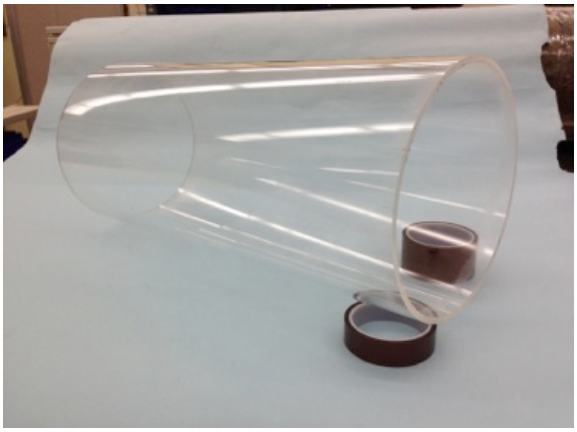

Figure 4. A 2' Section of Acrylic used as main section of test bed

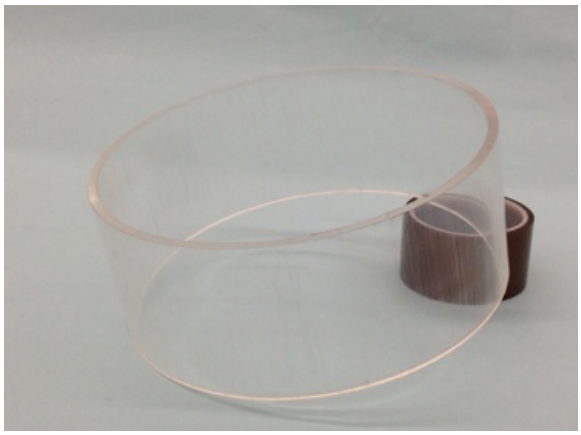

Figure 5. A 4" of Acrylic used as spacer to change location of various reflections in test bed

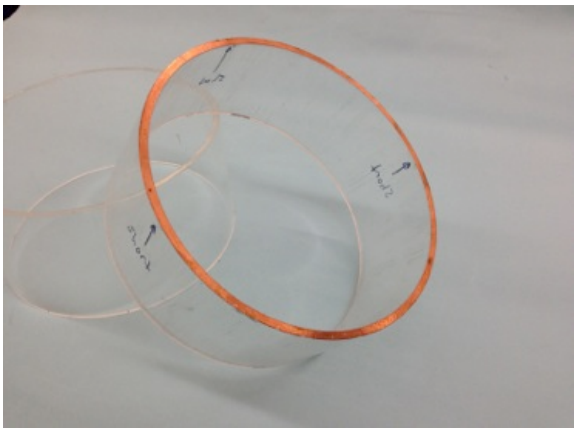

Figure 6. A 4" Section of Acrylic with copper shorting tape applied to face of acrylic

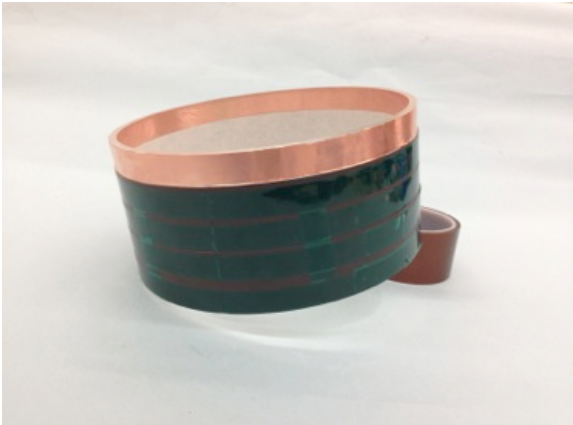

Figure 7. A 4" Section of Acrylic with absorbing material applied; used to simulate long sections of pipe

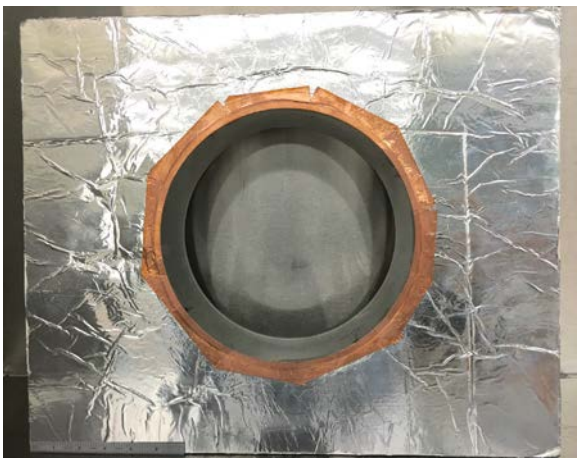

Figure 8. An aluminum plate attached to an acrylic cylinder segment to simulate a short

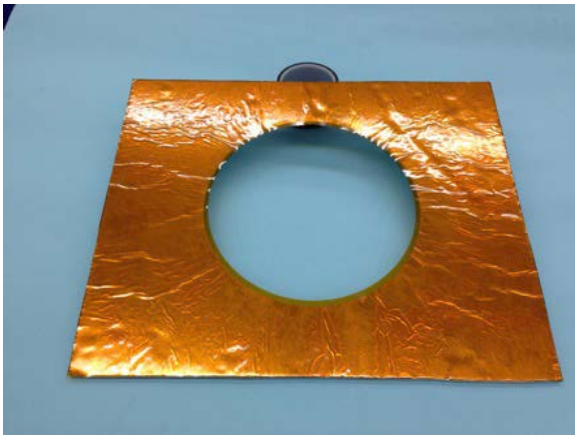

Figure 9. A copper plate with circular hole/aperture (foam-board). Several aperture sizes are used to test proximity of wave propagation concentration near metallic cylinder.

