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Container Seal Technologies and Processes
Phase I Final Report

1.0 EXECUTIVE SUMMARY

The Cargo Handling Cooperative Program (CHCP) Seal Technology and Process Program is a testing and evaluation effort intended to develop the technical knowledge and experience regarding electronic container seals (e-seals) that is necessary to support on-going and proposed container security initiatives.

Under the current phase of the program, the results of which are reported in this document, the CHCP tested and evaluated the operation of selected radio frequency (RF) based e-seals. Electronic seals were evaluated from four manufacturers that are currently supplying electronic container seals to the marketplace. In addition, the CHCP also evaluated one non-RF e-seal solution. This product has similar functionality, in terms of security and data, as the other tested e-seals but uses a contact memory linkage to transmit data instead of an RF link.

As part of the current effort, the CHCP first tested each of the evaluated RF e-seals in a laboratory to determine baseline communication performance both in free space and mounted on a container. Each seal was then evaluated for readability in three different field environments: on a container being moved through a container terminal gate, on a container moving along an open road, and on a simulated container being moved on a double-stack rail car. Seals were tested to not only determine how the technologies perform in these real-world environments but also to evaluate the various trade-offs that exist with e-seal design and the potential impact of those trade-offs on functionality, reliability, utility, and cost.

The goal of this effort was not to select a “winner” (i.e., a seal which would become an industry standard) but rather to develop the technical baseline that will help government and industry stake-holders select appropriate solutions based on security, operational, and economic requirements. As such, testing and evaluation was completed not to provide a head-to-head comparison of e-seals from different manufacturers but instead to identify the major design trade-offs that exist between the various seals and to identify how these design trade-offs might effect the deployment and performance of the seals and seal reading systems.

From the results of the testing and evaluation effort the CHCP was able to reach a number of conclusions regarding the state of e-seal technologies, the trade-offs involved in e-seal design, the need for and challenges of developing standards for e-seal deployment, and future work that should be pursued in e-seal development.

The most basic issue addressed during the electronic seal evaluation effort was an overall assessment of the current maturity of e-seal technologies and of the readiness for wide-scale deployment. The results of all the testing and evaluation efforts indicate that, as an overall product, e-seals are relatively mature and are based on technologies that have been proven in many other applications. There are no identified problems with the underlying technologies that would prevent immediate wide-scale deployment within the container industry.

The evaluation of e-seals showed that while the overall product was relatively mature, there are wide variations in the maturity of devices available from individual manufacturers. Some of the available e-seals exhibited more advanced levels of design and experience and product support from the vendors. In addition only a few e-seals have had significant previous deployment in actual operations and those vendors have developed valuable experience in problem solving and optimization of reader set-up. These factors have a major impact on the ability to achieve good system performance in the field.

A key finding of the evaluation effort is that although all RF based e-seals operate using the same basic underlying technology, there are widely divergent solutions in terms of how the technology is applied. E-seals from different manufacturers use not only different communication frequencies but also widely different communication protocols, reader infrastructure architectures, and tamper detection methods. Although there are a limited number of devices available in the marketplace, the devices tested showed a wide range of design features.

The major areas of design in which the trade-offs occurred are as follows:

- Frequency
- Communication Protocol
- Reader Infrastructure
- Seal Location

The results of the testing and evaluation clearly emphasize the need for standards in the area of electronic seals design and operations. There are a large number of potential e-seal design and operational parameters that can be selected. If there is to be any sort of interoperability of devices used by the various carriers and shippers in the industry then it is critical to develop a set of standards that will allow communication between seals and readers from various manufacturers.

The choice of frequency reflects numerous factors including not only technical considerations but also international availability of frequencies and economic considerations. Only the 2.44 GHz frequency band is available worldwide and in that case the allowable power levels vary by country. All tested e-seals use unlicensed, shared frequency bands that could result in future radio frequency interference problems in urban and terminal areas. A world-wide frequency with adequate bandwidth for future container security systems would ensure future inter-operability.

Beyond simply specifying a frequency at which seals should operate, it will be absolutely necessary to establish standards for data, communication protocols, seal placement, and reader placement. These standards will have to allow seals from a variety of manufacturers to be reliably interrogated by readers systems from all other manufacturers at the facilities of all stakeholders. At the same time standards must be open enough to provide for a competitive marketplace and to allow for future innovation and evolution.

The design of e-seals and maturity of the technologies will continue to improve along with significant gains in performance. For this reason, it is critical to allow for this growth in performance in any application to the industry. Any standards that are developed must allow for upgrades in products over time. In addition, it is important for the industry to provide feedback and guidance to the vendors in order to maximize these improvements. All of the vendors involved in this effort are very interested in improving their products to better support industry needs. However, they require direct interaction from users to guide this process.

A final important conclusion regards the future development of electronic seals and related technologies. While e-seal technology was, in general, found to be mature and immediately applicable to container security, it was recognized that these devices alone would have only a limited impact in improving container security. Future systems will certainly solve many of the problems by focusing on the entire container rather than just sealing the doors.

2.0 INTRODUCTION

2.1 Purpose

The Cargo Handling Cooperative Program (CHCP) Container Seal Technology and Process Program is a testing and evaluation effort intended to develop the technical knowledge and experience regarding electronic container seals (e-seals) that is necessary to support on-going and proposed container security initiatives. Previously under this program the CHCP reviewed the availability of e-seals in the marketplace and made an initial evaluation of product functionality. In addition, the CHCP conducted an industry survey to discuss opinions/concerns about e-seals and container security. The results of this effort detailed industry issues, concerns, and challenges with e-seal implementation.

Under the current phase of the program, the results of which are reported in this document, the CHCP tested and evaluated the operation of selected radio frequency (RF) based e-seals. Electronic seals were evaluated from four manufacturers that are currently supplying electronic container seals to the marketplace.

In addition, the CHCP also evaluated one non-RF e-seal solution, the Navalink from CGM. This product has similar functionality, in terms of security and data, as the other tested e-seals but uses a contact memory linkage to transmit data instead of an RF link.

As part of the current effort, the CHCP first tested each of the evaluated e-seals in a laboratory to determine baseline performance both in free space and mounted on a container. Each seal was then evaluated for readability in three different field environments: on a container being moved through a container terminal gate, on a container moving along an open road, and on a simulated container on a double-stack rail car. Seals were tested to not only determine how the technologies perform in these real-world environments but also to evaluate the various trade-offs that exist with e-seal design and the potential impact of those trade-offs on functionality, reliability, utility, and cost.

The goal of this effort was not to select a “winner” (i.e., a seal which would become an industry standard) but rather to develop the technical baseline that will help government and industry stake-holders select appropriate seal design parameters and functionality based on security, operational, and economic requirements. As such, testing and evaluation was completed not to provide a head-to-head comparison of e-seals from different manufacturers but instead to identify the major design trade-offs that exist between the various seals, to identify how these design trade-offs might effect the deployment and performance of the seals and seal reading systems.

2.2 Report Structure

The introduction describes the purpose of the effort, the report structure, and provides references. Section 2 summarizes all the test results and findings of the e-seal performance evaluation effort. Section 3 provides further analysis of the results and derives conclusions as they relate to the container and e-seal operational requirements. Five appendices follow the list of acronyms. Appendix A provides detailed results and observations of laboratory testing. Appendix B provides detailed results and observations of in-gate testing. Appendix C provides detailed results and observations of on-rail testing, Appendix D provides detailed results and observations of on-road testing, and Appendix E provides the simulation results.

2.3 References

1. CHCP- Agile Port and Terminal Systems Technologies: Report on Industry Requirements for Electronic Container Seals, August 23, 2002.
2. CHCP- Agile Port and Terminal Systems Technologies: Report on Electronic Container Seal Technologies, August 23, 2002.
3. CHCP- Agile Port and Terminal Systems Technologies: Test Plan, February, 2003.

3.0 CONCLUSIONS/RECOMMENDATIONS

From the results of the testing and evaluation effort the CHCP was able to reach a number of conclusions regarding the state of e-seal technologies, the trade-offs involved in e-seal design, the need for and challenges of developing standards for e-seal deployment, and future work that should be pursued in e-seal development:

Overall State of Technology: The most basic issue that was addressed during the electronic seal evaluation effort was an overall assessment of the current maturity of e-seal technologies and of the readiness for wide-scale deployment. The results of all the testing and evaluation efforts indicate that, as an overall product, e-seals are relatively mature and are based on technologies that have been proven in many other applications.

There are no identified problems with the underlying technologies that would prevent immediate wide-scale deployment within the container industry. Under favorable conditions (acceptable reader-seal range, good line of sight, optimized set-up and communications) all tested e-seals were found to be functional in the gate environment, the most basic e-seal application.

For other types of reader installation (on-road or on-rail) the results were found to be more variable. Because of differences in the design of products from the various vendors, different solutions produced widely different performances in these environments. The specific design trade-offs involved are discussed later in this summary.

In addition, the evaluation of e-seals showed that while the overall product is relatively mature, there are wide variations in the maturity of devices available from individual manufacturers. Some of the available e-seals exhibited more advanced levels of design and experience and product support from the vendors. Only a few e-seals had significant previous deployment in actual operations and those vendors have developed valuable experience in problem solving and optimization of reader set-up. These factors had a major impact on the ability to achieve good system performance in the field testing.

Evolutionary Products: During the six month testing effort, an attempt was made to use to most up-to-date versions of devices from each manufacturer. However, this is an industry that is very dynamic with new and updated products constantly being introduced. During the test period every vendor of RF e-seals introduced either improved seals or updated reader software. The CHCP included these updates whenever possible in order to evaluate the latest e-seal design. Many of these updated products resulted in improved e-seal performance.

The design of e-seals and maturity of the technologies will continue to improve along with significant gains in performance. For this reason, it is critical to allow for this growth in performance in any application to the industry. Any standards that are developed must allow for upgrades in products over time.

In addition, it is important for the industry to provide feedback and guidance to the vendors in order to maximize these improvements. All of the vendors involved in this effort are very interested in improving their products to better support industry needs. However, they require direct interaction from users to guide this process.

Design Parameters and Trade-Offs: A key finding of the evaluation effort is that although all RF based e-seals operate using the same basic underlying technology, there are widely divergent solutions in terms of how the technology is applied. E-seals from different manufacturers employ not only different communication frequencies but also widely different communication protocols, reader infrastructure architectures, and tamper detection methods. Although there are a limited number of devices available in the marketplace, the devices tested showed a wide range of design features.

This variance in designs was extremely beneficial to this effort because it allowed the CHCP an opportunity to explore trade-offs in the design of the electronic seals. As part of the testing, evaluators compared the design features of each e-seal with the measured and observed performance. From these evaluations they were able to reach conclusions regarding the impact of various design decisions on reliability, utility, and potential cost. In this evaluation, potential cost was assumed to be directly related to the complexity of the e-seals and reader infrastructure, the reusability of devices, and the availability of components. The actual cost of deployment may or may not reflect the potential costs. It was not possible to compare actual costs for a variety of reasons. First, the actual cost of these products is highly dependent on the volume of units manufactured. Second, it was not possible to verify the cost projections provided by individual manufacturers. Therefore, it was decided to simply compare the potential cost based on the complexity of the seals and reading devices.

In addition to these particular design parameters described below, there was also a wide range in the sophistication of the tested e-seals. The Savi e-seal for example is a fairly sophisticated device. Electronics have been designed to maximize performance. The result of this is a system that was found to have extremely good range and reading reliability. Conversely, other manufactures have developed less advanced solutions that have somewhat reduced performance but which they feel could be produced at a lower overall cost.

The major areas of design in which the trade-offs occurred are as follows:

- Frequency – One of the most discussed design decisions involves the communication frequency of the electronic seals. The four evaluated seals communicated to readers at three different frequency bands: the Savi and e-Logicity seals operate at 433.92 MHz, the Hi-G-Tek seal at 916.5 MHz, and the All-Set seal at 2.44 GHz.

  There are two major concerns over frequency choice that were investigated in this evaluation. The first is the ability of the signal from seal to reader to propagate around objects in the reading environment, allowing reliable reads in complex environments. The second is the potential for interference from other RF devices in the environment. The results from all of the testing and evaluation indicated that there was no *major* impact in selecting any one frequency over another in regards to either of these factors. All of the frequencies, in and of them selves, provided adequate reading performance. None of the frequencies exhibited a significantly improved ability to allow signals to propagate around interfering objects. Neither were any significant interference problems found during the testing. The subject of interference is further discussed later in these conclusions. The only potential variation found in performance due to frequency was in the simulated on-rail condition. In this case the testing and evaluation indicated that there might be some improvement in readability at higher frequencies.

  The choice of frequency reflects numerous factors including not only technical considerations but also international availability of frequencies and economic considerations. Only the 2.44 GHz frequency band is available worldwide and in that case the allowable power levels vary by country. The ultimate selection of frequency will likely depend on these other factors rather than performance considerations.

- Communication Protocol – Tested e-seals also employed various different communication protocols to transmit data from e-seal to reader. There were three basic methods that were used by different vendors. Products from e-Logicity use a timed transmission from seal to reader while the systems from AllSet and Hi-G-Tek employ a seal. That is queried from a reader. Savi uses a unique query type system that employs a “signpost” to query seals and a separate reader to receive the transmitted seal signal.

  In a timed transmission, the e-seal is set to transmit data at a specified interval. This transmission occurs continuously and requires no communication from reader to seal initiate the transfer of data. The seal and reader electronics are relatively simple for this type of seal because the reader is not required to transmit and the seal in not required to receive. Therefore, the complexity and potential cost of equipment for this seal type is relatively low. However, the timed seal transmission puts a constant drain on the seal battery. This can present problems with seal life and readability. If the seal is set to transmit at very short time intervals the seal life is significantly reduced. If the seal is times to transmit at greater intervals there can be readability problems, especially in conditions where the seal is moving past the reader at speed.

In a queried transmission, the reader periodically transmits across the read zone. If a seal is present, it is then activated and transmits data back to the reader. The seal and reader design involved in this type of seal are somewhat more complex than with a timed seal, potentially increasing cost. Both seal and reader must transmit and receive and the seal must be designed to detect a proper reader query and respond. The e-seal is required to transmit only when queried, extending the battery life and avoiding readability issues involved with the transmission rate.

The Savi SmartSeal differs somewhat from the other query-type systems. Savi uses fixed "sign posts" to transmit and query the e-seal. The e-seal then is activated and transmits back to a separate reader. The advantages of this system are that the reader design remains less complex and the number and orientation of signposts and readers can be optimized.

- Reader Infrastructure – The evaluation and testing effort revealed a major design trade-off between the e-seals produced by various manufacturers. This trade-off involved the range of the e-seals/readers versus the cost and number of readers required to cover a typical gate area.

  In a typical reader set-up at a terminal gate there is a relatively large area that containers pass through that must be covered be the reader infrastructure. The designs of the various e-seal products have a major impact on the range that the system can be effective and on the ability of the devices to communicate in complex environments. These differences in effective reader range have a major impact on the infrastructure required to cover a large reading area such as a terminal gate.

  For a more sophisticated type device, such as the Savi SmartSeal, which has a large effective range, a single reader (and signpost in this case) can effectively cover the entire area. For less complex and less sophisticated seals, it will most likely be necessary to install multiple readers to obtain reliable reads across the entire area. This is an important trade-off that will determine the total infrastructure cost of an installation. Less complex systems will have a lower potential cost per reader, however multiple readers will likely be required. More sophisticated devices could have greater potential cost per reader but only a single reader might be required.

This particular trade-off is also affected by the information requirements on the user. In particular, if the user wishes to discriminate between lanes in the gate (i.e. match e-seal data to a particular lane of travel) then, for most systems, an individual reader is required for each lane. In this case, where the required read range is small, then the less complex systems may be more appropriate. However, Savi's hybrid system has the ability to discriminate between lanes with only a single reader. In this case, a signpost can be placed in each lane. The e-seal detects the identity of the querying signpost and transmits that data to the reader.

- Seal Location: Various different seal locations and attachment methods were evaluated as part of this effort. Three of the manufacturers mount their seals near the center of the container doors close to the locking bars. The seals are affixed to the container and seal the doors either with a bolt through the hasp on the door handle or with a cable around the two vertical keeper bars. Tampering is detected if the bolt is removed or the cable is cut.

  The AllSet seal mounts on the upper right of the container door between the frame of the container and the door itself. The seal is either permanently or affixed or help in place by a magnet. Tampering is detected using a pressure sensor on the door that is able to detect when the door is opened or closed.

  There a few trade-offs that were observed in the selected seal location. CHCP evaluators felt, in general, that the location of the AllSet seal on the doorframe could provide improved tamper detection over the other solutions. Many stakeholders have questioned the security of e-seals that are attached to the door locking mechanism, particularly bolt seals. It has been shown in studies of mechanical seals that it is possible to bypass these types of solutions and open the doors without detection. The location and detection method on the AllSet seal provides positive detection of door opening.

  However, the location of the e-seal on the doorframe also presents potential logistical problems. The door of the container must be open to install the seal. In cases where seals might be installed in-transit, security could be compromised by having to open the doors.

  The testing did not show any particular performance advantage, in terms of readability, for either seal location. Both locations showed similar performance in all three field tests.

<u>Reading Limitations</u>: The testing of these devices showed that although all of the devices worked in good reading conditions, there were a number of

environmental factors that had a significant impact on readability. These environmental factors had widely different effects on each of the seals, depending on the design parameters of each. The more sophisticated systems provided good performance in more demanding situations, however the performance of all the evaluated seals was impacted by these factors:

- Line of sight from reader to seal
- Range of reader to seal
- RF interference

These factors alone have a much grater impact on readability than any of the e-seal design parameters such as frequency or communication protocol. It is critical to optimize the factors at any installation in order to provide adequate reading performance.

<u>Building Off Other Industries</u>: An observation was developed during the evaluation that has particular relevance to future e-seal development. The technologies and communication functionality being employed in e-seals are similar to those in many other industries. Devices employing wireless communication are currently are major area of development and new breakthroughs are constantly being made. These other industries also have the potential for much larger product volumes that the electronic seal industry will ever have.

In order to rapidly improve e-seal performance and reduce device costs, the container industry should take maximum advantage of the technology and product developments occurring in these other industries.

A major factor in the cost of electronic seals is the design and production of chipsets for the devices. Customized production required large volumes before costs can be reduced. If e-seals can be developed that employ standard chipsets that are used across industries, these reduced costs can be taken advantage off immediately.

<u>Potential for interference problems</u>: During the survey industry, a concern was put forward by a number of participants regarding interference with the e-seals from other RF devices. This was a particular concern for the 2.4 GHz frequency band, where a number of other devices, such as cordless telephones and wireless computer networks operate. It was felt that with the rapid proliferation of these types of devices, that there could be readability problems at that frequency.

The testing in the terminal environment indicated that interference is not a major concern *at the present time*. The terminal at which the gate testing was performed had several wireless devices operating at 2.4GHz in near proximity to the gate. The devices still managed to operate successfully. This is most likely due to the advanced electronics used in the 2.4 GHz device, the All-Set allSeal. This device employs spread spectrum technology, in which multiple frequencies within the approved band are used to improve communications.

Despite the successful performance of the 2.4 GHz seal in the tested environment, it must be noted that there is still potential for future interference problems. The number and types of wireless devices operating within this frequency band is quickly expanding. It is expected that these types of devices will become pervasive across most areas in the near future.

While the completed testing shows no evidence that interference from these types of devices will occur in the future, neither does it rule out the possibility. It will be important to consider this possibility in selecting e-seal frequencies for future use.

<u>On-Rail Performance</u>: A major concern raised by the industry regarding e-seal application is the ability to read electronic seals when the containers are being transported by rail on a double-stack container car. Specifically, there was concern that in the case where two 20-foot containers were placed on the bottom row of the container car with the container doors facing each other, it would be extremely difficult to get reliable reads from e-seals. In this situation, there is a very small distance between the doors and the line of sight from the reader to the e-seal would be very limited.