In addition to the basic elements of the test-bed, other elements were created to further demonstrate the ability to detect a damaged piece of coating. Damaged coating areas were simulated by removal of one-half the thickness of the acrylic material in certain spots on the outside as well as the inside of several 4” acrylic tube sections. Figure 10 show a typical case in which a groove of 1” width along the tube, and 45 degrees along the circumference, with a depth of half the thickness of the acrylic material.

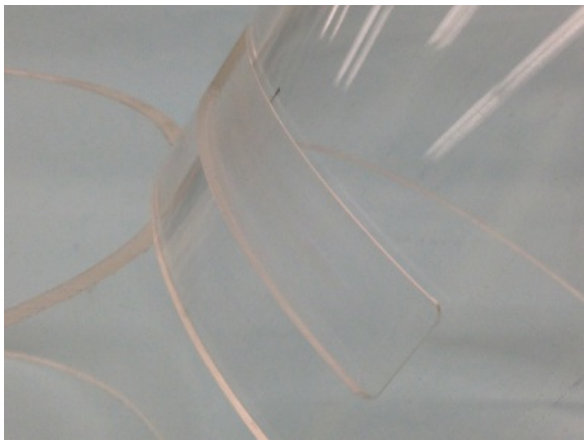

Figure 10. A 4” Section of acrylic tube with a part removed: depth 0.125”, width 1”, length: 1/8th circumf.

A transmitting segment of the test-bed which the array launcher and the power divider for the two halves of the array is shown in Figure 11 and the total test-bed including the surrounding anechoic chamber is shown in Figure 12.

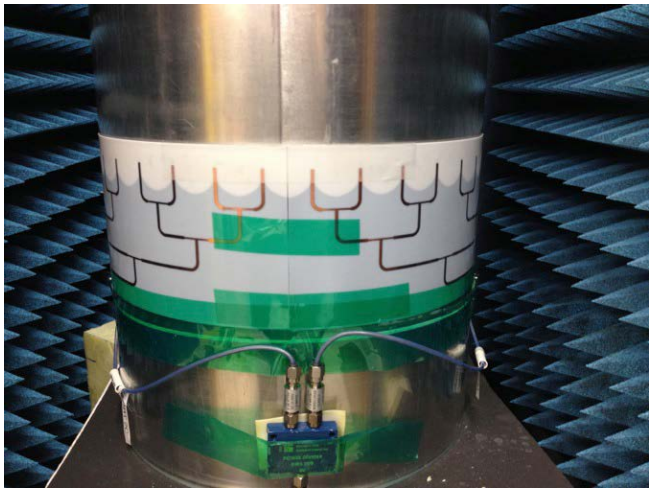

Figure 11. The wave-launcher wrapped around the dielectric-clad metallic pipe. A similar one is wrapped at the other end as receiver.

Figure 12. Test Bed configured for transmission-type characterization and performance measurements.

4. MEASUREMENTS

Once the launcher and test-bed components were constructed and assembled, the remaining part of the system to be integrated was the microwave instrumentation for generating and delivering an RF microwave signal to the launcher array for detecting reflected and/or transmitted signals. For this task an Agilent (now Keysight) automated vector network analyzer (ANA) was used. The immediate benefit of this choice is that the ANA is capable of performing all of the laboratory tests and calibrations that we are interested in, and is capable of both sending and receiving signals, measuring the ratio of power to/from the launcher, and more specifically, it is able to do basic time domain reflectometry. It is this latter capability that is used extensively. However, this benefit is somewhat countered by the fact that the ANA can provide limited output power, which curtails the sensitivity of the measurements.

Finally, as previously mentioned, since the launcher is capable of both launching and detecting signals on the pipe, a set of two launchers can be used to measure some other parameters in the test-bed when used as a transmit/receive pair.

In the following we describe the tests done to validate the launcher performance, the test-bed performance, and the

overall system performance (which includes the end-to-end test using time domain reflectometry). To this end we identified many different tests to be performed.

Some of these tests are done in what we call "Transmission" mode, whereby two launchers are located on the test-bed and separated by a fixed distance and we are looking at the ratio of the power launched by one to the power received by the other. Some of these tests are done in "Reflection" mode, whereby a single launcher is located on test-bed and we are looking at the ratio of power launched to the power received due to reflections along/or at the end of pipe.

These tests are summarized in Table 1. From Table 1 we identify four major types of tests:

(1) Those which validate the theoretical electromagnetic field propagation along the pipe,

(2) Those which identify the parameters of launcher and the acrylic coating loss,

(3) Those which validate the test-bed system operation, and

(4) Those which demonstrate the ability to detect damages to the acrylic in the test-bed.

They are explained in some detail below.

1) Validation of EM surface wave propagation

Tests 1, 2 and 3 from Table 1 were done using the previously mentioned foam-board plates. This test is done in the transmission mode whereby the foam-board is held around the pipe to determine if the signal between the two launchers is blocked. And in order to insure that the results do not include direct radiation from the transmit array to the receive array via free space radiation, the apparatus is set within the anechoic chamber such that the edges of the foam-board are very close to the anechoic wall. The conjecture here is that if the wave energy is fully contained in the acrylic coating and its vicinity, then a reflecting blockage immediately beyond this vicinity will have little effect on the wave as it flows from transmit launcher array to the receiver array.

The measured parameter is the ratio of the power received to the power transmitted in dB. Figure 13 shows the results of this test. In this figure, the top line is for no blockage case. The next line down is the foam-board with the ½" diameter larger hole. Note the relatively negligible effect. The next line down is the foam-board with a hole/aperture ¼" larger in diameter. Here one observes slightly more effect, yet still much of the energy is passing through the hole. The lowest line is for a foam-board that has a hole that is only as large as the coated pipe. Here one observes significantly more loss, but only slightly more than 6 dB. This suggests that most of the energy is indeed inside the coating and very tightly coupled to the pipe.

2) Validation of Acrylic tube and Launcher array performance

The characteristics of a test-bed must be understood in order to remove its effects from that of the devices or other signals/parameters one might be interested in measuring. Tests 4 and 5 from Table 1 were done to verify our understanding as to how the acrylic attenuates or dissipates the power in the surface wave as it moves down the pipe. We refer to this attenuation as the loss factor. A byproduct of that test is a measure of the efficiency (or equivalently the loss factor) of the launcher itself.

From previous measurements, using entirely different laboratory instrumentation, the loss factor of the acrylic material had been determined. The results from the measurements on the test-bed should provide the same value of loss factor. Also, the loss factor of the launcher was predicted using commercial software as part of the design process. Again, it would be expected that the results of these measurements should confirm the predicted value.

The measurements for Tests 4 and 5 were done on the test-bed in the transmission mode. In order to find the loss factor of the acrylic material one has to make two measurements of the relative power loss between the two launchers. These two measurements must be made at two different separation distances between transmitter and receiver. A subsequent analysis of the measurements is then required to determine the loss factors of interest. The analysis results come from a mathematical description of the measurement. This mathematical model is a simple summation of the various loss factors (in dB) along the entire signal path. The two measurements provide information for two equations for which there are two unknowns: the acrylic loss factor and the launcher loss factor.

Figure 14 summarizes the measurements and calculations for the two measurements when the two launchers are separated by first by 30" and then by 16" (a 14" difference). In Figure 14 the straight line at -40 dB shows the expected signal value for the 30" separation. The straight line at -37.5 dB shows the expected signal value for the 16" separation. Our mathematical model clearly accounts for the expected value since the measured values for these separations very near the calculated values. The 2.5 dB difference for the 14" yields a loss factor for the acrylic of 7 dB/m. The second line from the top in Figure 14 shows the acrylic loss as a function of frequency. Clearly the loss is between 5 to 8 dB in that frequency range. This is a good result and indicates that the test-bed is behaving as expected.

The launcher loss is a byproduct of this measurement. During the design phase the launcher efficiency was calculated as 10% (equivalent to 10 dB loss factor). From our modeling and these measurements, we can see clearly that the third line down in Figure 14, the launcher loss from

measured data, is at -10 dB. From this data we conclude that the test-bed and the launcher are operating as designed.

3) Validation of System Operations and Methods

The detection of disbonded/damaged pipe coating requires a measurement system that includes the launcher as well as the equipment to generate, transmit, receive, and analyze the signals. As already mentioned, for our tests we have chosen to use a standardized laboratory microwave automated network analyzer (ANA). Once the system is assembled with the launcher, coaxial cables, and ANA we need to show that discontinuities in the pipe coating are detectable. The largest possible reflection in the acrylic coating happens when there is a complete wall of metal in the dielectric and beyond. This was created and is shown in Figure 8 above. We installed this 4" section of acrylic at a particular location along the test-bed and used the ANA to detect reflections and to precisely measure the time between when a signal was sent and when a reflection was observed. This time represents the round-trip travel time for the signal, thus ½ of this time represents the time it took for the wave to reflect off the metal wall. Algebraic conversions of time and the wave speed provided us with the distance to the reflector.

Figure 15 below presents the results of a series of such measurements, summarizing Test 6 from Table 1. This series of measurements were done by carefully moving where the reflection wall is located. This is done by replacing and relocating the 4" piece of acrylic containing the reflector along the length of pipe while using unbroken pieces of 4" acrylic to ensure a continuously coated pipe. The figure shows five different positions of the reflector wall, each moved by 4". We measured the distance between the launcher and reflector with a tape measure, then performed the system measurement using the test-bed. It is clear that we were able to detect within a fraction of an inch the location of the reflection wall. Note also from this figure that the ANA detects the reflections of the wave at the launcher position as well, due to relatively inefficient design of the launcher.

Figure 16 below presents the results of a series of such measurements, summarizing Test 7 from Table 1. For this series of tests we created a gap at the interface of two of the 4" sections that is 34" from the launcher. This gap is around the whole circumference of the pipe. We used very small shims to create this gap, ranging from 0.031" to o.155". Once again, it is clear that we were able to detect the presence of the break in the dielectric coating. Also note that the relative intensity of the reflection is proportional to the gap size. This series of tests validate the ability of our instrumentation and testing methods to detect strong reflections of the wave.

4) Validation of ability to detect coating damage

The tests so far have incrementally prepared the system for the measurements that are of most interest, namely, attempting to detect coating disbondments and damages. We have not performed as yet a thorough theoretical analysis for such conditions due to the complexity of the theoretical formulation. It may be possible to do so in the future if necessary; however, we have determined that presently direct measurements seem to be the most viable method to identify limitations of this method.

We carried out Tests 8-13 per Table 1 to ascertain the bounds of the viability of our system. All of these tests were done in the reflection mode using time domain reflectometry (TDR). Tests 8 and 9 were done using the 4" test sections shown before, and placed in the test-bed a distance of 34" from the launcher. For these two tests we were interested in determining the effects of the loss of ½ the thickness of the acrylic coating; in one case the outer half and another case for the inner half. Four sections were constructed whereby the amount of material removed along the length of the acrylic tube varied from 0.25" to 1". The results of this testing is shown in Figures 17 and 18. In both figures we clearly see the effects of the missing material. Of special interest is the results shown in Figure 18 in which the effect seems to be somewhat scattered along the distance axis. It should be recalled that the defective material in all cases is located 34" from the launcher. This is an indication of the difficulty in detecting weak signals using standard laboratory equipment. However, we will briefly address this in the summary section.

Tests 10-13 represent the main goal of this work: namely to detect and isolate the location of disbonded or damaged dielectric coating around the metal pipe. For these tests we used 4" test sections as illustrated before. We had constructed four of these sections, each with slightly bigger damaged surface. The length of each was 1", and the width varied from 5° to 90° in circumferential direction. The sections were, in turn, placed on the test-bed at 35" from the launcher. The results of these tests are shown in Figure 19.