The testing conducted under this effort indicates that the concern over readability in the on-rail case is probably over-stated. It was found that the electronic seals allow for significant signal to escape from the gap between containers. While there was limited direct line of sight, the cavity between the containers, in effect, directed the signal out the sides towards the readers. This effect was found to be most prevalent at greater communication frequencies.

<u>Electronic Seal Standards:</u> The results of the testing and evaluation clearly emphasize the need for standards in the area of electronic seals design and operations. There are a large number of potential e-seal design and operational parameters that can be selected. To achieve any sort of interoperability of devices used by the various carriers and shippers in the industry, it is critical to develop a set of standards that will allow communication between seals and readers from various manufacturers. However, the wide variety of design decisions regarding show how difficult it will be to reach an agreement these standards.

Beyond simply specifying a frequency at which seals must operate, it will be absolutely necessary to establish standards for data, communication protocols, seal placement, and reader placement. These standards will have to allow seals from a variety of manufacturers to be reliably interrogated by readers systems from all other manufacturers at the facilities of all stakeholders. At the same time standards must be open enough to provide for a competitive marketplace and to allow for future innovation and evolution.

Alternative solutions to RF E-Seals: Although the main goal of this effort was to test the maturity and applicability of RF-based electronic seal technologies, the CHCP felt it was also important to make a comparison to other competitive devices that could provide the same functionality as RF e-seals. As such, the evaluation effort included an investigation of a contact memory e-seal. This seal functions in the same manner as the RF e-seals in providing security and in the collection and storage of shipment data. The only difference in operation is the method by which data is transmitted from the seal to the information system. RF e-seals are remotely read using a reader mounted some distance away from the container. Reads can be made while the container is still or moving without human intervention. Contact memory e-seals require a worker to physically touch the seal with a reading device (typically some sort of wand) to collect data. The major advantages of contact seals are significantly lower costs for both seal and reader, reduced infrastructure, and greater reliability in reads. The trade-off is significantly increased labor costs.

The CHCP found contact memory e-seals to be a viable alternative to RF seals. Depending on the economic and labor situation, contact memory seals could provide a more attractive security solution for some stakeholders. The evaluation of the device showed that in terms of data functionality and security provided there is no difference between the contact memory and RF solutions. In addition, some industry members felt that the requirement for human intervention was actually positive. “Manual” interrogation of the seal resulted in a visual verification of the integrity of both the seal and the container.

It should be noted that there could be other alternative e-seal products developed that would provide choices other than RF solutions. It is important that these options be considered when developing security systems. In many cases they could provide adequate functionality at significantly reduced cost.

Seal Solutions Versus Container Solutions: A final important conclusion regards the future development of electronic seals and related technologies. While e-seal technology was, in general, found to be mature and immediately applicable to container security, it was recognized that these devices alone would have only a limited impact in improving container security. Most stakeholders have observed that anyone who has sufficient motivation can bypass any of these existing electronic seals by accessing the container through the walls or ceiling. In addition, these current e-seals only have the ability to report tampering when queried from a reader. They do not provide any real-time indication of a security breach.

Future systems will certainly solve many of the problems by focusing on the entire container rather than just sealing the doors. This progression has already begun in the evaluated seals. For instance, the AllSet seal is manufactured with a data input port integrated with the seal. The port can be connected to sensors within the container to better detect tampering. Other vendors are beginning to experiment with integrating e-seals with on truck or on-chassis communication devices to provide real-time monitoring of the seals. These and other developments will ultimately provide significant improvements in both security and industry efficiency.

4.0 SUMMARY OF THE TEST RESULTS

This section provides a summary of the e-seal performance results obtained during the e-seal laboratory evaluation, during terminal testing, as well as the results obtained from computer simulation of e-seals in specific environments. Detailed laboratory test measurements are presented in Appendix A, in-gate test results are presented in Appendix B, on-rail test results are presented in Appendix C, on-road in Appendix D, and simulation results are presented in Appendix E.

It is important to note that the objective of this effort was to collect measurements that will be used to analyze a particular seal characteristic such as frequency, communication protocol, etc. Hence, this section does not compare and contrast specific vendor features and results.

4.1 Selected Seals

The seals that were selected for our evaluation are listed in Table I[1]. Note that all selected seals except CGM's are RF seals. CGM's is a Contact Memory seal, so a number of tests designed to test the performance of RF seals were not applicable to the CGM seal. Of the RF seals, two operate at the 433.92MHz frequency, one at the 916MHz frequency and one at the 2.44GHz frequency.

Seal	Vendor	Data Transmission	RF Freq.
eSeal	e-Logicity	Active RF	433.92 MHz
DataSeal	Hi-G-Tek	Active RF	916.5 MHz
SmartSeal	Savi	Active RF	123 kHz & 433.92 MHz
AllSeal	All Set Tracking	Active RF	2.44 GHz
MacSema + Navalink	CGM	Contact Memory	n/a

Table 1. Selected Seals

4.2 Laboratory Test Results

The objective of the laboratory testing and evaluation was to gain understanding of e-seal key features and their operation; to evaluate potential technical challenges and different methods of e-seal use in the terminal environment; and to establish baseline parameters of the selected e-seals in a controlled environment.

[1] Seals were selected based on the Phase I e-seal study and e-seal availability for Phase II testing.

In addition to e-seal functional evaluation, the laboratory effort also included:

- Frequency measurements of seals and readers
- Establishment of Seal Signal-strength Maps
- Establishment of Reader-to-seal strength maps
- Establishment of Reader-to-seal range maps
- Establishment of Seal-to-reader range maps

All the findings from the laboratory effort are presented in Appendix A.

E-seal Feature Summary

Table 2, below summarizes key characteristics of evaluated e-seals.

Seal Name	eSeal	DataSeal	ST-605-SL1 SmartSeal	AllSeal	Navalock+ MacSema
Vendor	e-Logicity	Hi-G-Tek;	Savi	All Set Tracking	CGM
RF Frequency	433.92MHz	916MHz[2]	433.92MHz[3] &123KHz[4]	2.44GHz	N/a
Container Protection	Bolt	Indicative	Bolt	Indicative	Loop or locking bar
Re-useable?	No	Yes	Yes (except bolt)	Yes	No[5]
Input (forward) methods and modulation	RS232	RF, 125 kHz or 916 MHz. FSK w/ 40 kHz dev.	132 kHz RF (on/off) (from "Signpost")	2.44GHz DSSS, ASK	contact
Output (reverse) methods and modulation	Active, always-on RF, 315 or 433 MHz. FSK at 8kHz mod. LEDs: OK/not OK	RF, 125 kHz or 916 MHz. FSK w/ 40kHz dev.	433 MHz, FSK (to Rdr), as "beacon" or under interrogation	2.44GHz DSSS, ASK query	contact
Range	13.3dB at 21m	30–80m (916 MHz). 0.6m (125 kHz)	8m (132 kHz) 100-300m (433 MHz)	30m tuned to 80m	N/a
Communication Protocol	Broadcast	Query	Proprietary: Query; Broadcast	Bluetooth lite	N/a
Tamper self-detection means	Change in resistance on cutting of bolt. Resistivity differs among bolts.	Impedance change in 48 parallel wires. Random connections.	Change in magnetic flux through steel bolt	Door gasket pressure sensor	Visual inspection
Transmitted Data	Seal ID[6].	All[7]	All	All sensors[8]	All

[2] For non-U.S. markets, DataSeal systems available in 315 MHz, 318 MHz, and 433.92 MHz versions.
[3] For non-US markets, eSeal available in 315 MHz version
[4] SmartSeal uses low frequency for short-range, one-way communication from "Signpost" to seal, and UHF for long-range, two-way communications between seal and "Reader."
[5] If bonded to the container rather than to the mechanical seal system, the memory component is re-useable

Seal Name	eSeal	DataSeal	ST-605-SL1 SmartSeal	AllSeal	Navalock+ MacSema
Event data recorded/sent	Tamper status always transmitted.	Time/date of: open, close, tamper. Reader ID	Time/date of: open, close, tamper. Tamper status sent by beacon.	Time/date of open, close, tamper, reader ID	
Data Space	[Some for container ID]	2kB	32kB (8kB typ. used)	5 kB	
Security Mechanism	No	Encryption: 3DES[9]	e-seal none Passwords for reader authentication	Challenge / response authentication	
Battery life (advertised)	3 months	4+ yrs at 50 reads/day	5 yrs	10yrs	

Table 2. Summary of Evaluated E-seals

Frequency Measurement

The objective of the frequency measurement test was to validate frequencies and time intervals reported for a particular seal. Most of the measurements were consistent with vendor reported data, with minor variations in measured packet durations and transmit intervals.

Signal-strength Maps

The Signal-strength Map measurements were conducted both with and without the container door. Without a container door, the measured field pattern is attributable primarily to the e-seal's antenna and its construction. With a container door present, the measured field pattern includes the effects of reflections of RF waves. The purpose of measurements was to provide data to help build and validate numerical models of the e-seal's RF characteristics (radiation patterns). The e-seal numerical models were then to be used in the computer simulation of various scenarios. The simulation scenarios and results are included in Appendix E.

The obtained signal-strength maps for e-Logicity and Savi e-seals were consistent with the vendor's expectations. The Hi-G-Tek measurements were conducted without the seal wire, and that may have affected the radiation pattern. The All Set seal signal-strength map was also different from what the vendor reported observing in their internal tests. With the door present, our

[6] The eSeal version tested does not store Container ID data. Seal ID and container ID are expected to be associated in the users database
[7] AllSet seals transmit their Seal ID. Additional Data capabilities are: (1) Container ID, (2) Reader ID and data, (3) Time stamp, (4) Manifest, (5) Encryption
[8] Integratable with sensors
[9] for the forward communications

measurements detected a weak signal region directly rearward from the door while All Set's did not. This weak signal may derive from the interference patterns generated by the door.

Range Maps

We attempted to collect measurements for range maps. However, all of the seals had a range of at least 30 meters, and our roof-top laboratory setting was too confined to reliably measure such ranges without concern about reflections from surrounding structures. As a result it was decided not to attempt to obtain range maps.

4.3 Terminal In-Gate Test Results

Test Objective

The objective of the in-gate testing was to evaluate performance of e-seals in the in-gate environment. The gate area at the terminal is a complex environment with many structures. Most of the time very heavy traffic was present. Check-in and check-out operations required about 6-10 minutes, and each lane queue was typically 3 to 4 trucks deep. It was not clear how well e-seals would perform in this kind of environment, whether the gate structures and vehicles would be obstacles, and how well different frequencies would perform in various situations.

The key objective of the in-gate tests was to gain understanding about e-seal readability in the in-gate environment, including any insights regarding e-seal frequency, placement of e-seals on containers, placement of reader antennas, etc.

Environment

The in-gate tests were performed at the Port Authority of New York and New Jersey Howland Hook Marine Terminal in Staten Island, NY (Figure 1).

Figure 1. Howland Hook Terminal Gate

Figure 2 details the geometry of the in-gate area. There are total of 20 lanes, 12 of which are in-bound (Lanes E-S), 4 are reversible (Lanes A-D), and four are out-bound lanes in the uncovered area. The blue boxes represent the booths/clerk houses; the tops of their roofs are typically nine (9) feet above the road surface. The yellow shapes between Lanes C and F represent piping and blowers suspended from the ceiling. Yellow triangles mark the beginning of the island.

Tests were conducted with the reader antenna placed both inside and outside of the gate structure. Inside of the gate, for the e-Logicity and Hi-G-Tek readers, a vertically-oriented, quarter-wave whip dipole antenna with a circular ground plane was positioned above the E/F island, as shown by the red dot in Figure 3. The antenna was about 12 feet above the ground. The All Set reader, with its built-in directional patch antenna was 10 feet above the ground. The Savi system is designed to operate outside of the gate environment , therefore the Savi reader antenna was not tested inside the gate structure.

Figure 2 shows the placement of reader antennae outside of the gate. The Savi antenna/reader was placed to the right of the in-gate area. The All Set reader antenna was placed in three different locations outside the gate structure (Locations A1, A2 and F1). At Locations A1 and A2, its height was about 23 feet. In Location F1, its height was at about 28 feet. The Hi-G-Tek measurements were taken with the reader antenna positioned at A2. Because of limited range, the e-Logicity reader was not tested with the antenna outside of the gate structure.

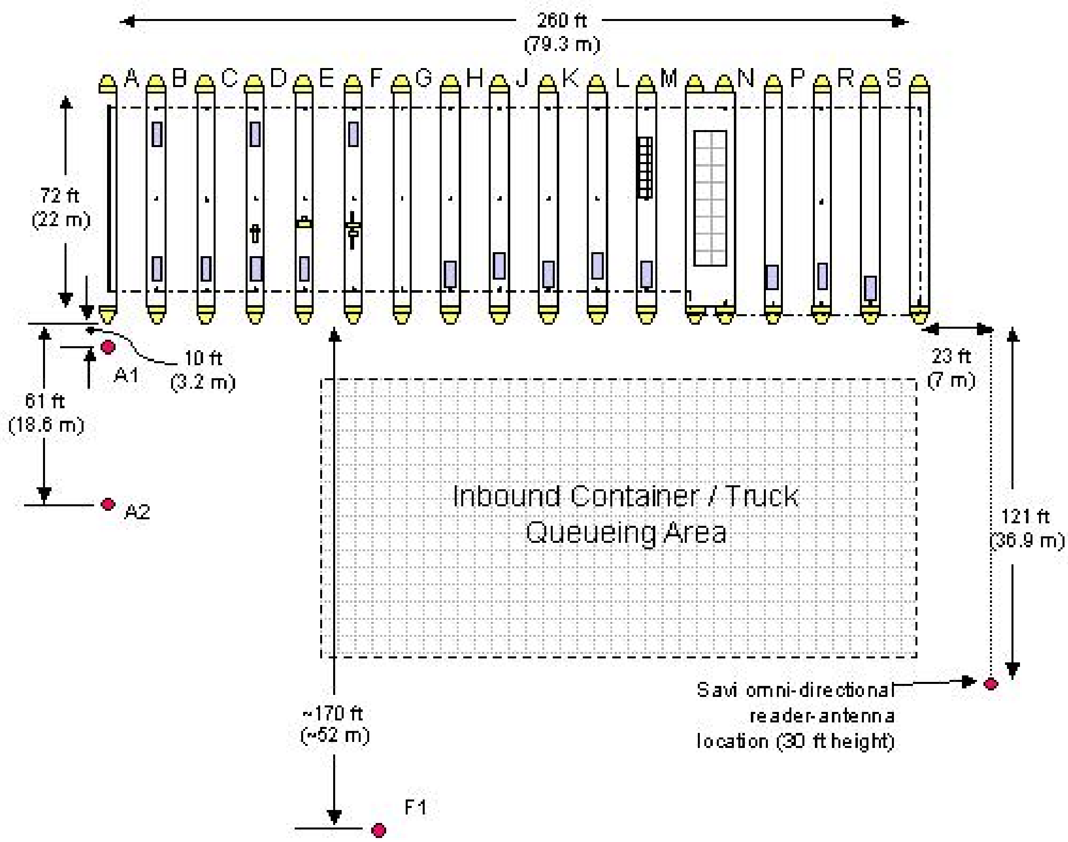
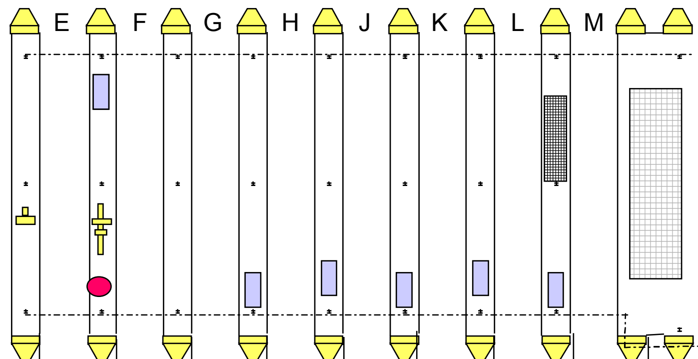


Figure 2. Gate Geometry and Antenna Placement Locations

<u>Summary of The Gate Test Results</u>

The testing was performed during terminal operational hours. Each seal, except the All Set seal, was typically placed on a functional container as it waited in the gate queue. The All Set seal was mounted in the hinge seam of an empty ISO container, and driven through different lanes. We attempted to read each seal as the container moved into the gatehouse. Since we were using functional containers during normal gate operations, the containers stopped at various locations. There was also continuous container traffic in the other lanes.

The first set of tests was performed with the reader antenna inside of the gate, between lanes E and F. Figure 3 provides a summary of those tests in a matrix format. The detailed results and observations from the gate testing are documented in Appendix B. The matrix summarizes quality of reads in each lane, for each frequency. “Very Good” indicates that all the attempted reads in that lane[10] were successful; "Good" indicates that some reads were missed; "Fair" indicates that between 50%-80% of the reads were successful; and "Poor" means that less then 50% of the reads were successful, and more typically there were no reads. Blank fields indicate that no data was available for that lane and for that frequency. The matrix summarizes results for in-bound traffic in lanes F-M.



433MHz (E-Logicity)				Good		Poor	Good	Very Good
916MHz (Hi-G-Tek)					Good	Fair	Good	Poor
2.44GHz (All Set)		Very Good	Very Good	Very Good	Very Good	Poor	Poor	Very Good

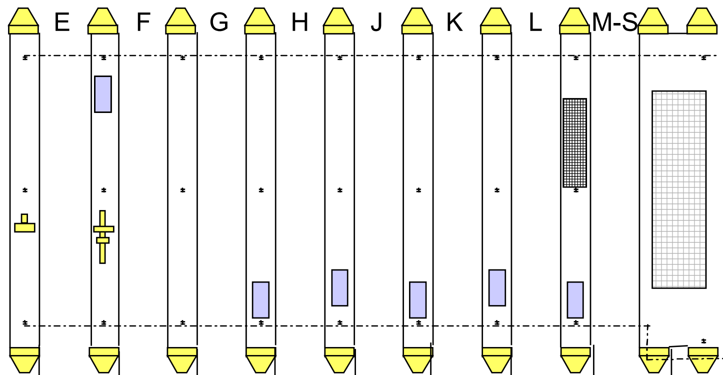
Figure 3. Summary of the Gate Test Results – Reader Antenna inside of the Gate (between E,F)

From Figure 3 one can see that no seal performed consistently well across all the lanes. The e-Logicity seal had very good reads in lane M, the farthest lane from the reader antenna, and poor (or no) reads in lane K. Hi-G-Tek readability was alternating between good and fair/poor. Note that during in-gate measurements, changes in the Hi-G-Tek reader software, that were delivered during the test period, resulted in uncertainty about the output-power levels from the reader when it queried the seal. Hence, some of the no-reads we recorded may have

[10] Matrix only summarizes results for the first half of the lane, shortly after the back-end of the container pulls into the gate.

been successful if the reader output power had been higher. This could have yielded a somewhat better performance outcome. All Set had successful reads in lane M, and then no reads in the two closer lanes. However, for the All Set seal, while all the reads were successful in lanes F, G, and H, no reads were detected at the entrance of each lane. Examining more closely each of the situations in Appendix B, one can see that read failures usually seemed to be associated with the presence of another container near the sealed container and between the seal and the reader. We could not conclude that any one frequency consistently works better than any other when the reader antenna is inside of the gate structure.

Figure 4 summarizes results when the reader antenna is placed outside of the gate. Note that the results for Lanes M through S are aggregated under Lane M in the figure. The 433MHz measurements were taken using the Savi seal system, and Savi selected the placement of their reader antenna, as indicated in Figure 2. The reader successfully registered all the attempted reads, except in lane G. In the first attempt only 1 out of 4 seals at this position was read was successful. In the second attempt, 2 out of 4 reads were successful. These seals were in an unusually tight region between two closely spaced containers.