Clearly the system observed the effects of the damaged sections. However, careful reading of this figure shows that the apparent location is from 40" to 42" from the launcher. Upon more careful review, this phenomenon was foreshadowed by all of the previous tests in which the reflected signal was weak (i.e., Tests 7 through 13). Obtaining the precise location of the surface anomalies/damages, therefore, requires much stronger signals and better detection and signal processing techniques which can provide better sensitivities.

Table 1. A listing of some of the tests performed.

	Configuration			Demonstration	Validation
Test	Mode	Description	Distance		
1	Transmission	Annular Refl 0" space midway between launcher	-	fields are confined to the dielectric and its vicinity	field expansion theory
2	Transmission	Annular Refl 0.5" space midway between launcher	-	fields are confined to the dielectric and its vicinity	Field expansion theory
3	Transmission	Annular Refl 0.25" space midway between launcher	-	fields are confined to the dielectric and its vicinity	Field expansion theory
4	Transmission	Loss at 12” separation	35”, 23”	used to identify acrylic loss and launcher loss	Test bed system performance
5	Transmission	Loss at 14” separation	16”, 30”	used to identify acrylic loss and launcher loss	Test bed system performance
6	Reflection	Full short in Acrylic	22”,26”, 30”,24”, 38”	Provides largest reflection to validate TDR and launcher	Strongest return signal. Validates test bed system operation
7	Reflection	Circumferential gaps in coating. 31, 62, 93, 124, 155 mil	34”	Small gaps are clearly visible in TDR difference mode	Fairly weak signal. Validates test bed system operation
8	Reflection	0.125" deep x 0.25", 0.5", 0.75", 1.0“, length x 360° circumferential groove on outside of coating	34”	Exterior damage	Test-bed senses maximum expected damage
9	Reflection	0.125" deep x 0.25", 0.5", 0.75", 1.0“, length x 360° circumferential groove on inside of coating	34”	Interior disbondment	Test-bed senses maximum expected damage. Most likely location for disbondment
10	Reflection	Groove on exterior of acrylic 1" x 0.125" x 90° circumferential	35”	Damage on exterior dielectric	Representative disbondment. Good results
11	Reflection	Groove on exterior of acrylic 1" x 0.125" x 45° circumferential	35”	Damage on exterior dielectric	Representative disbondment. Good results
12	Reflection	Groove on exterior of acrylic 1" x 0.125" x 10° circumferential	35”	Damage on exterior dielectric	Representative disbondment. Good results
13	Reflection	Groove on exterior of acrylic 1" x 0.125" x 5° circumferential	35”f	Damage on exterior dielectric	Representative disbondment. Good results

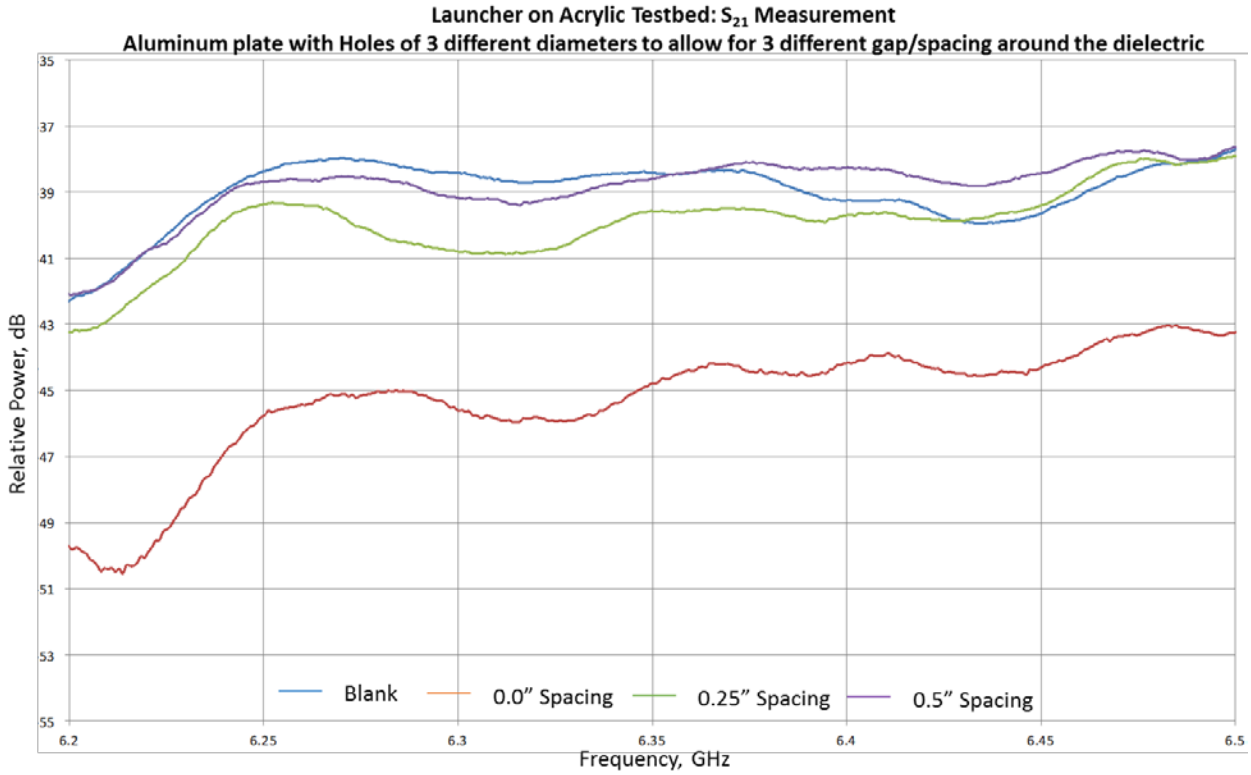

Figure 13. Results of Validation Tests 1, 2, and 3 from Table 1.