433MHz (Savi)			Fair		Very Good		Very Good	Very Good
916MHz (Hi-G-Tek)			Very Good	Very Good	Very Good		Fair	Fair
2.44GHz (All Set)		Good	Fair	Very Good		Very Good		Poor

Figure 4. Summary of the Gate Results – Reader Antenna Outside of the Gate

The 916 MHz, i.e., Hi-G-Tek, measurements were taken with the reader antenna in position A2. The reader recorded successful reads for lanes that were closest to the reader – G, H, and J. However, lanes L and M had a success rate of less then 50%. Those two lanes are more then 60 meters from the reader antenna, which is near the range limit expected by Hi-G-Tek. The All Set measurements were collected from three antenna positions: A1, A2, and F2. Two seals were tested simultaneously, at the upper- and middle-hinge locations. The matrix in Figure 4 captures the measurements obtained in A2. A1 results are not much different from A2. The F2 location was 52 meters away from gate H, likely making it too far for the All Set reader to have successful reads. With the reader in location A2, successful reads were obtained in lane H and K. The fair readability in gate G may have been caused by the e-seal being outside of the reader antenna lobe. Lanes M and beyond are past the range limit expected by All Set for the tested seals and antenna, hence the lack of reads may have been the result of inadequate signal strength in the communication channel.

The overall conclusion is that, when the reader antenna is placed outside of the gate and elevated, there are fewer obstacles in the line between the reader and the seal, hence there is a much better opportunity for successful reads. However, the results also indicate that if the antenna is placed too far from the gates, reads may fail because of inadequate signal strength from the seal or the reader. Direct comparisons among seal systems are complicated by differences in reader sensitivity and seal output-power. For example, the signals emitted by the Savi seals are about 15 dBμV higher than those from the e-Logicity seals. So, all else being equal, we would expect the Savi system to have a much longer range (~ 5 times) than the e-Logicity system.

4.4 On-Rail Test Results

Test Objective

The objective of the on-rail test was to determine e-seal readability in the on-rail environment. The test scenario addressed one of the worst-case scenarios for electronic seals on a railcar. In such a scenario, two twenty-foot containers are placed end-to-end with their doors facing each other. A forty-foot container is placed on top of them. If the containers were placed in a rail car well, the handle region of the doors may be below the sidewall of the railcar, and there would be a direct line-of-sight to the seal from only a narrow region on the sides of the car.

Environment

The simulated on-rail testing was performed at the Howland Hook (HH) Terminal[11]. The on-rail test set-up is shown in Figure 5.

Five empty containers were stacked up. These consisted of four, 20-foot containers, with doors facing inward, and a 40-foot container across the top. The seals were applied to the door of one of the upper 20-foot containers (the “Genstar” container on the left of Figure 5). This arrangement was intended to simulate a double-stack railcar configuration with a 40-foot container atop two 20-foot containers. The lower pair of containers that sat on the ground was used to elevate the sealed container above grade level, as if on a rail bed. A container sitting on a railcar platform is elevated about 4ft from the ground. In our test

[11] The Howland Hook Terminal does not have the on-rail facility. Nevertheless we had selected Howland Hook Terminal for this test, for the following reasons:

- The outlined on-rail test environment can be setup by using additional containers to serve as a railcar platform. Hence, we can achieve almost the same on-rail environment as when the railcar is in the stationary mode.
- Howland Hook management had offered full logistical support to enable this very challenging test setup.
- There was a concern that at another terminal with a rail facility, we would not be able to disrupt the on-rail operation to create the desired scenario. In the unlikely event that an on-rail facility had additional resources to commit to this test, the cost required to support those resources would have exceeded our available budget.

configuration, e-seal containers are elevated about 8.5ft from the ground, i.e. the height of the container. We mitigated the problem of the height difference by adjusting the height of the test antenna.

Figure 5. Seal Locations on Simulated Rail-Car Double-Stack

<u>Summary of The Simulated On-rail Test Results</u>

Detailed on-rail results are presented in Appendix C. Figure 6 shows the summary of "on-rail results". Green circles indicate locations where reads were successful and consistent, while red circles indicate locations where reads were non-existent or rare. Yellow circles indicate where a few intermittent reads were achieved, but no signal could be discerned above the noise using the spectrum analyzer, and the reads could not be repeated. Note that readability of each seal was tested from a distance of 6m.

It is also important to note that the e-Logicity and Hi-G-Tek seals were tested with the receiving antenna vertically polarized. In lab testing, the vertical component of signals from the e-Logicity seals was stronger than the horizontal component. Also, the Hi-G-Tek reader is designed for a vertical whip antenna. However, the on-rail tests were conducted before the computer simulations (see Sect. 4.6) that showed that vertically polarized signals did not couple well in the cavity between the containers, and thus the signals emitted from the cavity were predominantly horizontally polarized. We therefore would expect that better readings may have been obtained if a horizontally polarized reader antenna had been used. The All Set tests used the built-in patch antenna, which reportedly has similar horizontal and vertical sensitivities.

Figure 6 shows on-rail measurements for the e-Logicity, Hi-G-Tek, and All Set seals. Because of the large range, Savi results are not shown. The results show that the Savi and e-Logicity seals produce vertically polarized signals of similar magnitude in the vicinity of the gap. However, the Savi reader, with its built-in omni-directional antennae, was able to query and read the seal from a distance of at least 114 meters along the direction of the "track." In Figure 6, different seal results are shown one under the other for easier visual comparison.

The 433MHz (e-Logicity) seal was readable at a 10-foot range near the gap between the containers. At a range of 40 feet, there were intermittent reads, but no signal was detected. All other locations generated no reads. More reads may have been achieved with a horizontally polarized antenna. The situation was somewhat better when reading the 916MHz (Hi-G-Tek) seal. Of the eight measurement positions from 10 feet on the left side through 60 feet on the right side, reads were not achieved at two locations (0 feet and 30 feet). This intermittency may create communication problems at some speeds. In addition to the polarization issue discussed above, there was also uncertainty about the output power from the reader. This power level uncertainty did not affect the seal-to-reader link, but it may have limited the reader-to-seal link in some positions. It is also possible that the reader output power was unrealistically strong in these cases.

The broadest read region was achieved with the Savi seal system at 433 MHz, stretching from the 374-ft position along the "track" to the 60-ft position (no measurements were made between the 60-ft and 224-ft positions). The read zone likely extended further beyond the 60-ft position, but testing concentrated on the locations more distant from the seal rather than the nearer locations. The second largest continuous read zone was achieved with the 2.44GHz (All Set) seal system. It achieved a continuous read zone from +25 feet to –30 feet. Beyond that, on the left side, intermittent reads were achieved up to 50 feet. The simulation results, discussed in Appendix E, explains and illustrates a resonant cavity effect that should help higher-frequency e-seals perform well in this particular geometry. The fact that two seal systems using very different frequencies each performed adequately indicates the important roles that reader sensitivity, reader-antenna polarization, and seal output power, in addition to frequency, all play in determining readability in this scenario.

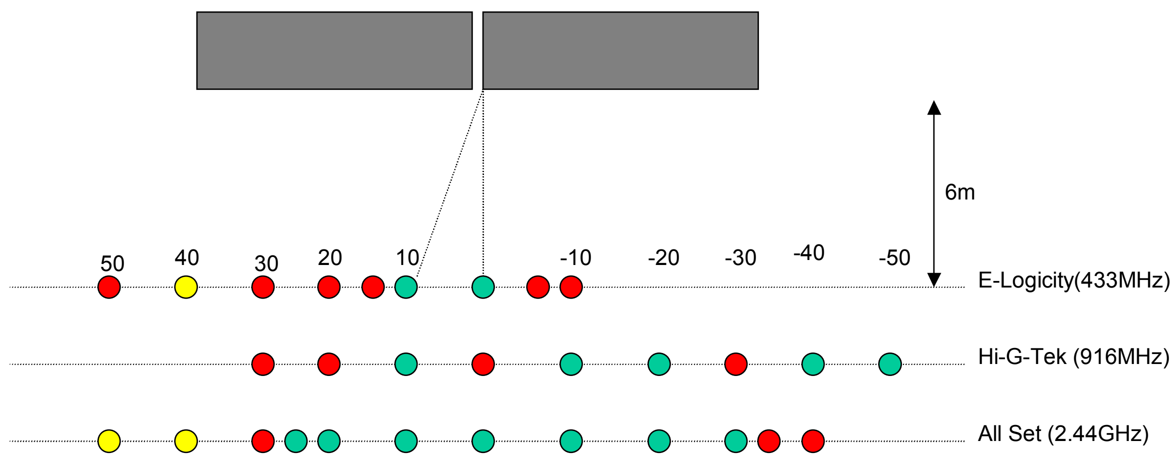


Figure 6. Reader Position Relative to Seals and Read Results

4.5 On-Road Test Results

Objective

The objective of the on-road test was to determine e-seal readability and e-seal performance in the on-road environment (specifically, when the truck simulating a moving container is moving at speeds ranging from 5 mph to 30 mph). The findings enable evaluation of the feasibility of security screening of containers without having the trucks slow down or stop. If feasible, placing e-seal readers at various check points on the road (e.g., at the approach to the terminal, border crossings, etc.) will improve efficiency of e-seal reading.

Test Set-Up

The On-Road tests were conducted on a rural road near Leesburg, Virginia. To simulate a container, we rented a commercial box truck. The seals were mounted on the roll-up door of the truck. Because of this, the placement of the All Set seal was, relative to the other seals, less representative of its typical placement on an ISO container door. Multiple passes were made in each direction, starting with speeds of about 30 mph, and slowing down until successful reads where achieved.

Summary of The Test Results

The on-road test results are presented in Appendix D. The tables below provide the summary of these results.

e-Logicity Results:

Direction of travel	Speed (mph)	Results
Stationary	0	Read range is 0 to 170ft
Right-to-left	30	One read
Left-to-right	30	No reads.

Beacon time interval =10sec (preset)

Hi-G-Tek Results:

Direction of travel	Speed (mph)	Results
Stationary	0	Inconclusive
Right-to-left	30	Multiple reads, all successful
Left-to-right	30	Multiple reads, all successful

Time interval from start of query to start of response window = 3sec (manually set)

Savi Results:

Direction of travel	Speed (mph)	Results
Right-to-left	30	No read
Right-to-left	30	One read, at about 10-15 feet before door reached antenna location
Right-to-left	30	Two reads. First about 100 feet before door reached antenna location; second about 250 feet beyond antenna. Speed at second read estimated as 25 mph.
Left-to-right	20	One read, about 50 feet before door reached antenna location
Left-to-right	30	Two reads. First about 25 feet before door reached antenna location; second about 400 feet beyond antenna, based on sustained speed of 30 mph.
Left-to-right	30	No read

Beacon interval = 10sec

All Set Test Results:

Direction of travel	Speed (mph)	Results
Right-to-left	30	Multiple reads until 225 feet
Left-to-right	30	Multiple reads to 100 feet, then intermittent as far as 500 feet (150 meters)
Right-to-left	30	Multiple reads
Left-to-right	30	Multiple reads until 70 feet (25m) from the reader

The e-seal readability when the container is on the road largely depends on the transmission protocols employed by the seal system, and especially the time interval between e-seal transmissions. In the case of e-Logicity and Savi, the beacon time interval was 10 seconds. For both seals, zero, one, or two reads were achieved at 30mph. This seal was also found to have a range of about 170 feet in this configuration. In the 10-second interval between beacons, the seal would pass through a 170-foot read zone at any speed above about 11 mph. Hence, as container speeds increase beyond 11mph, there is a decreasing chance that the seal will be in the read zone when the beacon occurs.

Although we tested with the Savi seal beaconing, Savi's system architecture would typically accommodate on-road requirements differently. Before the Savi seal reaches the read zone, it would pass by a Signpost that activates the seal's broadcast mode. Once the seal passes the on-road read zone, another Signpost deactivates the broadcast mode. Savi reports successful communications with Signposts at up to 100 mph or more.

The Hi-G-Tek reader registered multiple reads at 30mph. The query duration was 3 seconds; a longer query duration allows the seal to wake-up and listen for queries less frequently, which can save battery life. There is a trade-off between container speed, read range, and query duration.

The All Set reader showed very good reads at 30mph, and from as far as 225 feet up the road when the seal was "facing" the reader, i.e., passing it from right to left. When facing away from the reader (passing it from left to right), reads were achieved out to 70 to 100 feet up the road, depending on reader-antenna orientation. The All Set seal listens roughly twice a second for a query from the reader, which queries about once every 0.8 second. The seal responds if it detects a query.

4.6 Simulation Results

<u>Objective</u>

The purpose of the e-seal field-testing was to collect and analyze e-seal performance data in the operational environment. However, some of the e-seal characteristics (e.g., frequency) and their impact on e-seal performance can be better understood by evaluating e-seal performance in the simulated environment. The primary focus of the e-seal simulation effort was to examine e-seal performance as a function of different frequencies. The simulation effort investigated signal propagation and radiation patterns of three frequencies (433MHz, 916MHz and 2.44GHz) in the in-gate, simulated on-rail, and on-road test environments.

The objective of the in-gate simulation was to investigate signal propagation in the terminal environment and, in particular, signal propagation and radiation patterns when signals are affected by obstacles commonly found in the in-gate area, such as booths and other containers. The objective of the on-rail simulations was to examine the effectiveness of e-seals in transmitting RF signals to the reader when the e-seal is in the gap between stacked-up containers. The on-road simulation scenario was similar to the in-gate scenarios with no obstructions.

Simulation Tools

The e-seal simulation was performed using the SAIC-developed Cold-Test and Large-Signal Simulator (CTLSS) Tool that operates in a frequency domain and predicts resultant signal patterns from antenna sources around complex geometries. The use of CTLSS has been validated for RFID-type devices through past CCDoTT efforts. The Tool was hosted on a PC with a 1.4 GHz AMD Athlon processor. The operating system was Windows 2000.

Summary of The In-Gate Simulation Results

The e-seal simulation results are presented in Appendix E. The following is a brief summary of those results.

For our in-gate simulation, we constructed two sets of scenarios. The first set simulated an e-seal on the back of the container with no obstructions in the region. Each e-seal was modeled as a vertical dipole radiator offset 2cm from the “door” surface. Thus, our simulations examined frequency effects, but not the performance of actual seals. For each of the three e-seal frequencies, we performed simulation runs in space with no obstructions. We performed several simulation runs, each time maximizing the X, Y or Z dimension of the simulated space. This approach was needed because of the practical constraints on the size of the simulation region for a single run. The purpose of these runs was to obtain radiation patterns for each of the frequencies and compare them with each other (Figures E.3.2.2.a-c and E.3.2.3.a-c.)

The next set of scenarios investigated signal propagation in the environment with obstacles present. The objective was to determine how well different frequency signals traveled around objects and the potential impact from signal diffractions. We performed several simulation runs, applying the same structure setup for each e-seal frequency.

For 433MHz signals, the in-gate simulation results show that signal strength contours, when there are no obstructions in the region, are fairly uniform. Signals wrap around the edges of the container somewhat better then do signals for the other two frequencies. For 916MHz signals, radiation contours are less uniform. Finally, for 2.44GHz with a 12-cm wavelength, the contours evolving around the radiator are not uniform but have directional lobes. One reason is the reflection from the container door (backplane). The dipole is modeled as being offset from the container door by a few centimeters. This sets up a reflected “image” RF source that behaves as if it were “behind” the door. The combined radiation from the image source and the actual source can set up interference patterns, i.e., radial nodes of high and low signal strength. This directivity may create gaps where signal drops off sharply, and may result in regions with no-reads. A second contributor may be an artifact of the simulation: the dipole has all three dimensions comparable to the wavelength. This may produce unrealistic predictions in the near-field where the simulations were focused. In either case, it is important to note that these are models of an idealized radiator, not actual seals.

The patterns produced in the environment with structures are not as uniform as the patterns in the case where there are no obstructions (Figures E.3.2.4 - E.3.2.7). The pattern of RF intensity exhibits wave-like variations, which is typical of interference due to superposition with reflected signals from all the structures. Examining the patterns, one can conclude that their propagation characteristics are somewhat similar. This is consistent with a rule-of-thumb in radio communications that operating effectiveness decreases by only 5%-10% as frequency increases from 433MHz to 2.44GHz. Hence, within the simulation region, we saw no great advantages of one frequency over the others.

<u>Summary of The On-Rail Simulation Results</u>

The objective of the on-rail simulations was to examine the effectiveness of e-seals in transmitting RF signals to the reader when the e-seal is in the gap between stacked containers (Figure E.3.3.1.a). The model geometry was intended to simulate the situation where a 40' container was placed atop two 20' containers on a flat railcar, rather than in a well car.

The CTLSS simulation was conducted by placing an RF dipole antenna near the handle area in the gap between two containers. The gap is enclosed by end surfaces of two containers, with two necks of 2.25" sticking out from either side separated by a 4.5" space in the middle (see Fig. E.3.3.1.c). The container on the top and the railcar on the bottom also enclose it vertically. Therefore, the gap can act as an RF cavity with open slots on both sides.

In Figure E.3.3.3, contour plots (in a plane normal to the X axis) are shown passing through in the middle of the gap, with "lumps" vertically along the slot. This is the result of the e-seal effectively being in a microwave resonant cavity. I.e., the empty space between two containers is a microwave cavity with side slots that allow RF signals to leak to the outside. With the e-seal acting like a microwave antenna within the cavity, certain cavity modes are excited that have distinct mode patterns (the "lumps") within the cavity. Figure E.3.3.4 shows the RF pattern in a cut plane along the side of the container (normal to the Y axis); this view shows the same lumpy structures. Such a lumpy intensity distribution may also be viewed as the "diffraction" pattern of the RF waves as they emerge from the cavity slot on the sidewall. Since signal propagation is lumpy in nature outside the gap space, the overall radiation pattern around the container will not be uniformly distributed. This may create no-read regions. Note that further away from the cavity, these signal peaks blend together, and the pattern becomes more uniform.

The RF patterns for 2.44GHz show fairly uniform signal intensity distribution coming out of the slot. (Figure E.3.3.13). The RF pattern shows many very fine striations in front of the slot, which is consistent with the trend that intensity striations become finer in space as frequency increases. At 2.44 GHz, the striations are fine enough so that the overall RF distribution in space is somewhat uniform.

In summary, the on-rail simulation results show non-uniformity of signals observed alongside the container. This is due to resonance of RF signals in the gap between the containers and diffraction as the signals propagate out of this slot and the outside. Because of these physical effects, higher-frequency e-seals may offer two advantages:

- Better coupling to the gap which acts as a microwave cavity; or better excitation efficiency in the gap cavity (or waveguide).
- More uniformity of signal distribution outside the gap, which may reduce sharp spatial variation of signal strength that can cause strong location dependency in reader responses.

Hence, higher frequency e-seal may be more desirable for the on-rail environment because of its signal uniformity outside the gap.

Geometries in which there is a small gap between container doors favor the emission of signals that are polarized perpendicularly to the container door and/or of shorter wavelengths. Regardless of frequency:

- Non-uniformity may be less of a problem as the reader antenna is moved away from the rail bed. This entails a trade-off since average signal strength will drop with distance.
- If a polarized reader antenna is used, a horizontal polarization may result in higher signal levels at the reader.

However, for seals on container doors that are not heavily shielded by another container, all of these guidelines have less of a benefit. Some of them may even reduce readability; for example, moving further away will reduce the received signal strength, and using higher frequencies may reduce a signal's ability to diffract around other obstacles near the railroad or in the rail yard.

<u>Summary of The On-Road Simulation Results</u>

The on-road results also indicate that for lower frequencies (longer wavelength), contours are more uniform. At higher frequencies (shorter wavelength), signals are more directional, producing contours that are not as uniform. In the regions between the signal lobes, the signal drops off, and that may result in no-reads in those regions. As discussed above, these non-uniformities are likely due to (a) the gap we assumed between the seal and the door and/or (b) an artifact of the relatively large size of the antenna in the model.

Since radiation patterns may vary significantly among various e-seals even at the same frequency, signal uniformity becomes an important factor. Uniformity helps ensure that if signal strength is maintained above a certain level for a particular distance along the road or rail, there should be no "no-read" regions within this distance as a result of a poor signal strength.

5.0 ANALYSIS OF TEST RESULTS

In this section we will analyze obtained results in the context of the e-seal operational requirements. The e-seal operational requirements were expressed by the members of container industry and captured in the CHCP Report on Industry Requirements for Electronic Container Seals, August 23, 2002. The report encompassed industry opinions on the actual operation of e-seal technologies and the application of these technologies to the container operations. That report also brought up major issues that were identified for e-seal operational requirements and presented the various opinions expressed by industry.

<u>E-seal Operational Frequency</u>

The industry was impartial as to what frequency is selected (or even that RF is used at all), as long as the devices are reliable and functional and that a standard can be developed that is applicable worldwide.

We had tested three representative e-seal frequencies: 433MHz, 916MHz and 2.44GHz. Our findings indicate that there is no great advantage in using one frequency over the other in the gate area. All three frequencies had some problems when the seal was not in the line-of-sight with the reader. This was particularly the case in the crowded physical environment inside of the gate. The simulation results confirm that the radiation patterns are somewhat similar where there are obstacles. However, the simulation was short range, and differences among frequencies may be more noticeable over longer ranges.

In the on-rail environment, when the e-seal is embedded in the gap between two containers, simulation results indicate that better reads may be achieved at higher frequencies. In-terminal testing results, in which 433 MHz and 2.44 GHz systems performed well, suggest that reader sensitivity, reader-antenna polarization, and seal output power, in addition to frequency, all play important roles in determining readability in this scenario.

The operation frequency had no direct impact on the on-road test results.

Of the three frequencies, only 2.44GHz is approved for use worldwide. Seals that operate at 315 MHz, 433 MHz or 916 MHz will have to implement at least one more frequency to achieve worldwide applicability or another world-wide standard frequency requested and approved.

Contact seals are a relatively low-cost and reliable solution that is applicable worldwide. The only requirement is that, to be interrogated, the container must come to a complete stop. This may have an impact on the operational effectiveness at the terminal.

Communication Protocol

E-seals can communicate data in one or more of the following modes:

- Queried by other devices at certain points in the logistics chain.
- Set to transmit at a pre-selected time intervals (broadcast mode).
- Set to transmit at the occurrence of some event (such as tampering or transfer).

Our investigation focused on the first two modes. Our findings indicate that in either mode, successful reads are largely dependent on the time interval at which a seal beacons. The larger intervals (e.g. 10 seconds) are adequate in the gate area. However, on the road, larger intervals may have an adverse affect on readability. For example, if a container is moving at higher speeds (e.g. 170 foot distance traveled at speeds >11mph and 10 second interval), the reads become unreliable.

While we did not conduct any specific tests to evaluate the broadcast mode among various e-seals, one might argue that continued broadcasting may have an adverse effect on the ability to read other seals, especially in the crowded gate area. To mitigate this problem, 2.44GHz sources apply DSSS modulation, enabling them to spread the signal across a portion of the spectrum, and at the same time recover the signal from a very noisy environment.

A separate issue that also needs to be addressed is standard vs. proprietary communication protocols. Some seal vendors, such as Savi, have developed their own proprietary protocol that will set/reset broadcast mode, change time interval, etc. Other vendors, e.g. All Set, use Bluetooth™, a standard data link protocol for communication between the reader and e-seals. An e-seal requires a very simple data link protocol, and one can argue that communication protocols such as Bluetooth™ are overly complex for this application. While this may be true, the big advantage of using a standard protocol is that over time a wide use of standardized devices by this and other applications will bring the economy of scale to the container industry and enable production of much lower cost e-seals. Another benefit of using a standard protocol such as Bluetooth™ is that it already has the features that will be necessary to employ as the e-seal functionality expands.

One such example is extended sensor capabilities. The current generation of e-seals, which monitor only the integrity of container doors, will be limited in their ability to protect against other means of breaching container security. As with the barrier type devices, persons with enough motivation and resources will find ways to infiltrate a container without ever tampering with the seal. In order to be more effective at detecting container tampering, future e-seals will have to incorporate the capability to take data from sensors within the container. These sensors (light, temperature, infrared, etc.) would detect entry into the container. This data would be recorded on the seal and either immediately communicated or stored for future query. Bluetooth™ already has the functionality in place to collect and disseminate this information.

<u>Transmission Range</u>

The simplest type of e-seal, contact memory devices, will require physical contact and human interaction to read data. While at present this may appear the most effective and immediately implementable solution, in the long run the demands for container monitoring will increase, and solutions will be necessary that are more operationally effective. One of the factors that affect operational effectiveness is the range at which the seals will operate.

Our findings indicate that, for in-gate operation, the best place to locate the readers is outside of the gate. However locations that appeared to have a good line-of-sight to gate entrances (e.g., F2), proved to be infeasible because the distance exceeded the range limit of the reader. Hence, the positions of reader devices will need to be based on the e-seal system capability. An alternative to placing one reader at a location that will cover a number of lanes is to install one reader for each lane. This will mitigate the problem of possible obstructions, and the required transmission range is well within the range limits of every vendor but will increase the infrastructure costs.

For the on-rail environment, a reader will most likely be located to cover each track, to ensure that another train will not block the line-of-sight to the reader. The on-rail tests were conducted with the reader position 6 meters from the rail. In reality, this distance may be much smaller, possibly making the cavity effect even more pronounced. On the other hand, as the reader is moved further away from the track, the cavity effects are diminished.

Frequency and data rates

In general, higher frequencies allow more data transfer per unit time. The lowest frequency seals tested here performed had sufficiently fast communications, but our test scenarios did not severely limit the available communication times. For this to become an issue of concern, it appears that the application must involve one or more of the following constraints:

- high speeds
- movement through small read zones,
- a large amount of data, or
- a large number of seals vying to communicate with the reader.

Vendor-specific communication protocols will influence the time required, and the spatial pattern of transmissions from the installed seal will affect the size of the read zone. It may be useful to identify realistic scenarios, each of which imposes a severe requirement corresponding to one of the four constraints above (e.g., a yard with many containers, a high-speed choke point, etc.). Seal systems at various frequencies and protocols would be tested under each scenario to determine if the systems can address each worst-case scenario.

Lane Specificity

The testing in this project did not fully address lane-specific reading of seals, i.e., shaping a read zone through antenna patterns, attenuation, and placement to ensure that only seals from a particular lane are read. This may be applicable in rail, gate, and, to a lesser extent, on-road applications. It was not tested largely because the antenna-selection and attenuation options become dependent on the signal-strength and antenna patterns from a specific seal design, on the available antenna locations at a particular site, container speed, and some other factors. The question is one of how to place antennae to accomplish lane-specificity for a particular seal system.

It is precisely this customization and system design process that may make lane-specific reading a challenge if the container population eventually has RF e-seal transmitters from multiple vendors at various locations (door handles, door seams, chassis), even if they all use the same frequency. There may need to be a maximum output power limit on e-seal transmitters so that a reader system designed to read a weak e-seal is not overwhelmed by signals from a seal in a distant lane. Spatial uniformity of signals from e-seals may also be important.

Our lab testing showed some e-seal signal patterns (installed on the door) with variations of as much as 14 dBμV/m over as little as 60° of arc in the horizontal plane (azimuth). This is a factor of 5 in absolute volts-per-meter, which resulted in a similar factor in readability range for a given reader. This could lead to overwhelming a reader in an adjacent lane. It may also require an attenuated reader antenna to view the seal from a narrow read range of incidence angles; this in turn will shorten the read zone.

LIST OF ACRONYMS

3D – three-dimensional
CCDoTT – Center for Commercial Deployment of Transportation Technologies
CHCP – Cargo Handling Cooperative Program
CPU – Computer Processing Unit
CTLSS - Cold-Test and Large-Signal Simulator
DB - decibel
DES –Data Encryption Standard
GUI – Graphical User Interface
HH – Howland Hook (Terminal)
ED – Energy Density
EM – electro-magnetic
ID – identification
ISO – International Standards Organization
RF – radio frequency
RSSI – received signal strength indicator
SAIC – Science Applications International Corporation
SPAWAR – Space and Naval Warfare Systems Center
UHF – Ultra-high frequency

Appendix A E-SEAL LABORATORY TESTING

A.1 INTRODUCTION

The objective of the laboratory testing was to establish the baseline parameters of selected seals in a controlled environment and to evaluate potential technical challenges in seal performance. The laboratory testing included the following:

- Frequency measurements of seals and readers
- Establishment of Seal Signal-strength Maps
- Establishment of Reader-to-seal strength maps
- Establishment of Reader-to-seal range maps and
- Establishment of Seal-to-reader range maps

In addition, laboratory testing also included evaluation of baseline data capabilities.

This section presents results and observations from laboratory testing of selected e-seals.

Test Environment

Laboratory Tests were performed at the SAIC facility in McLean, Virginia, on the top deck of the parking garage (Figure A.1).

Figure A.1. Area Used for Outdoor Laboratory Tests (shown with components for On-Door tests installed)

Two means were used to minimize the possibility of reflections from surrounding surfaces. First, the seal and antenna were placed at least 8 m (26 ft, or about 11 wavelengths) from the nearest portion of the low concrete wall and metal railing that surround the parking deck. Second, to offset the effect of any reflections from the floor (specifically the reinforcing bars in the concrete), each data point was generated by placing the seal in two different locations, with the second location approximately one-half wavelength (35 cm) further away from the antenna than the first.

Selected E-seals

Table A.I. lists e-seals that were tested in the laboratory environment.

Seal	Vendor	Data Transmission	Container Protection	Re-Use	Data[(a)]	RF Freq.
eSeal	E-Logicity	Active RF	Bolt	No	--- [(b)]	433.92 MHz[(e)]
DataSeal	Hi-G-Tek	Active RF	Indicative	Yes	1,2,3,4,5[(c)]	916.5 MHz[(e)]
SmartSeal	Savi	Active RF	Bolt	Partial	1,2,3,4,5	123 kHz & 433.92 MHz[(f)]
AllSeal	All Set Tracking	Active RF	Indicative	Yes	1,2,3,4,5,6	2.44 GHz
MacSema + Navalink	CGM	Contact Memory	Loop or Locking Bar	No[(g)]	1,2,3,4,5[(d)]	n/a

Table A.I. Characteristics Of Selected Seals

(a) All seals can transmit their Seal ID. Codes for Data capabilities are: (1) Container ID, (2) Reader ID and data, (3) Time stamp, (4) Manifest, (5) Encryption, (6) Integratable with sensors
(b) The eSeal version tested does not store Container ID data. Seal ID and container ID are expected to be associated in the users database
(c) Hi-G-Tek's DataSeal uses 3DES encryption for the forward communications.
(d) CGM's Navalock+MacSema system transmits data via contact, but tamper status is indicated only visually.
(e) For non-U.S. markets, DataSeal systems available in 315 MHz, 318 MHz, and 433.92 MHz versions. eSeal available in 315 MHz version.
(f) SmartSeal uses low frequency for short-range, one-way communication from "Signpost" to seal, and UHF for long-range, two-way communications between seal and "Reader."
(g) If bonded to the container rather than to the mechanical seal system, the memory component is re-useable.

Equipment

Table A.II lists specialized equipment used for laboratory testing.

Description	Supplier	Model number
Spectrum analyzer	Advantest	3131A
Log-periodic antenna (300 – 1800 MHz)	A.H. Systems	SAS-200/510
Yagi antenna (2.4 GHz)	Cisco Systems	n/a
Receiver card	e-Logicity	n/a
Echopoint Reader w/ integrated antenna	Savi Technology	SR-640-101
Data Reader w/ separate dipole antenna	Hi-G-Tek	IG-RS-43D-916
Fixed Reader	All Set Tracking	ATR 20 116/1 R0A
w/ attached HyperGain antenna	All Set Tracking	HG2409P
Discrete Attenuators	various	various
Variable attenuator, 0-11 dB	Hewlett-Packard	8494B
Variable attenuator, 0-110 dB	Hewlett-Packard	8496B
Power supply	Hi-G-Tek	HGT-5171
Simulated container door	SAIC	Custom built
Simulated container corner	SAIC	Custom built

Table A.II Equipment used in Laboratory Testing

A.2 E-LOGICITY ESEAL

In this subsection we present results from laboratory testing of e-Logicity's eSeal. The model number tested was ES433V1. Specific Seal ID AA021634.

A.2.1 E-Logicity E-seal System Description

The e-seal system provided by e-Logicity operates nominally at 433 MHz. The e-seal begins transmitting upon activation, which occurs when the bolt is inserted into the body of the seal (see Figure A.2.1). Once the seal is bolted to the door handle hasp, it is intended to be removable from the door handle hasp only by cutting the bolt, hence, destroying the seal. If there is an attempt to cut or remove the bolt, internal circuitry detects tampering. The communication is one-way; the reader does not communicate data to the seal[12].

[12] In a different version of the seal, a handheld programmer is used to enter the container ID into the seal's memory via an RS-232 physical port. The container ID is then also transmitted by the seal.

The information transmitted by the seal includes its identification string[13] and its tamper status (which is presumed to be irreversible once tampering is detected). With the E-seal, all "chain-of-custody" data is maintained off-board in a database.

Figure A.2.1. E-Logicity E-seal with Bolt Inserted

E.J. Brooks, cooperatively with e-Logicity, provided E-seals handheld reader, and a standalone reader. The seals provided use frequency shift keying (FSK) modulation with an 8 kHz frequency modulation, and transmit data at intervals of 10-12 sec. In the seal version provided, this value is pre-set at the factory. In another version, this interval is reportedly adjustable by the user. Longer intervals conserve battery life but reduce the allowable speed at which a seal may travel through a reader zone and still be reliably read.

A.2.2 E-Logicity E-seal LabTest Results

2.2.1` Frequency Measurement of Seals and Readers
The objective of the frequency measurement test was to validate frequencies and time intervals reported for this seal.

Measurement results of representative seal frequency scan are shown in Figure A.2.2. The curve represents the maximum value detected at each frequency. The resolution bandwidth was set to 10 kHz to help resolve the peaks. In Figure A.2.2, the two peaks are separated by 22 kHz and are centered around 433.984 MHz.

Using a narrower bandwidth of 3 kHz on the analyzer, peaks were discerned at 433.975 and 433.991, a separation of 16 kHz, matching the ±8 kHz modulation reported by the vendor.

[13] in a different version of the E-seal, an identification string for the container to which it is attached is also available.)

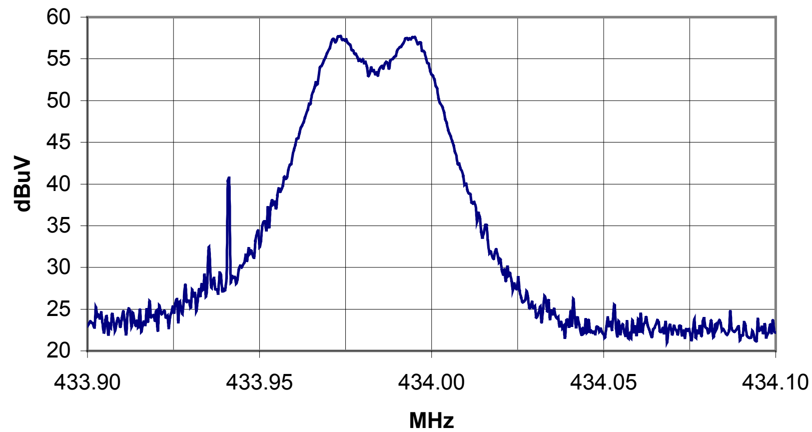


Figure A.2.2. Envelope of E-seal Transmissions Showing Peaks From FSK

E-Logicity indicated that their seals transmit data in packets, each with a 113-msec duration, on a 433 MHz carrier (nominal wavelength of 69.3 cm [27.2"]). . Measured time traces of the transmission from the E-seal, using various bandwidth settings, all show pulse durations of 110 msec, compared to the 113 msec pulse reported by the vendor.

The interval between packets, as reported by vendor, is about 10-12 sec The measured interval between pulses varies, and all measured values fell between 10 and 12 sec, consistent with what the vendor reported.

2.2.2 Seal Signal-Strength Maps Test

The purpose of this test set was twofold:

- To generate data to validate numerical modeling of the E-seal's radiation pattern.
- To measure RF signal-strength data that, together with the output of the numerical models, can be compared against seal-to-reader range measurements.

The RF field strength radiated by the E-seal in a given direction is expected to correlate with the seal-to-reader range in that direction.

Tests were conducted both with and without the container door.

Without a container door, the measured field pattern is attributable primarily to the E-seal's antenna and it's construction. These measurements provide data to help build and validate numerical models of the E-seal's RF characteristics. With a container door present, the measured field pattern includes the effects of reflections of RF waves. These reflections introduce the possibility of constructive and destructive interference, especially in the vicinity of the seal. Because the spacing between the installed E-seal and the container door is small (a couple of cm) relative to the transmission wavelength, the resulting interference effects are expected to be small. Still, the field-strength map will differ from that of the E-seal without the door.

The tests were conducted outdoors on the top deck of a parking garage (see Figure A.2.3).

Figure A.2.3. Area Used for Outdoor Laboratory Tests (shown with components for On-Door tests installed)

Two means were used to minimize the possibility of reflections from surrounding surfaces. First, the seal and antenna were placed at least 8 m (26 ft, or about 11 wavelengths) from the nearest portion of the low concrete wall and metal railing that surround the parking deck. Second, to offset the effect of any reflections from the floor (specifically the reinforcing bars in the concrete), each data point was generated by placing the seal in two different locations, with the second location approximately one-half wavelength (35 cm) further away from the antenna than the first.

All tests were conducted using a log-periodic antenna, RG-58 co-axial cable, and an Advantest R3131A spectrum analyzer. The resolution bandwidth of the analyzer was set to 100 kHz with a sweep time of 50 msec. For each data point, multiple seal transmissions were measured in the frequency domain, and the maximum signal strength was recorded. The peak signal strength typically occurred within about 10-20 kHz of 434.00 MHz.

The calibration distance for the log-periodic measuring antenna was 3 m (about 4.3 wavelengths), and both measurements were made with the antenna-to-seal distance within one-half wavelength of this calibration distance. The two voltage measurements (dBμV) were each corrected for:

- cable losses at 434 MHz,

- the antenna factor at 434 MHz, and
- the difference between the measurement distance and the calibration distance (this correction ranged in magnitude from 0.5 to 0.9 dBμV).

The two resulting field-strength values were converted to μV/m and averaged, and the average was then converted back to dBμV/m.

Open-Air Testing

Description

The E-seal was attached to a plastic mount, atop a leveled, rotary stage on a tripod. The tripod was adjusted so that the center of the E-seal was 1.52 m (5 ft) above ground level (Figure A.2.4).

Figure A.2.4. Rotary Mounting for E-seal

Two sets of measurements were made:

- one with the antenna axis in the same horizontal plane as the seal and aimed at the seal (Figure A.2.5.a), and
- one with the antenna elevated above the seal plane, with the antenna axis aimed downward at the seal at an angle of 30° (Figure A.2.5.b).

For both the at-level and elevated configurations, measurements were made with the antenna rotated into two orthogonal positions: with the antenna elements in the vertical plane (Figure A.2.5.c), and with the elements in a plane that also contains the seal (Figure A.2.5.d). For each set of measurements, the antenna was mounted on a mast and located so that its center element was nominally 3 m from the seal. Temperatures for these tests were around 4°C (40°F).