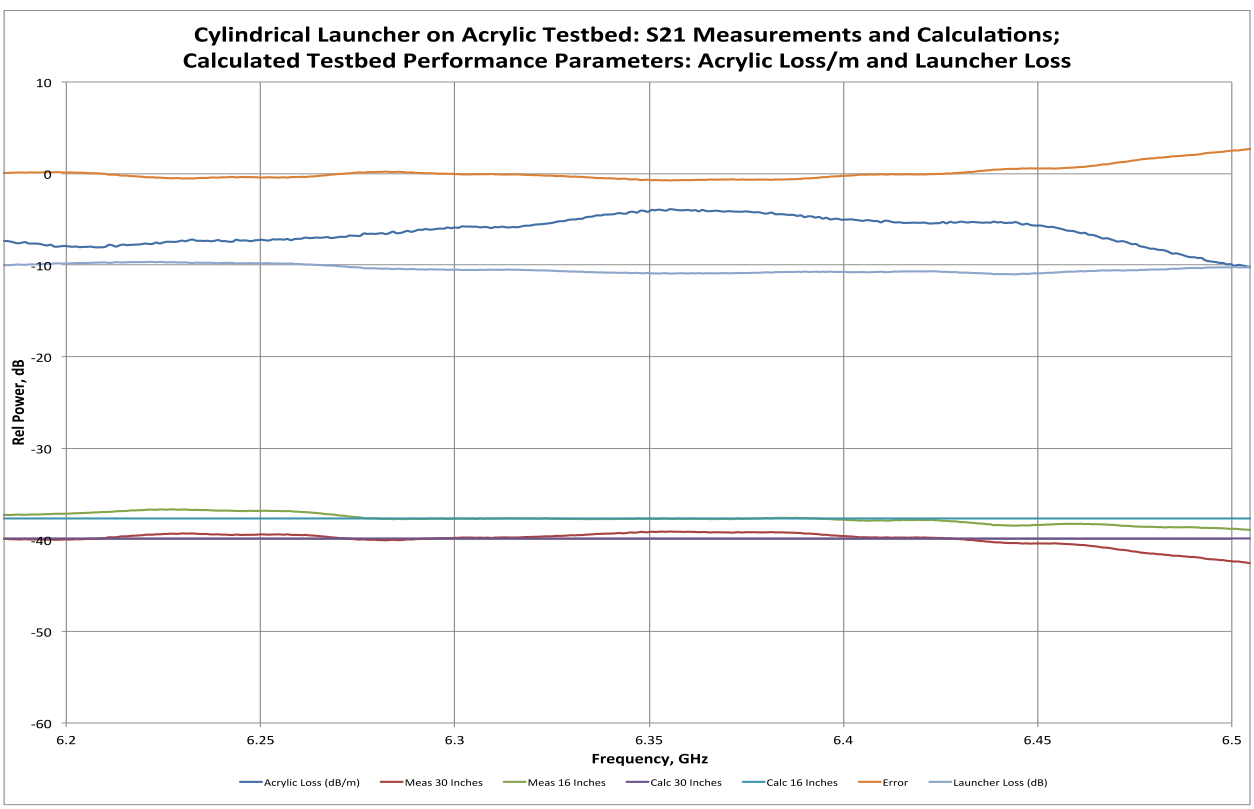

Figure 14. Results of Validation Tests 4, 5 from Table 1.

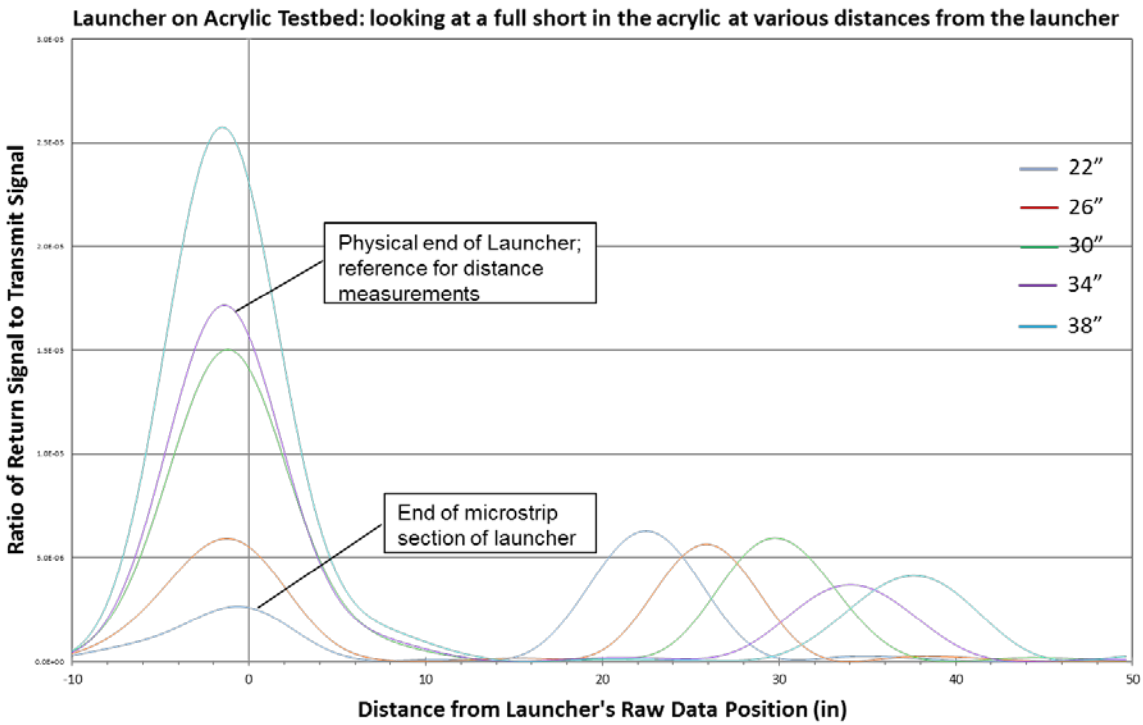

Figure 15. Results of Validation Test 6 from Table 1.