(a) Level, horizontal (b) Elevated, "vertical" (c) Vertical elements (d) Elevated, "horizontal"

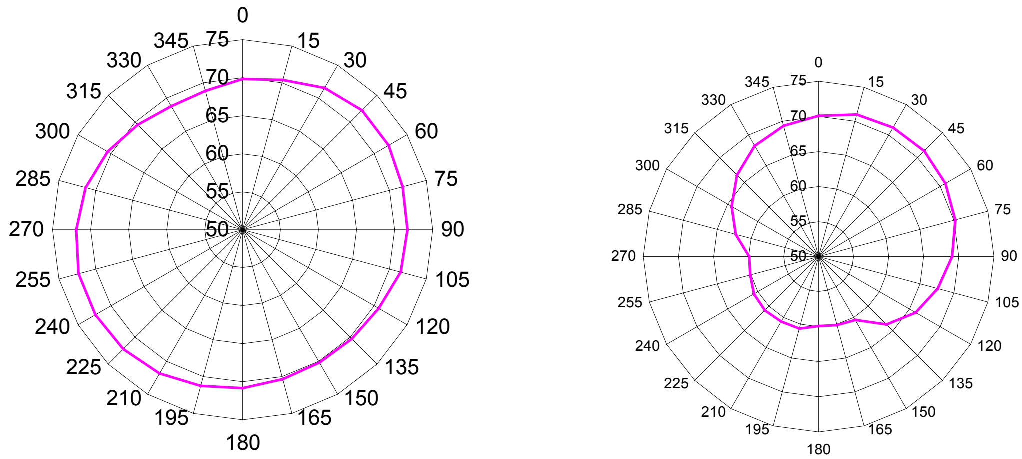
Figure A.2.5. Four Orientations of the Log-Periodic Measuring Antenna

Using the rotary stage, the seal was rotated through 360°, in 15° increments. Measurements were made with the seal tripod at the nominal 3 m distance from the antenna. The measurements were repeated with the seal tripod moved one-quarter wavelength (about 17 cm) closer to the antenna mast, and also one-quarter wavelength further from the antenna. In the results presented below, only the "closer" and "further" measurements were used to calculate the average[14].

Open-Air Test Results

Figure A.2.6 shows the corrected, averaged signal strengths measured with the elements of the measuring antenna in a vertical plane. In the plane of the seal, signal intensity varies over a ±2 dBμV/m range, with the maxima detected at azimuthal angles of about 60° and 240°. A stronger non-uniformity (±6 dBμV/m) is observed in the measurements made at a 30° inclination to the horizontal. In the 30° inclination tests, all three sets of raw data (at the nominal position and at plus and minus one-quarter wavelength in the horizontal plane) showed at least this much variation, with the maximum always occurring near the 45° position as shown in the plot. Although the minima near the 270° and 165° angles may be an artifact of taking data at only one radial distance, the raw data suggest that the signals around the 225° position are generally about 10 dBμV/m less than those around the 45° position.

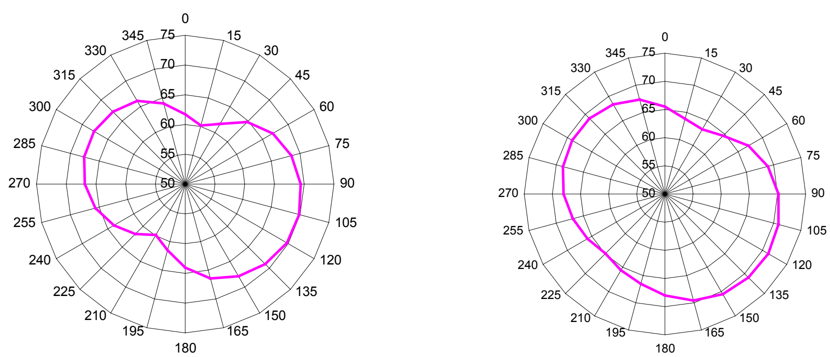
[14] If the RF field has strength fluctuations due to reflective interference, the average value is more accurately calculated from two points separated by a half wavelength than by three points each separated by a quarter wavelength.



(a) At Seal Level (b) At 30° Inclination

Figure A.2.6. Measured Signal Strength in dBμV/m, Horizontal Plane Pattern (Vertical Polarizaton)

Figure A.2.7 shows the corrected, averaged signal strengths measured with the elements of the measuring antenna normal to the vertical plane. In Figure A.2.7a, the antenna axis and elements are in the same horizontal plane as the seal, as in Figure A.2.5.a. In Figure A.2.7.b, the antenna axis is aimed at the seal from above, and the antenna elements are horizontal, as in Figure A.2.5.d.



(a) At Seal Level (b) At 30° Inclination

Figure A.2.7. Measured Signal Strength in dBμV/m, Horizontal Plane Pattern (Horizontal Polarizaton)

The variations around the seal are slightly stronger than for the vertical-plane polarizaton measurements of Figure A.2.6. At the level of the seal, they range over ±4 dBμV/m, and average about 3 dBμV/m less than the vertically polarized signals. The major axis of the lobes is also rotated about 60° relative to that of the vertical-polarization map (Figure A.2.6.a). At a 30° inclination, the same general shape is maintained and the variations still range over ±5 dBμV/m, but the lobes are more pronounced. The average signal strength is about the same as for the vertically polarized signals.

For both the at-level and inclination measurements, all three sets of raw data had the same general shape, differing only in signal amplitude. This suggests that the lobe pattern derives from the seal's construction and not from reflections from the environment.

On-Door Testing

Description
The activated (bolted) E-seal was placed into the door-handle hasp on a structure built to simulate the lower half of the rear doors of an ISO container (Figure A.2.8). The installed seal sat at an elevation of about 1.5 m (5 ft). Many ISO containers have corrugation-like recesses on the doors. However, the door handle mounting hardware cannot be placed in one of these recesses, so the E-seal will not be directly over one. Therefore, these tests simulated the placement of the E-seal only over a smooth metallic backplane. Around the E-seal's installed location, the door surface extended for 0.7 wavelengths above the seal and a minimum of one wavelength in the other three directions. With the seal oriented as in Figure A.2.8, there is a gap of about 3 cm (0.04 wavelengths) between the door surface and the back of the seal housing. Temperatures during these tests ranged from –1 to 3°C (30 to 37°F).

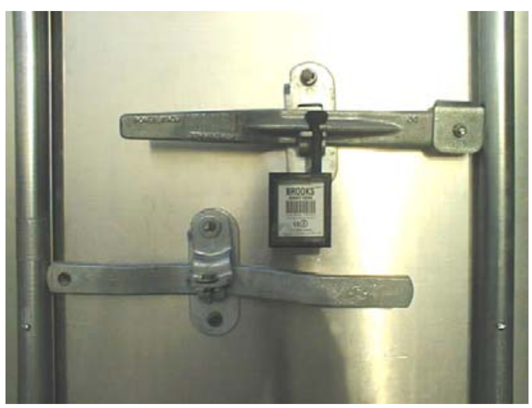


Figure A.2.8. Detail of Simulated Container Door, Handles, and Keeper Bars

The antenna was mounted on a mast, its axis in the same horizontal plane as the seal and aimed at the seal. The mast and antenna were moved into seven angular positions in a 180° arc around the seal (Figure A.2.9).

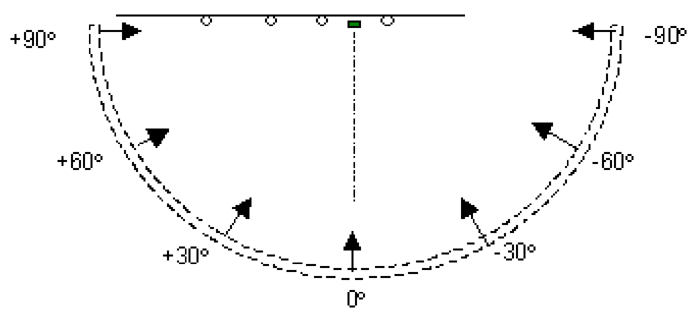


Figure A.2.9. Diagram of Nominal Antenna Positions Around Seal on Container Door

At each position around the seal, the antenna was rotated into two orthogonal positions, to measure the vertical and horizontal polarization of the RF field. Also at each angular position, measurements were made with the antenna located so that its center element was approximately 3 m from the seal, and again with the antenna moved one-half wavelength (35 cm) away from the seal, along the same angular path from the seal. After the corrections discussed earlier, these two measurements were averaged to calculate representative field strength for that position.

With the e-Logicity eseal, the bolt axis is off-center. When installed in the handle hasp, the seal is able to rotate through approximately 210° (see Figure A.2.10). Therefore, at each antenna position described above, the signal strength is measured with the E-seal in five different rotational positions, as shown in Figure A.2.10.

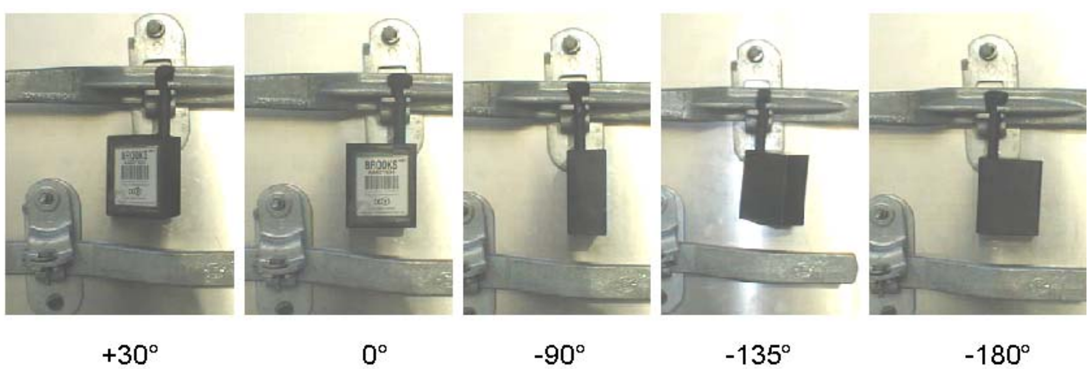


Figure A.2.10. Range of Possible Seal Orientations

On-Door Test Results

The on-door test results were measured with the monitoring antenna at the level of the seal, not at the 30°-inclination positions. The results are plotted in Figures A.2.11 and A.2.12 for each of the five seal rotational orientations discussed earlier. Figure A.2.11 shows the vertical polarization measurements.

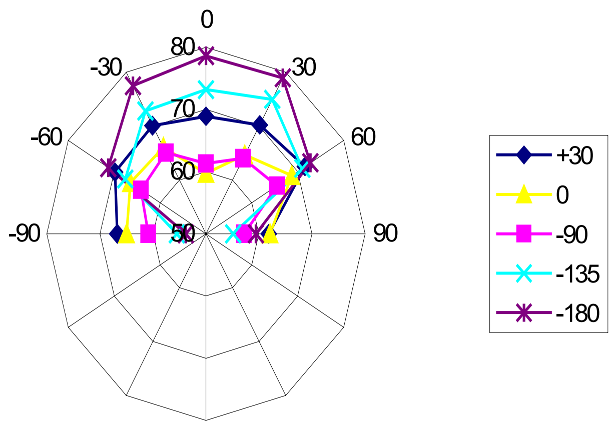


Figure A.2.11. Measured Signal Strength in dBμV/m, Vertical Polarization (legend shows seal orientations)

Several features are worth highlighting. First, for a wide spread of angles (±60°) around the centerline of the door, the strongest signals occur when the seal is rotated to -180°, i.e., "facing" the door. At this seal position, as with the -135° position, there is a strong drop-off as the viewing angle moves to the sides of the container (±90°). Of all the viewing angles tested, the broadest variation in received signal strength occurs directly behind the doors (view angle = 0°): rotating the seal from 0° to -180° increases the received signal by 19 dBμV/m (almost one order of magnitude in absolute volts-per-meter).

Second, with the seal in the +30°, 0° and -90° positions, there is a region directly behind the doors where the signals are somewhat weaker (by 3 to 6 dBμV/m) than at view angles of ±30°and ±60°. This relative weakness was detected at both monitoring-antenna positions (4.3 and 4.8 wavelengths from the seal). Full-scale on-door range testing, or possibly modeling, will determine whether this is a near-field effect or whether it occurs at longer ranges.

Finally, the weakest overall vertically-polarized signals seem to occur with the seal in the -90° position.

Figure A.2.12 shows the horizontal polarization measurements. In the open-space tests (Figure A.2.6.a) there was a ±4 dBμV/m deviation, with the weak direction being about +20° when the seal is in the 0° rotational position. That weaker direction is not immediately discernible in the patterns obtained when the door is present.

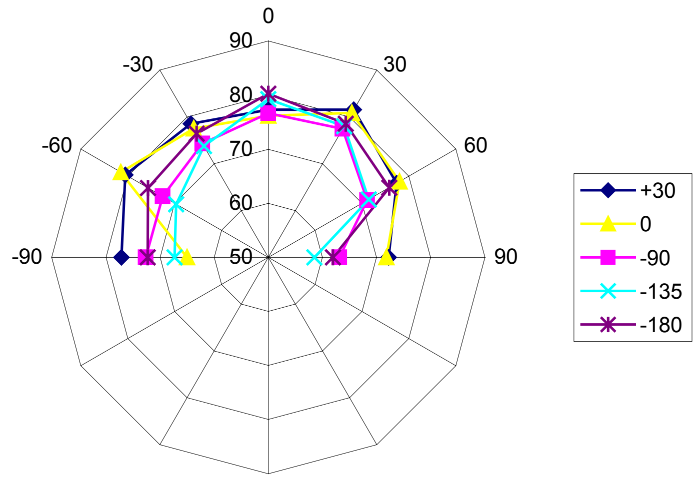


Figure A.2.12. Measured Signal Strength in dBμV/m, Horizontal Polarization, Horizontal Plane Pattern

As with the vertical-polarization results, there is a slight weakness directly behind the doors (view angle = 0°) with the seal in the +30° and 0° positions.

In contrast to the vertical-polarization results, rotating the seal generally has a lesser effect on the signal transmitted in a given direction. As shown in Figure A.2.12, signal strength in the +90°, -60°, and -90° directions varies over a range of up to 12 to 14 dBμV/m as the seal is rotated.

The potential for the E-seal to be in a range of rotational positions spanning about 210° at the time it is read suggests that a given seal, when "viewed" by a reader at a given incidence angle, may have a broad spread of seal-to-reader ranges depending on how the seal is oriented about the bolt axis.

The On-Door Signal-Strength Maps show that changes in seal rotation can alter signal strength over a range of 5 to 19 dBμV/m, depending on polarization and view angle. Signal strength (V/m) drops linearly with distance. So, a 5 dBμV/m increase corresponds to roughly a 75% increase in range, but a 20 dBμV/m change in corresponds to a factor of 10 in distance.

2.2.3 Reader-to-Seal Range Maps Test

E-Logicity' e-seals do not listen for signals from other system hardware, so they were not evaluated in this test.

2.2.4 Seal-to-Reader Range Maps Test

While tests reported above largely measure the performance of the seal and are designed to generate data that can be scaled to account for changes in reader design, this test measures performance that depends heavily on reader sensitivity (e.g., reader hardware, firmware, and antenna designs).

This test was initially intended to generate an azimuthal map (in the horizontal plane) of the range at which the seal can successfully communicate to the reader. It was anticipated that this Seal-to-Reader Range Map would have a profile that was analogous to the Seal Signal-Strength Map.

Using the handheld reader, a seal-to-reader range of at least 35 meters was observed. However, at these ranges in the test areas, there was evidence of reflections from surrounding structures affecting the apparent range. Specifically, the reader was moved away from the seal until the seal was no longer read. Moving further way eventually resulted in the seal being read again. This was interpreted as passing through a region of destructive interference among reflected signals[15].

To minimize reflections, we attempted to reduce the range by adding attenuation between the receiving antenna and the fixed reader. This test would provide a value for the signal strength that must be presented to the receiver to achieve a consistent, successful read. However, during this set of tests, we found that at ranges of about 8 meters, the receiver was able to detect the seal regardless of the amount of attenuation applied. Our investigation suggested that the BNC connector on the e-Logicity receiver card was not grounded to the case. The connector casing itself, as well as the ground shield of any cabling between the receiver card and antenna, was acting as an antenna and bypassing any attenuators.

[15] The long seal-to-reader range observed with the handheld reader suggests that the handheld reader will detect the next seal that transmits from within a very large area around the user, and not necessarily the seal that the user is closest to and inspecting. The reader may have a feature that allows the user to adjust its sensitivity and therefore the effective range

We added a solid, short connection from the connector (via the receiver-card ground plane) to the case. In-door, benchtop testing indicates this may have solved the problem[16].

The range was subsequently measured in conjunction with the On-Road tests. For range tests, the seal was mounted on the roll-up door of a rental truck. Most of the door (the region around the seal) was covered in conductive metal sheeting to provide a large back-plane similar to that of a cargo container. Efforts were made to install the seal with a stand-off from the door similar to that observed when installed on a cargo container. For the e-Logicity e-Seal, this involved passing the bolt through a small piece of Styrofoam, and taping the Styrofoam to the door. The e-Seal was installed with its label facing outward from the door.

Seal #21546 was newly activated by inserting the bolt with a hard push. (Although the bolt felt secure, it reported itself as “tampered,” and was later removable with a hard pull.) This initiated the seal beaconing at 10-second intervals.

A directional log-periodic antenna, with a peak gain of about 4.7 dBi at 434 MHz, was aimed down the road at a height of 11 feet above the road surface. This is about 2 dB higher than the peak gain of a dipole antenna, which would be omni-directional. The antenna was aimed horizontally at about 15° off of parallel to the road (90° would have been looking directly across the road). The truck was incrementally stepped away from the reader antenna. Two sets of measurements were made, with the antenna elements oriented in the vertical plane and then in the horizontal plane. In both configurations, the seal was read out to a range of about 170 feet. Since these tests were conducted on a lightly used rural road with trees present off to the sides, no “mapping” of seal-to-reader ranged at various angles was practical

A.3 HI-G-TEK: DATASEAL

In this section we present laboratory test results and observations for the DataSeal product provided by Hi-G-Tek. Please note that some of the laboratory tests were done without the seal wire, which may have affected measurements.

[16] Identifying, diagnosing, and fixing this hardware problem has consumed more time than was allocated for this test, hence, full mapping of the range pattern using attenuation was not performed

A.3.1 Hi G-Tek DataSeal System Description

The DateSeal is a re-usable electronic loop seal that transmits information about itself via a radio frequency carrier. Hi-G-Tek provided:

- DataSeals (model number IG-RS-40-916),
- a 24V Outdoor DataReader (Model IG-RS-46D-916) with a vertical whip antenna
- a Hand Held Terminal (Model IG-MA-31)

The DataSeal operates nominally at both 916 MHz (also reported as 916.5 MHz) and 125 kHz. The DataReader, intended for long-range operation (reportedly 30-80 meters depending on environment), operates at 916 MHz. When queried by the DataReader, the seals respond at 916 MHz. The system uses frequency shift keying (FSK) modulation with a 40 kHz deviation. The Hand Held Terminal (HHT) is intended for short-range communications (to 60 cm [2 ft]), and operates at 125 kHz. When queried by the HHT, the seals respond at 125 kHz. The HHT was not evaluated in the tests reported here.

The seal, shown in Figure A.3.1, is a tamper-indicating seal. The flexible, metal seal wire (85 cm) can be easily removed from and reinserted into the seal body. The seal detects whether the wire has had either of its ends removed from the seal body or whether there has been any tampering with the wire. Hi-G-Tek supplies a mounting fixture for mounting the DataSeal adjacent to a keeper bar on the door. The seal internally records:

- the time and type of events (tamper events and others),
- reader IDs, and
- uniquely generated "seal stamps" when the seal is "set" or detects tampering.

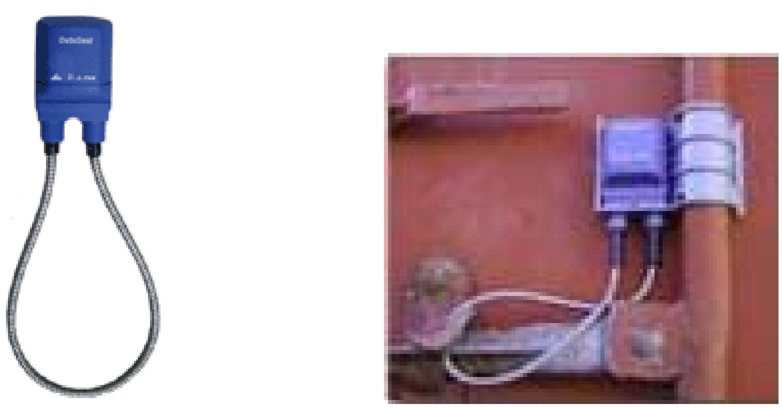


Figure A.3.1. DataSeal Looped through Door Hasp

The seal can transmit in response to an interrogating reader, or it can be set to transmit a tamper message upon detecting a tamper event. In general, the seals wake-up periodically to monitor the environment for signals from a reader. This wake-up cycle time can be between about 0.4 and 10 seconds and is definable by the user. Longer intervals between wake-ups conserve battery life but reduce the allowable speed at which a seal may travel through a reader zone and still reliably communicate with a reader.

The commands from the reader are transmitted in an initial window (the default is about 3 sec). One data field in the transmission tells the listening seals how many times they should transmit their response. The seals may respond with either their short-status or long-status data. Each short-status response burst lasts about 10 msec. By requesting multiple responses, the reader seeks to assure that it can read at least one clear response from each of the seals in its vicinity. With more seals in the vicinity, more retries must be requested. For a given number of seals, Hi-G-Tek provides recommendations on the optimum number of retries and the minimum number of reader attempts ("sessions").

The results reported herein are based on measurements using one of these DataSeals (Seal ID IAHA01052768). The number of retries requested per interrogation session was typically four. The advertised life of the seal battery is four years at 50 reads per day (about 73,000 reads). Most likely, this is the number of retries (i.e., about 18,000 sessions with 4 retries per session). Over roughly three months since the receipt of this seal, it was subjected to approximately 1550 sessions totaling about 6200 retries. This should have consumed less than 10% of the seal's battery life.

A.3.2. Hi-G-Tek Lab Test Results and Observations

3.2.1. Frequency Measurement of Seals and Readers

Measurements indicated that DataSeals and DataReader transmit on a nominal 916.5 MHz carrier (wavelength = 32.7 cm [12.9"]).

Figure A.3.2a is a representative frequency scan of the DataReader (which has the same features as the seals). The resolution bandwidth was set to 30 kHz to help resolve the peaks. Multiple pulses were measured, and the curve represents the maximum value detected at each frequency. In Figure A.3.2a, the two peaks are separated by about 34 kHz and are centered around 916.505 MHz. This is close to the 40 kHz deviation described by Hi-G-Tek. In cases with stronger signals, with the resolution bandwidth set to 100 kHz, two peaks could usually be discerned, and their separation was typically about 35 kHz.

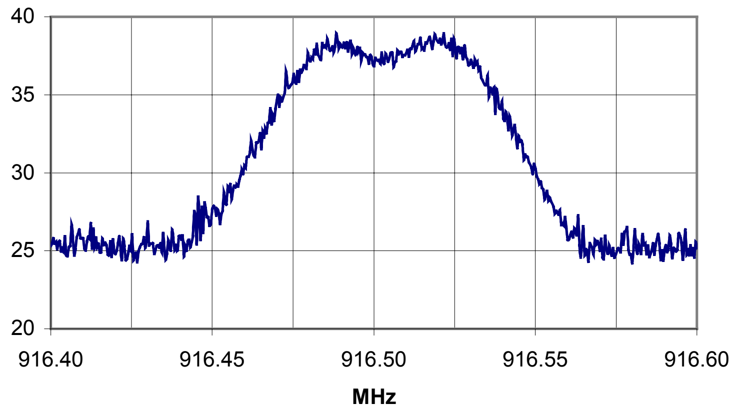


Figure A.3.2a. Envelope of DataReader Transmissions Showing Peaks From FSK

A representative time trace of the transmissions at 916.5 MHz from the DataReader and the four responses from the DataSeal is shown in Figure A.3.2b. The intervals between the response retries appear to be relatively random.

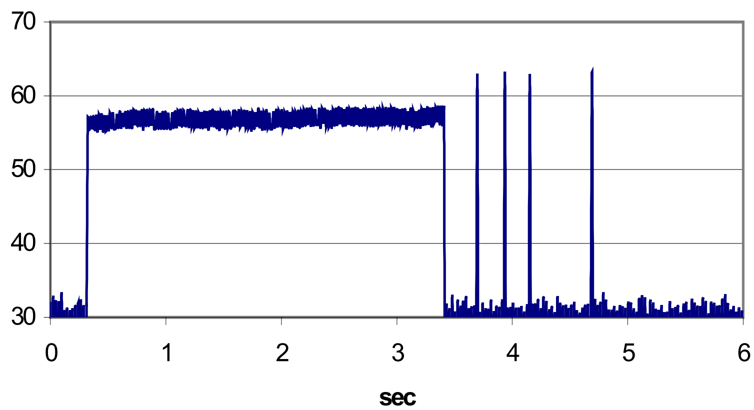


Figure A.3.2b. Trace of DataReader Interrogation and Four Re-transmissions from One DataSeal

<u>3.2.2 Seal Signal-Strength Maps</u>

It is expected that, all else being equal, the RF field strength radiated by the DataSeal in a given direction will correlate with the seal-to-reader range in that direction. The purpose of this test set is twofold:

- To generate data to support numerical modeling of the DataSeal's radiation pattern.
- To generate RF signal-strength data that, together with the output of the numerical models, can be compared against seal-to-reader range measurements discussed later.

Tests were conducted both with and without a container door present. Without a container door present, the measured field pattern is attributable primarily to the DataSeal's antenna and construction. These measurements provide data to help build and validate numerical models of the DataSeal's RF characteristics. With a container door present, the measured field pattern includes the effects of reflections of RF waves. These reflections introduce the possibility of constructive and destructive interference, especially in the vicinity of the seal. Hence, the field-strength map may differ from that of the DataSeal without the door.

3.2.2.1 Test Environment

All tests were conducted using a log-periodic antenna, RG-58 co-axial cable, and an Advantest R3131A spectrum analyzer. The resolution bandwidth of the analyzer was set to 100 kHz with a sweep time of 50 msec. For each data point, multiple seal transmissions were measured in the frequency domain, and the maximum signal strength was recorded. The peak signal strength typically occurred within about 15-25 kHz of 916.5 MHz.

3.2.2.2 Open-Air Testing

Description

The DataSeal was attached to a plastic mount, atop a leveled, rotary stage on a tripod. The tripod was adjusted so that the center of the DataSeal was 1.52 m (5 ft) above ground level (Figure A.3.4).

Figure A.3.4. Rotary Mounting for DataSeal

Two sets of measurements were made:

- one with the antenna axis in the same horizontal plane as the seal and aimed at the seal (Figure A.3.5.a), and

- one with the antenna elevated above the seal plane, with the antenna axis aimed downward at the seal at an angle of 30° (Figure A.3.5.b).

For both the at-level and elevated configurations, measurements were made with the antenna rotated into two orthogonal positions: with the antenna elements in the vertical plane (Figure A.3.5.c), and with the elements in a plane that also contains the seal (Figure A.3.5.d). For each set of measurements, the antenna was mounted on a mast and located so that its center element was nominally 3 m from the seal. Temperatures for these tests were around -1 to 4°C (30 to 40°F).

(a) Level, horizontal (b) Elevated, “vertical” (c) Vertical elements (d) Elevated, “horizontal”

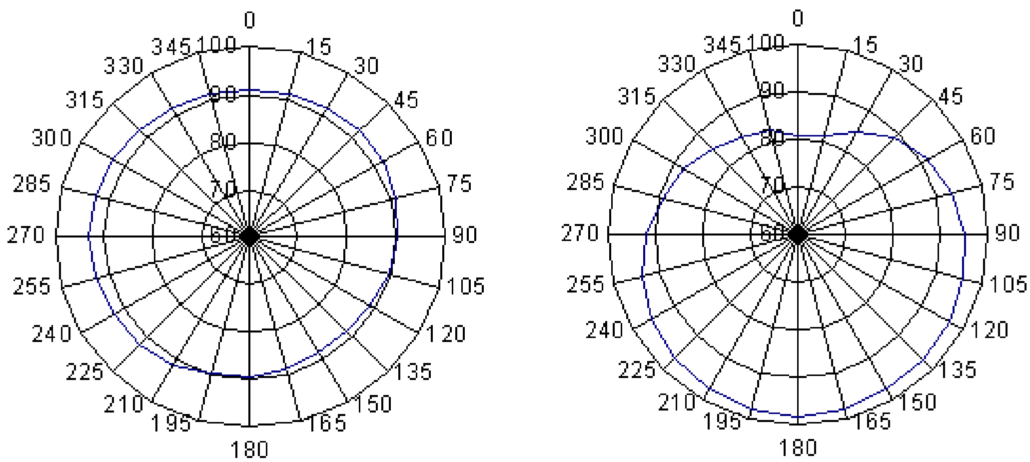
Figure A.3.5. Four Orientations of the Log-Periodic Measuring Antenna

Using the rotary stage, the seal was rotated through 360°, in 15° increments. Measurements were made with the seal tripod at the nominal 3 m distance from the antenna. The measurements were repeated with the seal tripod moved one-half wavelength (about 16 cm) further from the antenna. In the results presented below these measurements, after applying correction factors to each, were used to calculate the average.

Open-Air Test Results

The DataReader provided by Hi-G-Tek is supplied with a vertical whip antenna, and certain Hi-G-Tek documentation specified the seal antenna as being vertically polarized.

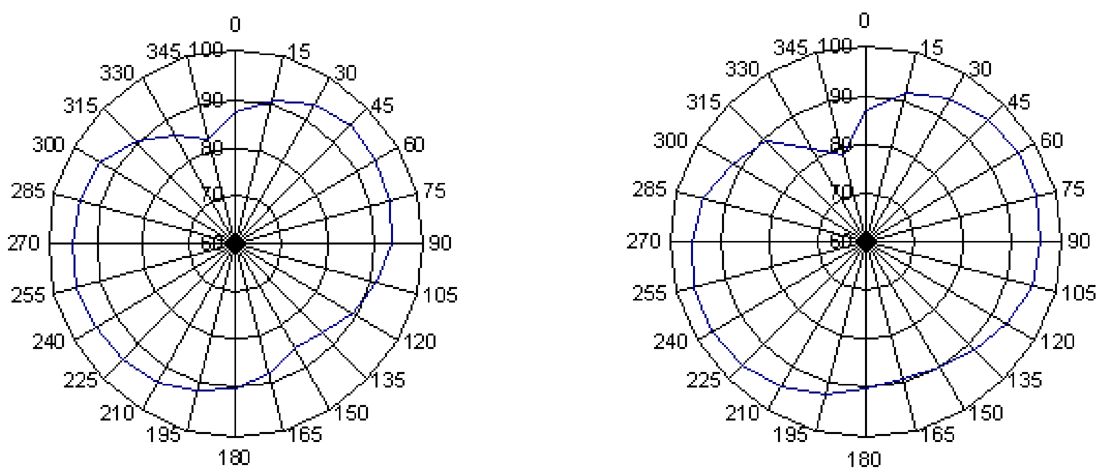
Figure A.3.6 shows the corrected, averaged signal strengths measured with the elements of the measuring antenna in a vertical plane. In the plane of the seal, signal intensity is nearly isotopic, It varies over a ±2.5 dBμV/m range, with the maximum detected at an azimuthal angle of about 270° and the minimum at about 140°. A much stronger non-uniformity is observed in the measurements made at a 30° inclination to the horizontal. In the 30° inclination tests, the raw data (at the nominal position and at one-half wavelength away in the horizontal plane) showed an overall decrease in signal strength at the 0° position compared to the 180° positions, but also a strong spatial variation between the two measurement radii. Since these measurements were made 9 to 10 wavelengths from the seal, we do not expect near-field effects to be so strong. There may have been some local reflections causing a "null" and peak in this region. On-site, on-door testing will help determine the importance of these results. This configuration may also warrant additional measurements to help in the seal-modeling effort.



(a) At Seal Level (b) At 30° Inclination

Figure A.3.6. Measured Signal Strength in dBμV/m, Horizontal Plane Pattern (Vertical Polarizaton)

Figure A.3.7 shows the corrected, averaged signal strengths measured with the elements of the measuring antenna normal to the vertical plane. In Figure A.3.7.a, the antenna axis and elements are in the same horizontal plane as the seal, as in Figure A.3.5.a. In Figure A.3.7.b, the antenna axis is aimed at the seal from above, and the antenna elements are horizontal, as in Figure A.3.5.d.



(a) At Seal Level (b) At 30° Inclination

Figure A.3.7. Measured Signal Strength in dBμV/m, Horizontal Plane Pattern (Horizontal Polarizaton)

The variations around the seal are stronger than for the at-level, vertical-polarizaton measurements of Figure A.3.6a. At the level of the seal, they range over ±5 dBμV/m, and have an average strength about equal to that of the vertically polarized signals. There is a discernible lobe pattern with maxima occurring towards the 60° and 240° directions.

At a 30° inclination, the same general shape is maintained and the average strength is fairly similar, but the variations range over ±9 dBμV/m. For both the at-level and inclination measurements, both sets of raw data had the same general shape, mainly differing only in signal amplitude. This suggests that the lobe pattern derives from the seal's construction and not from reflections from the environment.

3.2.2.3 On-Door Testing

Description
The DataSeal was placed into the door-handle hasp on a structure built to simulate the lower half of the rear doors of an ISO container (Figure A.3.8). The installed seal sat at an elevation of about 1.58 m (5'2"). Many ISO containers have corrugation-like recesses on the doors. However, the door handle mounting hardware cannot be placed in one of these recesses, and the DataSeal would be placed near the hasp. So, the DataSeal will likely not be directly over a recess. Therefore, these tests simulated the placement of the DataSeal only over a smooth metallic backplane. Around the DataSeal's installed location, the door surface extended for 1.6 wavelengths above the seal and a minimum of two wavelengths in the other three directions. With the seal installed as in Figure A.3.8, there is a region about 0.5 cm (0.015 wavelengths) deep between the door surface and the back of the seal body, and this region is largely filled by part of Hi-G-Tek's plastic mounting fixture. Temperatures during these tests were about 3°C (37°F).

Figure A.3.8. Detail of Simulated Container Door, Handles, and Keeper Bars

The antenna was mounted on a mast, its axis aimed at the seal. The mast and antenna were moved into seven angular positions in a 180° arc around the seal (Figure A.3.9).

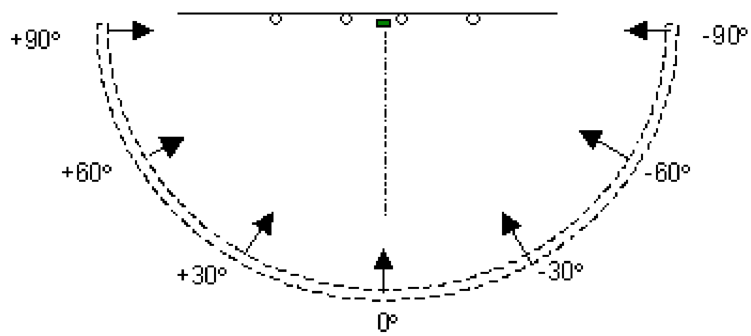


Figure A.3.9. Diagram of Nominal Antenna Positions Around Seal on Container Door

At the level of the seal, the antenna was rotated into two orthogonal positions, to measure the vertical and horizontal polarization of the RF field. At the 30°-inclination positions, the measurements were made only with the antenna elements in the vertical plane. Also at each angular position, measurements were made with the antenna located so that its center element was approximately 3 m from the seal, and again with the antenna moved one-half wavelength (16 cm) away from the seal, along the same angular path from the seal. After the corrections discussed earlier, these two measurements were averaged to calculate a representative field strength for that position.

On-Door Test Results

The on-door test results were measured with the monitoring antenna at the level of the seal and also at the 30°-inclination positions. The results are plotted in Figures A.3.10 through A.3.12. Figure A.3.10 shows the vertical polarization measurements at the seal level.

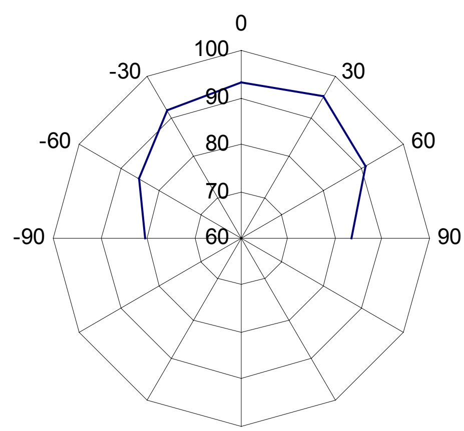


Figure A.3.10. Measured On-Door Signal Strength (dBμV/m) at Seal Level, Vertical Polarization

The seal was installed with a keeper bar to its immediate left (towards the negative-angle side of the door). This may or may not contribute to the generally stronger signals received when measuring from the positive-angle side of the door. Even at ±90°, the signals were well above the noise floor (around 60 dBμV/m) so that the reader has a good likelihood of detecting the seal. From the –60° to +30° viewing angles, there is about a 10 dBμV/m change in detected signal strength (about a factor of 3 in absolute volts-per-meter).

Figure A.3.11 shows the horizontal polarization measurements at the seal level. In the open-space tests (Figure A.3.6.a) there was a ±5 dBμV/m deviation, with the weak direction being about 345°. With the door present, a similar but more pronounced weak-signal region is detected directly "behind" the door (view angle = 0°). This weakness may derive from the seal or from interference patterns generated by the door; modeling will help resolve the cause. From the 0° direction to the ±60° directions, signal strength increases by up to 14 dBμV/m (a factor of 5 in absolute volts-per-meter).

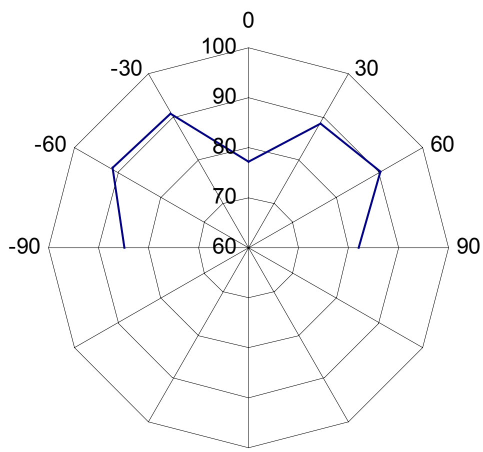


Figure A.3.11. Measured Signal Strength (dBμV/m) On-Door at Seal Level, Horizontal Polarization, Horizontal Plane Pattern

Figure A.3.12 shows the vertical polarization measurements from the 30°-inclination positions. At viewing angles between –60° to +60°, the signal strength is fairly uniform, and drops off as expected at the ±90° positions. At seal level, generally stronger signals were measured on the positive-angle side of the door (Figure A.3.10); that feature is not seen in these measurements.

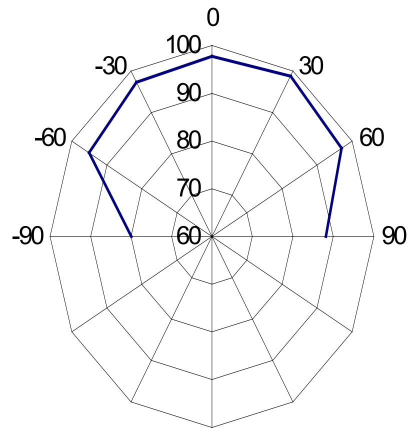


Figure A.3.12. Measured On-Door Signal Strength (dBμV/m) at 30°-Inclination, Vertical Polarization

The On-Door Signal-Strength Maps show that signal strength can vary over a range of 10 to 14 dBμV/m, depending on the view angle from the receiving antenna to the DataSeal. Signal strength (V/m) drops linearly with distance. So, a 10 dBμV/m increase corresponds to roughly a 3x increase in range. Since vertically polarized signals show a somewhat lesser variation in strength than do the horizontally polarized, using a vertically polarized receiving antenna could help better control the size and shape of a read zone, given the variety of viewing angles the antenna will have to seals in its vicinity.

3.2.3. Reader-to-Seal Range Maps

The DataReader control software allows the user to vary the transmission power supplied by the reader to its antenna. This setting (allowable range 0 to 100) was varied from a value of 1 to 60, changing the measured field strength by about 20 dB. Even with the reader power set to“1”, with the seal mounted on the door, the seal was able to detect the reader from a distance of at least seven meters at a view angle of +30°. This suggests that the reader-to-seal distance could easily exceed 70 m at maximum reader power-output.