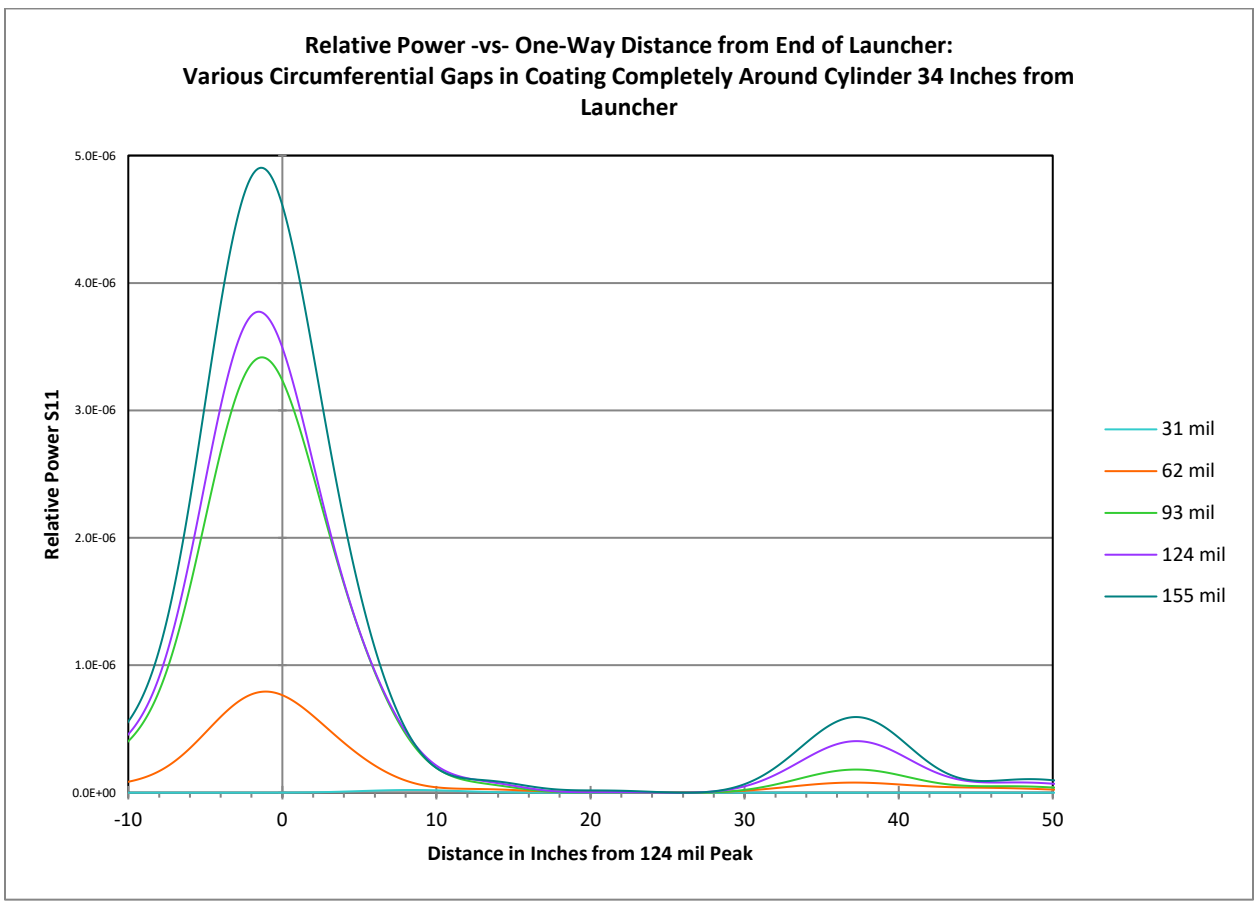

Figure 16. Results of Validation Test 7 from Table 1

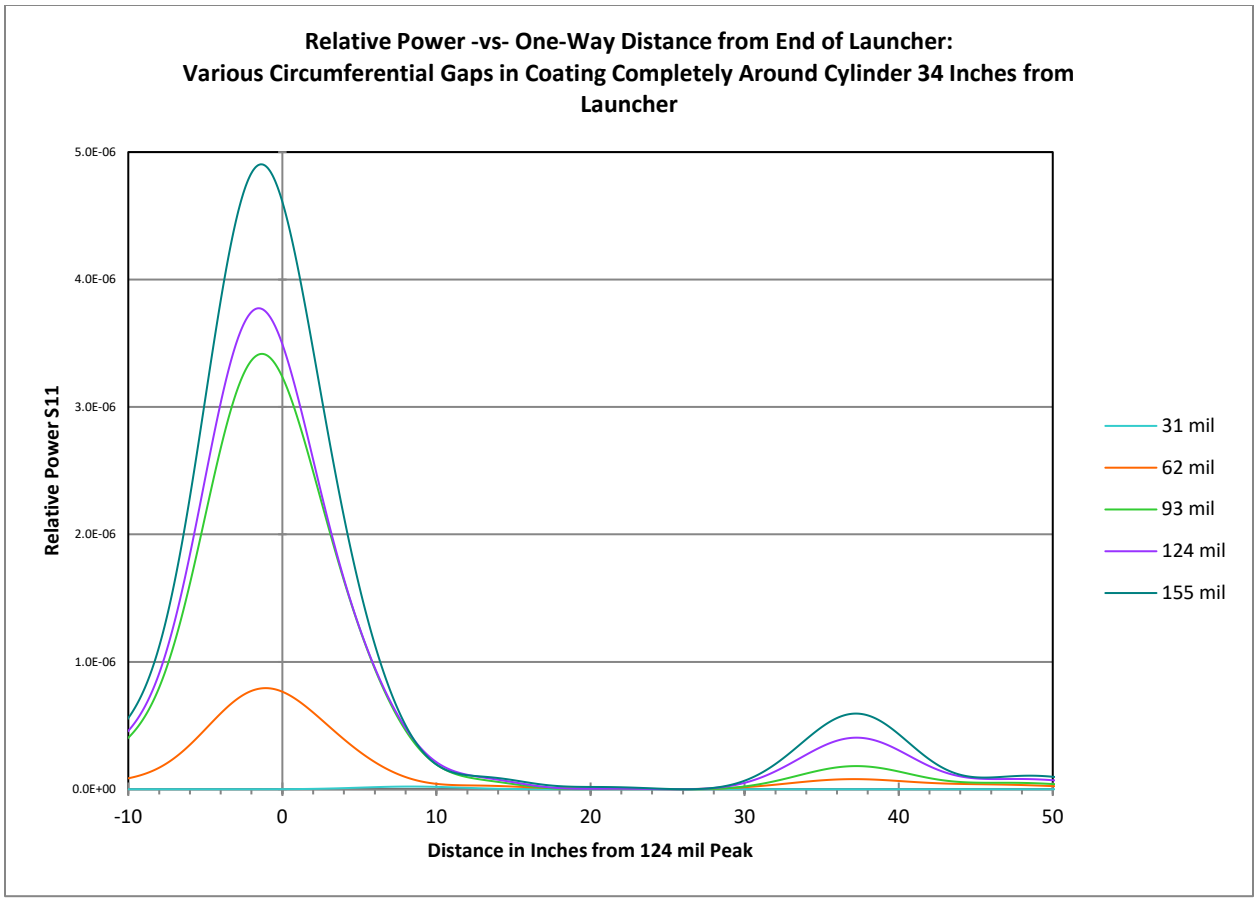