At distances of 7 m or more, the effect of reflections from the boundaries of the test area becomes a concern. Because of the space limitations in the lab setting and concern about reflections, the range map data measurements were not done.

3.2.4. Seal-to-Reader Range Maps

For the same reason as above, the seal-to-reader range maps were not done.

3.2.5. Data Capabilities

The commands from the reader are transmitted in an initial time slot (the default is about 3 sec). One data field in the transmission tells the listening seals how many times they should transmit their response. The seals may respond with either their short-status or long-status data. Each response burst lasts about 10 msec. By requesting multiple responses, the reader seeks to assure that it can read at least one clear response from each of the seals in its vicinity. With more seals in the vicinity, more retries must be requested. For a given number of seals, Hi-G-Tek provides recommendations on the optimum number of retries and the minimum number of reader attempts ("sessions").

The demo software offers several graphical user-interface (GUI) windows through which to control the reader, write to the seal, and read the seal and reader parameters. Figure A.3.14 shows one GUI, the Reader Setup window, through which the duration of some of these time slots can be set. For example, the "Thw" value of 997 corresponds to a duration of 3.063 sec for the "reader interrogation header." During this time slot, the reader sends data or queries to the seals. Shortening this duration increases system time response, but it also shortens the required "wakeup cycle time" of the seals. In "Normal" mode, the seals are sensing the seal-wire status but are in standby except when they periodically sense the surroundings for reader transmissions; this is a major power conservation measure. The interval between these awakenings is the "wakeup cycle time," and it can be set individually for each seal to between 0.39 seconds and 9.77 seconds. Thw must be at least 130 msec longer than the wakeup cycle time, or the seal may miss the interrogation. Thw can be set from 1.2 seconds to 30 seconds. Selecting Thw is an important factor in optimizing the trade-off between a system's response times and the seals' battery life. (Thp has the allowable values and requirements as Thw, but applies to a "hard wakeup" command that must be used to wake seals from their "Sleep" mode. The "Sleep" mode is an extreme power-saving mode in which, among other things events are not recorded.)

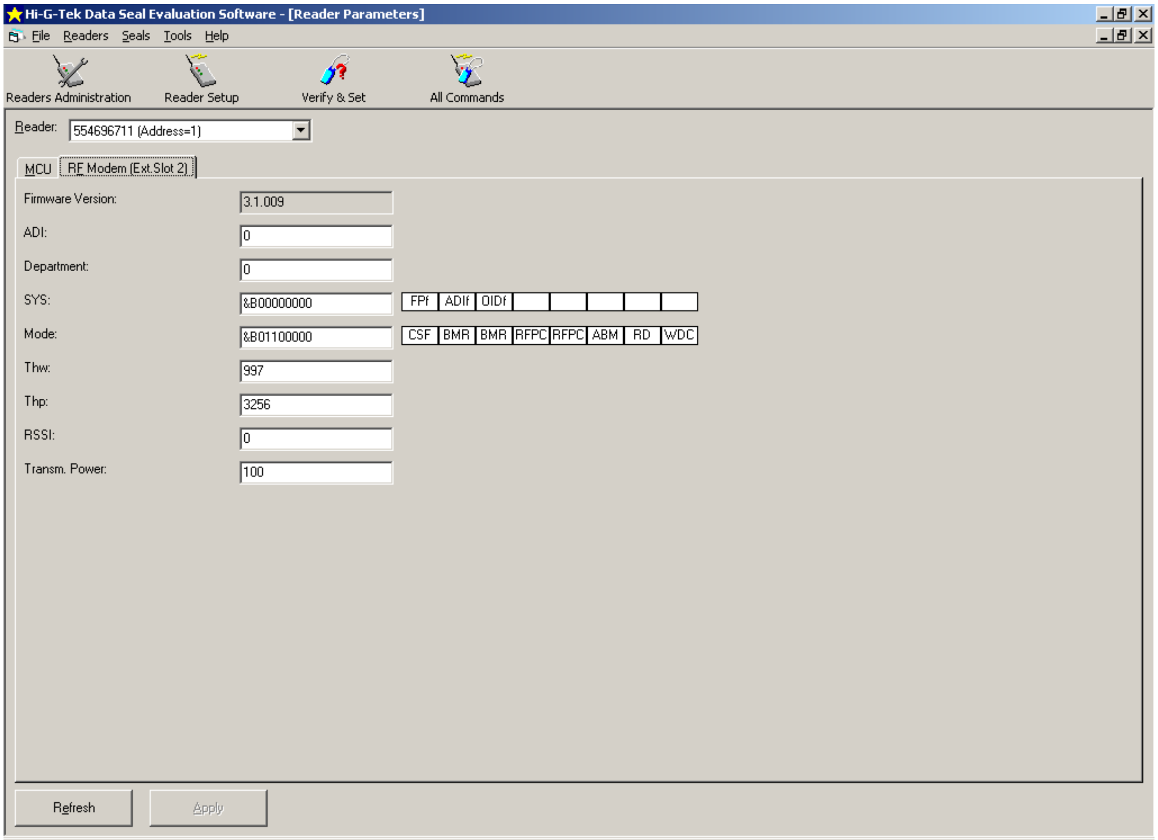


Figure A.3.14. One of Two Pages Under the "Reader Setup" Tab of the Demo GUI

Figure A.3.15 shows a demo window through which most of the test querying was performed. The value of "Rr" in the upper right sets the number of re-transmissions that each seal should send, to work around seal collision problems in multi-seal situations.

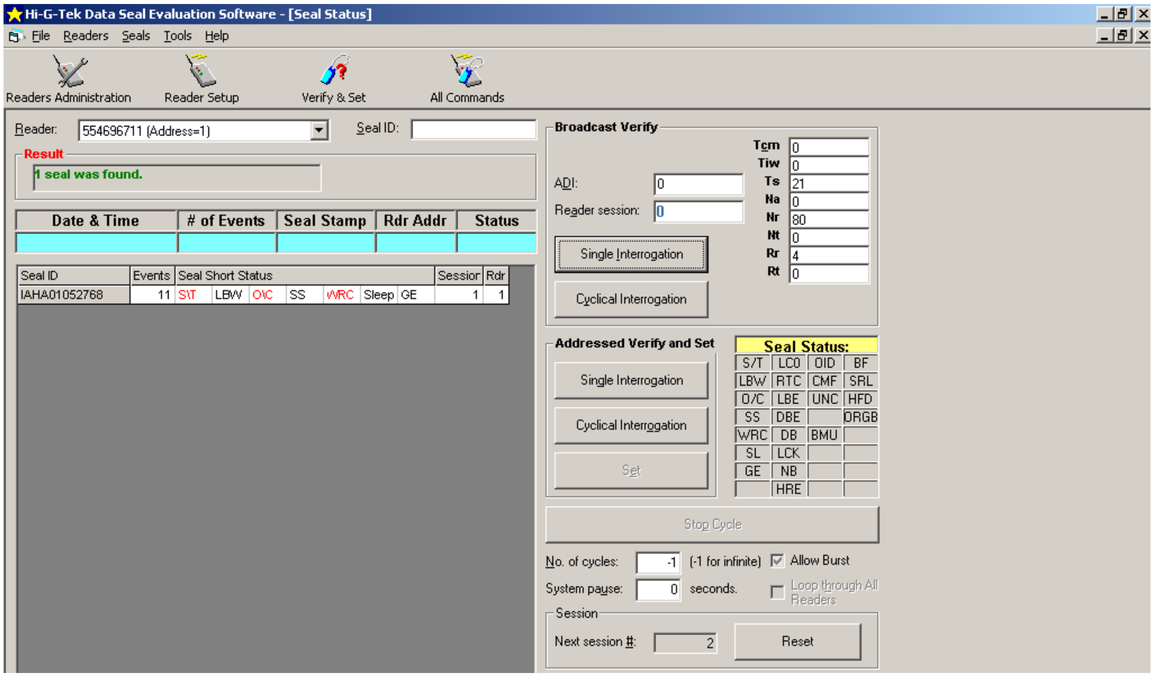


Figure A.3.15. "Verify & Set" Window of the Demo GUI

Here, the short status (1 byte = 8 bits, of which 7 are currently used) has been received for seal "IAHA01052768." The black/red lighting of the status codes indicates their bit setting. The codes are:

- S/T: Indication of whether the seal is SET or TAMPERED
- LBW: Low battery voltage warning
- O/C: Open/close status of seal wire
- SS: Suspended Set. Indicates a "suspended sleep" mode of operations
- WRC: Indication that the electrical characteristics of the seal wire have been changed relative to the SET conditions
- Sleep: Indication of "deep sleep" mode of operation
- GE: General error flag for any errors in the long-status bytes.

Most of the bits in the long-status bytes are used for diagnostics of communications and hardware.

The number of events (openings, closings, settings) is stored in seal memory and is reported in Figure A.3.15 as "11." Other seal parameters of interest include:

- Time and date (5 bytes)
- A seal stamp, which is uniquely generated internally with each SET command, and modified whenever a tamper event is detected (2 bytes)
- "ADI" and "department" codes, that allow a seal to be assigned as one of a group of seals, and allow identifications of a department with an organization.

Figure A.3.16 shows the "All Commands" window. The demo program handles queries and response data largely in hexadecimal characters as shown. This allows the application developer and evaluators to see (by decoding the hex strings) the individual bits. In the response window, the "0D" indicates the number of bytes (1 byte = 2 hex characters) in the response (0Dhex = 13). The next six bytes are the seal ID, in which each alphanumeric character of the ID has been converted into 5 bits, and the resulting string of bits converted into hex characters (4 bits per hex character). The next two hex characters, "64," indicate the message type, and correspond to the "Read Parameters" command that was sent (near the top of the window). The short status for the seal follows ("A8" = 10101000). The high values for the 1st, 3rd, and 5th bits correspond to the 1st, 3rd, and 5th parameters (S/T, WRC, O/C) being highlighted in Figure A.3.15.

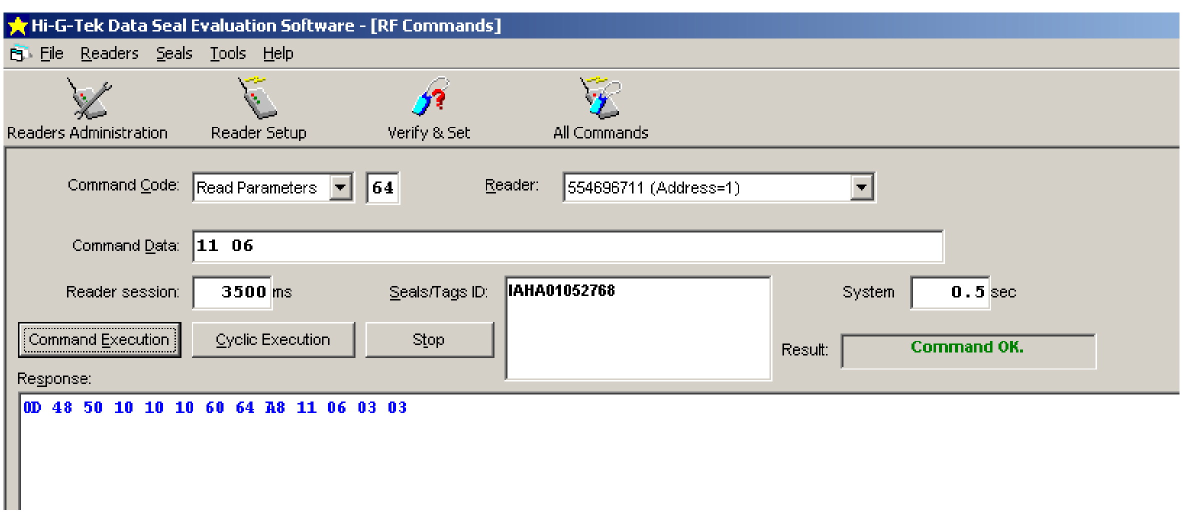


Figure A.3.16. "All Commands" Window of the Demo GUI

A.4 SAVI SMARTSEAL

In this section we present results and observations from laboratory Testing of the "Smart Seal" product provided by Savi Technology as part of their EchoPoint system, Model number ST-645-12, and ID 4000109.

A.4.1. Savi SmartSeal System Description

The SmartSeal is a partly re-usable electronic bolt[17] seal that transmits information about itself via a radio frequency carrier. Savi provided:

- SmartSeals (model number ST-645-12),
- an EchoPoint reader (Model SR-640-101with built-in antenna)
- an EchoPoint medium-range SignPost (Model SR-600-101)

The seal system provided has two communication paths. First, there is one-way, low-frequency (123 kHz inductive) communication from the Signpost to the seal. This is intended for ranges up to 5 m (with the longer-range Signposts, model SR-600-201). A seal can log its location history by having Signpost IDs written to its memory with an internally generated time stamp. The Signpost can also be used to put the seal into various modes (beaconing, set to detect tampering, etc.)

Second, there is two-way UHF (434 MHz) communication between the seal and the reader. This is intended for long range (up to ~100 m) communication. The system uses frequency shift keying (FSK) modulation with a reported 35 kHz deviation for UHF communications. On-Off keying is used in the inductive link.

The seal, shown in Figure A.4.1, is a tamper-detecting barrier seal. Once sealed, the bolt is intended to be removed with bolt-cutters. With replacement of the bolt (reported by Savi to cost a couple of dollars), the seal is re-useable. The seal detects tampering with or removal of the bolt. A magnetic element is adhered to the back of the seal to help hold the seal in position flush against the container door. This also provides some small standoff of the internal antennae from the metallic door, which reportedly improves the seal's RF performance.

Each seal has 4-16 bytes for a factory programmed ID, in addition to system-controlled memory and firmware. According to Savi, each data pulse (~5 msec) contains 98 bits of data. The initial pulse includes the Tag ID, owner ID (if stored), tamper status, and an identifier for its operating mode (beaconing, broadcast, point-to-point), in addition to error-checking bits. The seal can be provided with up to 28kB of additional memory, although a few kB is likely to be more typical, since each event can reportedly be recorded in about 10 bytes of

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[17] New bolt required

data. Thousands of events could potentially be stored. The seal has an on-board clock that allows events to be time-stamped. Password authentication of a reader is also possible.

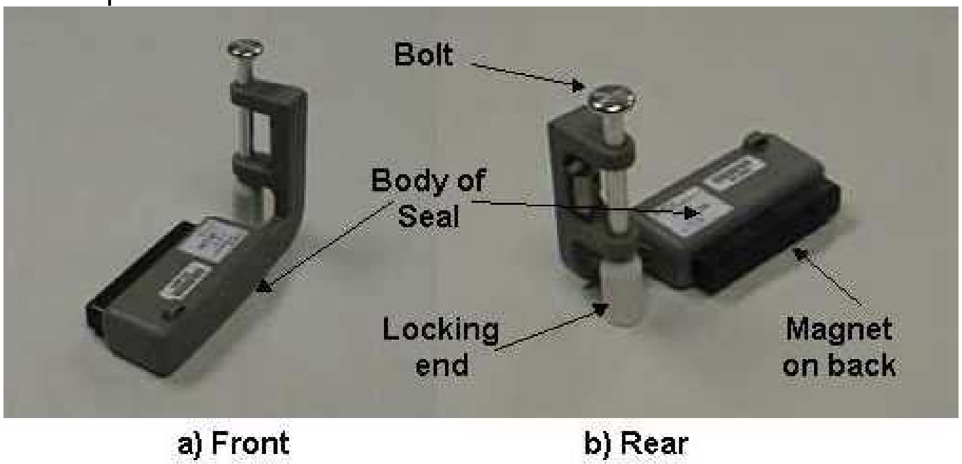


Figure A.4.1. Views of SmartSeal with Bolt Installed

Figure A.4.2 shows a seal (without the bolt) taped in position on the handle hasp.

Figure A.4.2. SmartSeal on Simulated Container Door (taped to handles)

A.4.2. Test Results and Observations

<u>4.2.1: Frequency Measurement of Seals</u>

Savi reports that the SmartSeals transmit on a nominal 433.92 MHz carrier (wavelength = 69.1 cm [27.2”]). Each transmission pulse from the seal lasts about 5 msec. The fastest sweep time available on the spectrum analyzer is

50 msec, so many pulses must be read to obtain a continuous spectral plot. The results are shown in Figure A.4.3.

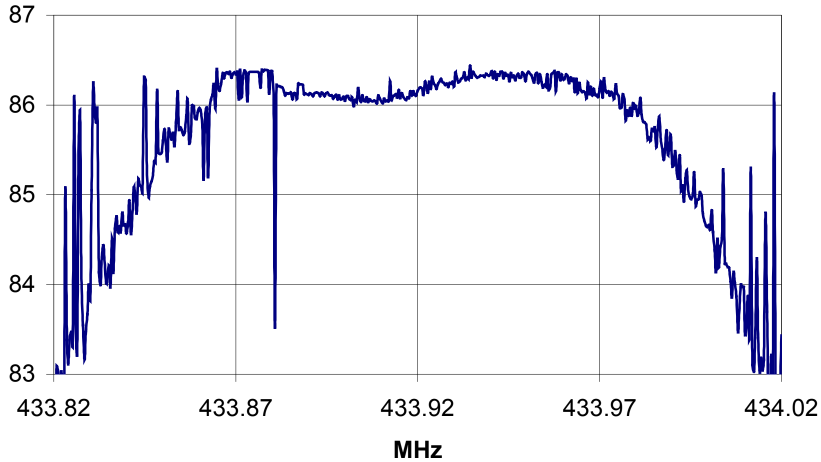


Figure A.4.3. Envelope of SmartSeal Transmissions Showing Peaks From FSK

The resolution bandwidth was set to 100 kHz to help resolve the peaks. Multiple pulses were measured, and the curve represents the maximum value detected at each frequency. In Figure A.4.3, the two FSK peaks are separated by about 60 kHz and are centered around 433.91 MHz. Any drift in the seal or analyzer properties over this time could lead to inaccuracies in the combined plot. For example, the low frequency peak in Figure A.4.3 is not as well defined as would be hoped due to drift in the analyzer.

The long-range reader uses the same communication means (FSK on 434 MHz) as the seals.

4.2.2 Seal Signal-Strength Maps

It is expected that the RF field strength radiated by the SmartSeal in a given direction will correlate with the seal-to-reader range in that direction. The purpose of this test set was twofold:

- To generate data to support numerical modeling of the SmartSeal's radiation pattern.
- To generate RF signal-strength data that, together with the output of the numerical models, can be compared against seal-to-reader range measurements.

Tests were conducted both with and without a container door present. Without a container door present, the measured field pattern is attributable primarily to the SmartSeal's antenna and construction. These measurements provide data to help build and validate numerical models of the SmartSeal's RF characteristics. With a container door present, the measured field pattern includes the effects of reflections of RF waves. These reflections introduce the possibility of constructive and destructive interference, especially in the vicinity of the seal, so that the field-strength map will differ from that of the SmartSeal without the door.

Test Environment

The tests discussed in this subsection were conducted outdoors on the top deck of a parking garage (Figure A.4.4).

Figure A.4.4. Area Used for Outdoor Laboratory Tests (shown with components for On-Door tests installed)

All tests were conducted using a log-periodic antenna, RG-58 co-axial cable, and an Advantest R3131A spectrum analyzer. All measurements represent relative dBμV values at the analyzer, without correction for cable losses or antenna factor. The resolution bandwidth of the analyzer was set to 100 kHz, with a center frequency of 433.92 MHz and a sweep time of 22 sec. For each data point, several seal transmissions (at 10 second intervals) were measured in the time domain, and the individual dBμV values were averaged.

Open-Air Testing

Description
The SmartSeal was attached to a plastic mount, atop a leveled, rotary stage on a tripod. The tripod was adjusted so that the center of the SmartSeal was 1.60 m (5’3”) above ground level (Figure A.4.5).

Figure A.4.5. Rotary Mounting for SmartSeal

Two sets of measurements were made:

- one with the antenna axis in the same horizontal plane as the seal and aimed at the seal (Figure A.4.6.a), and
- one with the antenna elevated above the seal plane, with the antenna axis aimed downward at the seal at an angle of 30° (Figure A.4.6.b).