Figure 17. Results of Validation Test 8 from Table 1.

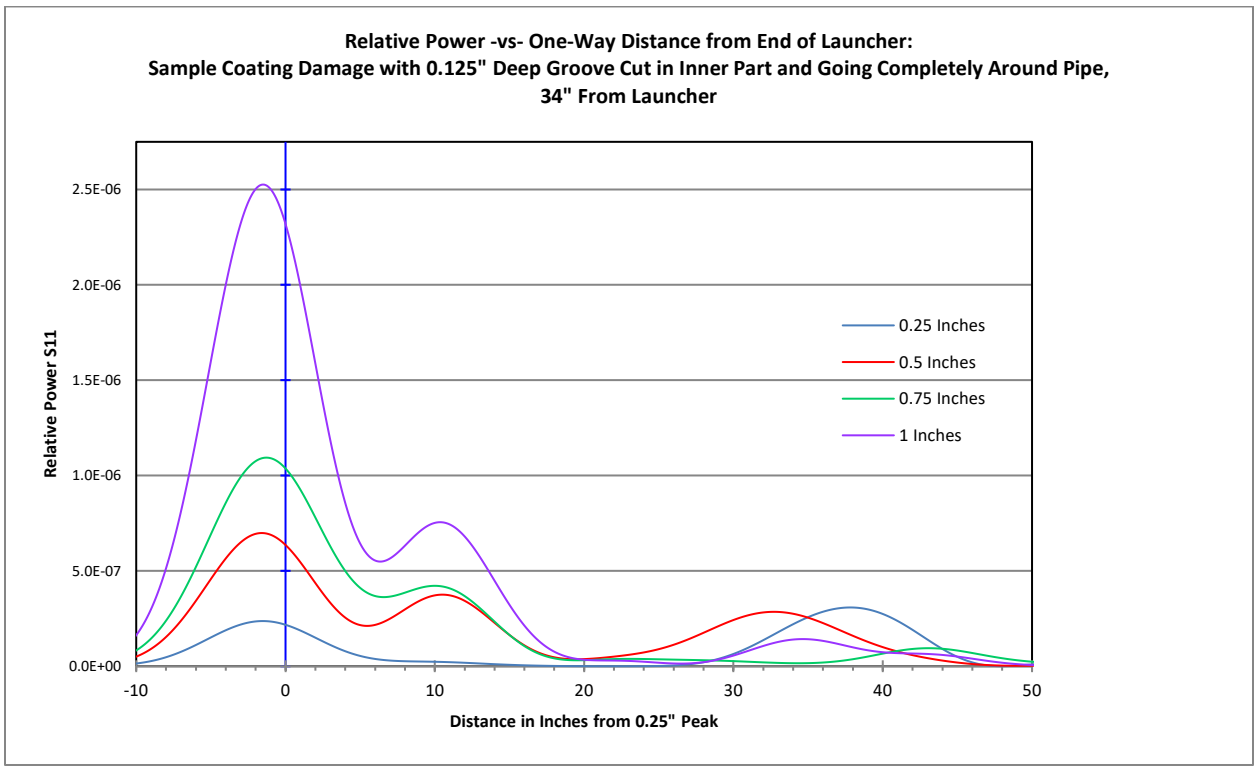

Figure 18. Results of Validation Test 9 from Table 1.

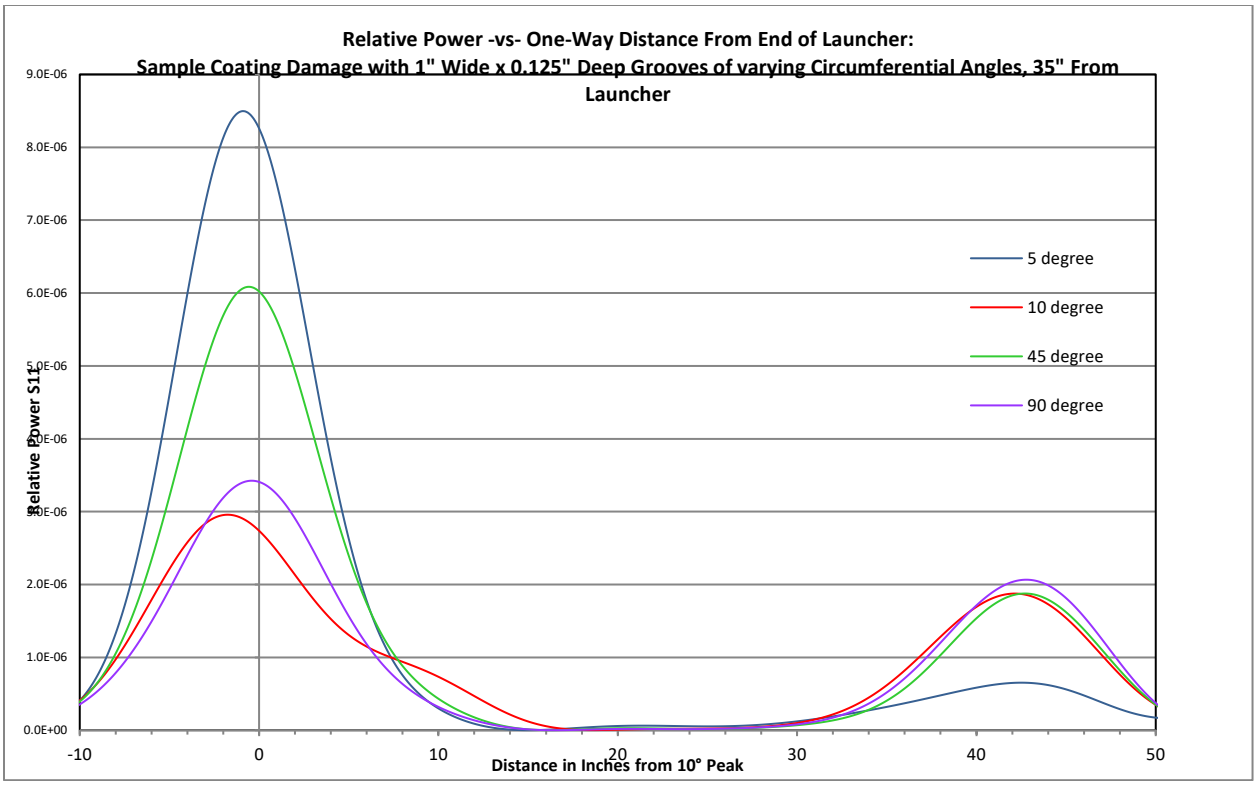

Figure 19. Results of Validation Test 10, 11, 12, 13 from Table 1.

5. Summary and Conclusions

We have developed a test-bed to assess the feasibility of the use of EM surface waves for detection and location of damaged coating on coated metal pipes. Numerous tests were performed. From the results of these tests and careful observations the following statements can be made:

- The design performance of the prototype launcher was validated.

- The acrylic coating dielectric loss was successfully measured in multiple ways.

- The theory regarding the behavior of a propagating electromagnetic wave on the outside surface of a dielectric-clad metal pipe was validated.

- The performance of the test-bed and the overall measurement system has been validated for relatively strong reflection signals.

-The effects of a set of representative surface anomalies simulating actual coating disbondments have been observed. However, we have not been able to identify their locations accurately as yet. This is primarily due to the fact that the laboratory instruments do not provide sufficiently strong signals and/or adequate detector sensitivity needed for observing the location of the anomalies.

Indeed, this is a significant part of the work presently underway which would provide these necessary capabilities. It will involve the design, fabrication and test of a purpose-built TDR/radar system which includes the appropriate power levels and signal processing techniques, and will provide the initial breadboard for an actual field system implementation.

Additional future work will also include the design of a more efficient launching array with a better form and fit on the actual coal-tar-clad transmission pipes.

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BIOGRAPHIES

Mark Gatti *has been at JPL since January 1981. He has worked on spacecraft and ground antenna systems as a technologist and manager. He has delivered spacecraft antennas, developed near-field measurement facilities, and radiometric characterization systems for large ground antennas. He managed the instrumentation of the first Beam Waveguide Antenna constructed for research and development in the Deep Space Network (DSN) and supported the research efforts for a myriad of users. He has managed several large research projects including the delivery of the ground system element for the Cassini Radio Science Gravity Wave Search and the development of technologies for large arrays of small antennas for the DSN. Currently Mark is the Manager of the Communications Ground Systems Section at JPL, responsible for engineering development, design, and delivery of all elements of the antenna systems for the DSN including the transmitters, low noise amplifiers and cryogenics, feeds, RF electronics, digital receivers, mechanical/structural, pointing and control systems.*

Mark received his BSEE from NMSU in 1980 and the MSEE from Cal State Northridge in 1986.

Hung-Sheng Lin *is an RF Engineer at the Jet Propulsion Laboratory, California Institute of Technology. He received his M.S. and Ph.D. from the Polytechnic Institution of New York University specializing in photonics and electromagnetics. After joining JPL, he has been engaged in research and hardware development in various areas of microwave technology and communication systems. In his early career at defense industry, he was involved in the study, design, measurement and development of microwave components, antenna system from L band to G bands for military applications. His latest work on communication systems involved the development of high power components for X band 80KW CW system. In the past few years, he has been active in development in parallel active and passive microwave subsystem as well as in developing array antennas for digital beam forming for NASA Deep Space Network (DSN).*

Ezra Long *is a microwave engineer at the Jet Propulsion Laboratory, California Institute of Technology. He received a B.A. in mathematics and a M.S. in electrical engineering from California State University Northridge. His career at JPL has focused on cryogenic low-noise receivers for the Deep Space Network. In addition he has extensive experience with antenna and microwave metrology.*

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