For both the at-level and elevated configurations, measurements were made with the antenna rotated into two orthogonal positions: with the antenna elements in the vertical plane (Figure A.4.5.c), and with the elements in a plane that also contains the seal (Figure A.4.5.d). For each set of measurements, the antenna was mounted on a mast and located so that its center element was nominally 3 m from the seal. Temperatures for these tests were around 16°C (60°F).

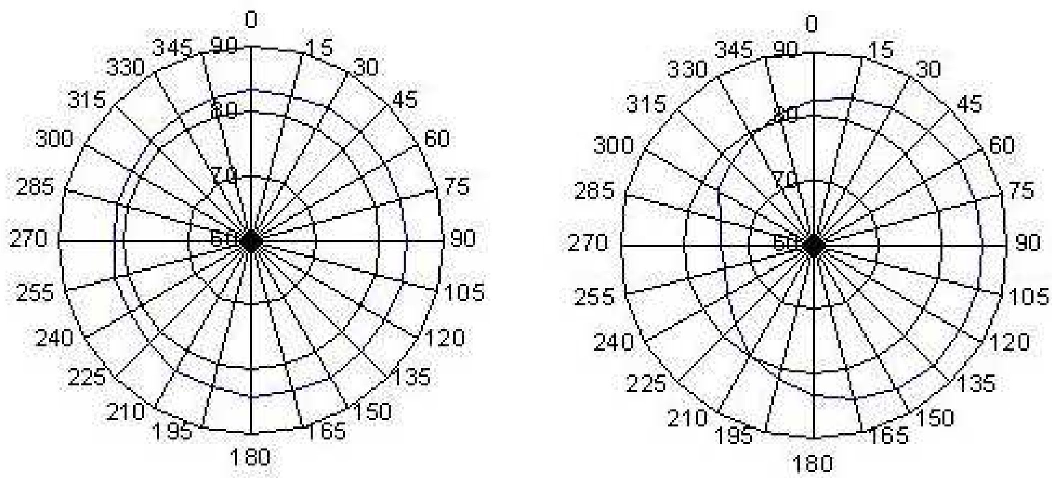
(a) Level, horizontal (b) Elevated, "vertical" (c) Vertical
elements (d) Elevated, "horizontal"

Figure A.4.6. Four Orientations of the Log-Periodic Measuring Antenna

Using the rotary stage, the seal was rotated through 360°, in 15° increments. Measurements were made with the seal tripod at the nominal 3 m distance from the antenna. The measurements were repeated with the antenna moved one-half wavelength (about 34 cm) further from the seal. In the results presented below, these measurements, after applying correction factors to each, were used to calculate the average.

Open-Air Test Results

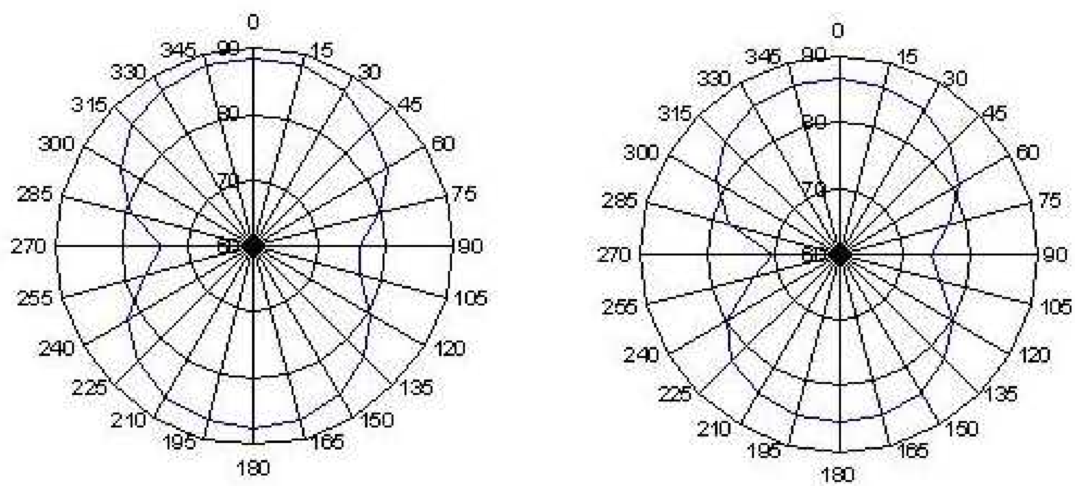
Figure A.4.7 shows the corrected, averaged signal strengths measured with the elements of the measuring antenna in a vertical plane. In the plane of the seal, signal intensity is nearly isotropic. It varies over a ±1.5 dBμV/m range, with the maximum detected at an azimuthal angle of about 105° and the minimum directly opposite at about 285°. A much stronger non-uniformity is observed in the measurements made at a 30° inclination to the horizontal, reaching ±6 dBμV/m, with the maximum and minimum positioned similarly to those in the "at-level" readings. At 30° inclination, both sets of raw data show peaks around 120° and minima around 255°, though one set had a larger variation (±8 dBμV/m) than the other (±5 dBμV/m). Since these measurements were made 4.3 to 4.8 wavelengths from the seal, near-field effects may be responsible for the distortion of the 30°-inclination pattern.



(a) At Seal Level (b) At 30° Inclination

Figure A.4.7. Measured Signal Strength in dBμV/m, Horizontal Plane Pattern (Vertical Polarizaton)

Figure A.4.8 shows the corrected, averaged signal strengths measured with the elements of the measuring antenna normal to the vertical plane. In Figure A.4.8.a, the antenna axis and elements are in the same horizontal plane as the seal, as in Figure A.4.6.a. In Figure A.4.8.b, the antenna axis is aimed at the seal from above, and the antenna elements are horizontal, as in Figure A.4.6.d.



(a) At Seal Level (b) At 30° Inclination

Figure A.4.8. Measured Signal Strength in dBμV/m, Horizontal Plane Pattern (Horizontal Polarizaton)

The variations around the seal are stronger than for the at-level, vertical-polarizaton measurements of Figure A.4.7, and lobes are readily apparent. In the level and inclined cases, the signal strengths range over ±6 and ±8 dBμV/m, respectively, and average about the same as the vertically polarized signals. The maxima occur towards the 0° and 180° directions. For both the at-level and inclination measurements, both sets of raw data had the same general shape, mainly differing only in signal amplitude. This suggests that the lobe pattern derives from the seal's construction and not from reflections from the environment.

On-Door Testing

Description

The SmartSeal was placed on the door-handle hasp on a structure built to simulate the lower half of the rear doors of an ISO container. This was shown in Figure A.4.2. The installed seal sat at an elevation of about 1.45 m (4'9"). Many ISO containers have corrugation-like recesses on the doors. However, the door handle mounting hardware cannot be placed in one of these recesses, and the SmartSeal would be placed near the hasp. So, the SmartSeal will likely not be directly over a recess. Therefore, these tests simulated the placement of the SmartSeal only over a smooth metallic backplane. With the seal installed as in Figure A.4.2, the seal is kept parallel to the door by the 1.3-cm thick (0.018 wavelengths) magnet. Temperatures during these tests were about 16°C (60°F).

The antenna was mounted on a mast, its axis aimed at the seal. The mast and antenna were moved into seven angular positions in a 180° arc around the seal (Figure A.4.9).

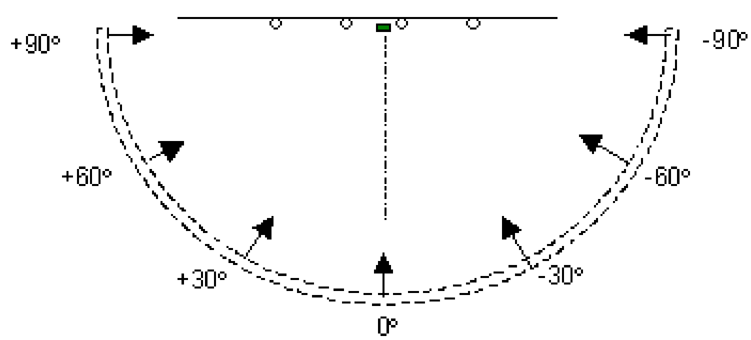


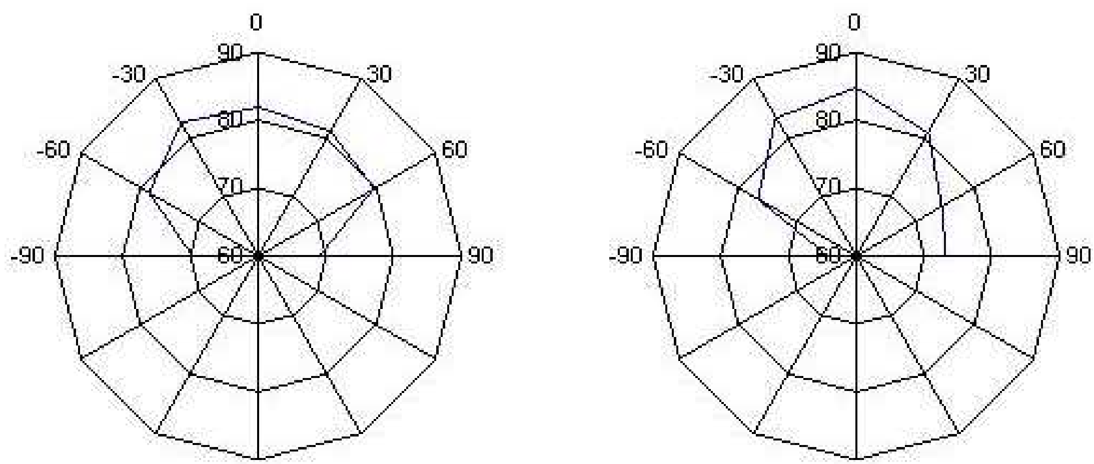
Figure A.4.9. Diagram of Nominal Antenna Positions Around Seal on Container Door

At each position around the seal, the antenna was rotated into two orthogonal positions, to measure the vertical and horizontal polarization of the RF field. Also at each angular position, measurements were made with the antenna located so that its center element was approximately 3 m from the seal, and again with the antenna moved one-half wavelength (16 cm) away from the seal, along the same angular path from the seal. After the corrections discussed earlier, these two measurements were averaged to calculate a representative field strength for that position.

On-Door Test Results

The on-door test results were measured with the monitoring antenna at the level of the seal and also at the 30°-inclination positions. The results are plotted in

Figure A.4.s 10 and 11. Figure A.4.10 shows the vertical polarization measurements.



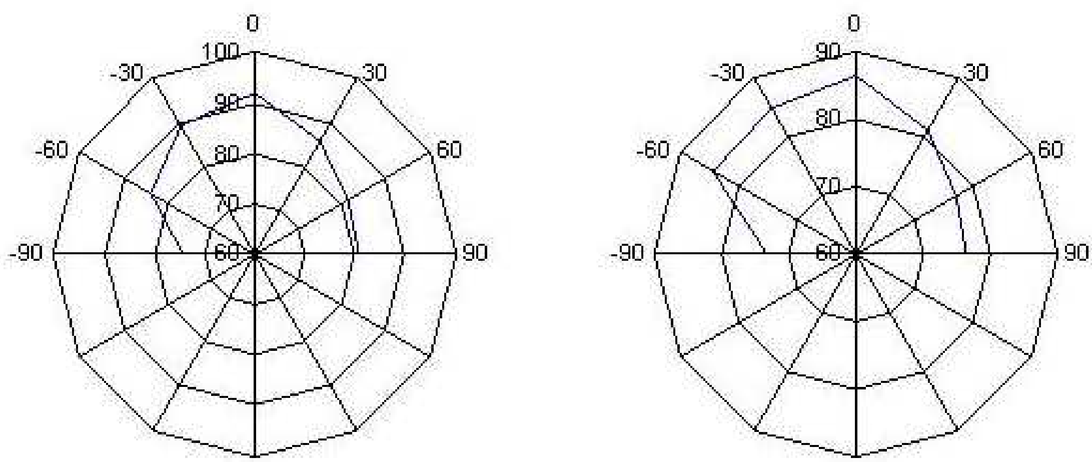
(a) at seal level (b) at 30° inclination

Figure A.4.10. Measured On-Door Signal Strength (dBμV/m), Vertical Polarization

As shown in Figure A.4.2, the seal was installed with a keeper bar to its immediate right (towards the positive-angle side of the door), and the distance from the seal to the edge of the door was greater on the positive side of the door (left rear). These features may or may not contribute to the generally stronger signals received when measuring from the negative-angle side of the door. Note that to keep the seal useable in later tests, no bolt was installed; the seal was taped into its proper position.

Even at ±90°, the signals were above the noise floor so that the reader has a good likelihood of detecting the seal. At the seal level, the strongest variation (excluding the drop-offs at the ±90° positions) occurs between the –60° and –30° viewing angles, but it is only about 4 dBμV/m (a factor of about 1.5 in absolute volts-per-meter).

Figure A.4.11 shows the horizontal polarization measurements at the seal level and at a 30° inclination. In the open-space tests (Figure A.4.8) the maxima and minima varied by ±6 to ±8 dBμV/m from the average, and the lobes were fairly symmetric about the 0°-180° plane, which is normal to the door in this test. In contrast, Figure A.4.11 shows a slight distortion of the field towards the "negative" side of the door (right rear of the container). The signals at –30° and –60° are 2.2 to 7.4 dBμV/m stronger than their counterparts on the positive side. This effect is somewhat stronger than that observed for vertically polarized signal. Note also that in the plane of the seal, the horizontally polarized signals (Figure A.4.11.a) are several dB greater than those measured in the other configurations (Figure A.4.10 and Fig 11.b).



(a) at seal level (b) at 30° inclination

Figure A.4.11. Measured Signal Strength (dBμV/m) On-Door, Horizontal Polarization, Horizontal Plane Pattern

4.2.3. Reader-to-Seal Range Maps

For the on-door testing, at distances of 7 m or more, the effect of reflections from the boundaries of the test area shown in Figure 4 become a concern since constructive and destructive interference can lead to inaccurate estimates of a system's true range. Savi indicated that the EchoPoint reader-to-seal distance is on the order of 100 meters in open spaces and with the seal on a container door. Because such large distance were not available at the Lab site, and because, with internal antennae, the reader output power could not be readily attenuated, tests of reader-to-seal range were conducted at the cargo terminal test facility.

With several seals attached to the doors of a container on a chassis, and with the reader at a height of about 30 feet, the reader was able to query the seals successfully from a range of abut 90 m, even when the rear of the container faced away from the reader. Open distances greater than this, without concern about reflections from nearby container stacks or buildings, were not available at the various test sites used at the terminal.

4.2.4. Seal-to-Reader Range Maps

Whereas tests reported above largely measure the performance of the seal and are designed to generate data that can be scaled to account for changes in reader design, this test measures performance that depends heavily on reader sensitivity (e.g., reader hardware, firmware, and antenna designs).

This test is intended to generate an azimuthal map (in the horizontal plane) of the range at which the seal can successfully communicate to the reader. It was anticipated that this Seal-to-Reader Range Map would have a profile that is analogous to the Seal Signal-Strength Map.

However, as discussed above with regards to Test 3, the seal-to-reader range is advertised as being on the order of 100 m. At these ranges, reflections from structures around the outdoor laboratory test area become a concern. The signals received by the reader cannot be attenuated to shorten the range because the antenna is built into the reader housing. Therefore, seal-to-reader measurements were performed in conjunction with in conjunction with the On-Road tests.

For these tests, Seal #4000109 was set to beacon at 10-second intervals. The seal was mounted on the roll-up door of a rental truck. Most of the door (the region around the seal) was covered in conductive metal sheeting to provide a large backplane similar to that of a cargo container. The backing magnet was held against the door, thereby setting the stand-off distance between the plastic seal housing and the door. This mounting is shown in Figure A.4.12.

Figure A.4.12. Savi Seal Attached to Coated Roll-Up Door

The omni-directional Savi reader was raised to height of about 19 feet above the road surface and about 10 feet from the center of the lane. The truck was incrementally stepped away from the reader antenna, so that the reader had a view of the seal on the rear door. The seal was consistently read out to a range of about 160 m (550 feet). Since these tests were conducted on a lightly used rural road with trees present off to the sides, no “mapping” of seal-to-reader ranged at various angles was practical. It is expected that the trees would mainly have been signal absorbers rather than providing any significant reflections.

<u>4.2.5. Data Capabilities</u>

As discussed in Section A.4.1, each seal has 4-16 bytes User ID for a factory programmed ID, in addition to system-controlled memory and firmware. According to Savi, each data pulse (~5 msec) contains 98 bits of data. The initial pulse includes the Tag ID, owner ID (if stored), tamper status, and an identifier for its operating mode (beaconing, broadcast, point-to-point), in addition to error-checking bits. The seal can be provided with up to 28kB of additional memory, although a few kB is likely to be more typical, since each event can reportedly be recorded in about 10 bytes of data. Thousands of events could potentially be stored. The seal has an on-board clock that allows events to be time-stamped. Password authentication of a reader is also possible.

In the course of testing the seal and reader performance, we demonstrated the ability of the reader to query a specific seal, to broadcast a query to all seals, and to record and report the RSSI (received signal strength) from each seal. We set seals into and out of beacon mode via a broadcast instruction from the Signpost. We also daisy-chained together multiple Signposts with overlapping read zones and moved a seal among them. The demo software rapidly reported the updated location (i.e., Signpost) of the seal as it received a stronger signal from one or another Signpost.

A.5 ALL SET ALL SEAL

In this section we present results and observations from laboratory testing of ALL Seal product provided by All Set Tracking AB, Serial numbers #35 and #28.

A.5.1 All Set ALL Track System Description

The ALL Seal is part of the ALL Track system offered by All Set Tracking. The seal is a re-usable electronic sensor that transmits information about itself via a radio frequency carrier. All Set provided:

- ALL Seals (model number ATT 10 1-2/1 R0A), and
- a 5V fixed reader with an integrated patch antenna

The seal system operates nominally at 2.44 GHz, using Direct Sequence Spread Spectrum (DSSS) modulation with a 23 MHz broadband bandwidth. The range of the system is advertised as being about 100 feet (30 m), but able to be "tuned" to achieve a range of 100 m. The reported data rate is 1 Mbps. The reader transmits for a period of 0.51 seconds and then listens for a response during a shorter window. The seal listens for a reader twice per second, and it will respond to a broadcast query if it is not instructed to ignore such broadcasts. The advertised life of the seal batteries is several years, with a power draw of 10's of μA.

The seal, two of which are shown in Figure A.5.1(a), is a tamper-indicating sensor. With the container doors opened, the device is inserted over the doorframe, as shown in Figure A.5.1(b). There is a pressure sensor in the long, horizontal section of the seal. Based on readings from this sensor, the seal's internal processor decides whether the door is open or closed. The seal can be placed anywhere along the starboard-side doorframe, but is intended to be placed above or just below the upper hinge. With the door opened, the seal can be easily removed and relocated. The seal can internally record up to 2 kB of data, including:

- a log of the time and type of events (tamper events, reads, writes, sealing, unsealing),
- container ID and its own seal ID
- bill of lading

(a) production units tested (b) prototype being installed

Figure A.5.1. ALL Seals

The seal includes a standard DB-9 serial data connector to accommodate communications with another sensor that the end-user may choose to install inside the container. Such devices could include temperature, motion, or radiation sensors, or digital cameras. We did not test the use of this feature

A.5.2 Test Results and Observations

5.2.1 Frequency Measurement of Seals and Readers

Measurements indicated that seals and reader transmit on a nominal 2.44 GHz carrier.

Figure A.5.2a is a representative frequency scan[18] of the reader output. The resolution bandwidth of the analyzer was set to 1 MHz, its maximum. The sweep time was as fast as possible for the analyzer, 50 msec, so roughly 10 sweeps of this spectral band were made during each 0.51-second query. The curve represents the maximum value detected at each frequency during one or two queries. (The exact amplitude of the signal is not important here, and it has not been corrected for antenna gain or cable losses.)

[18] Figure A.5.2a is not calibrated

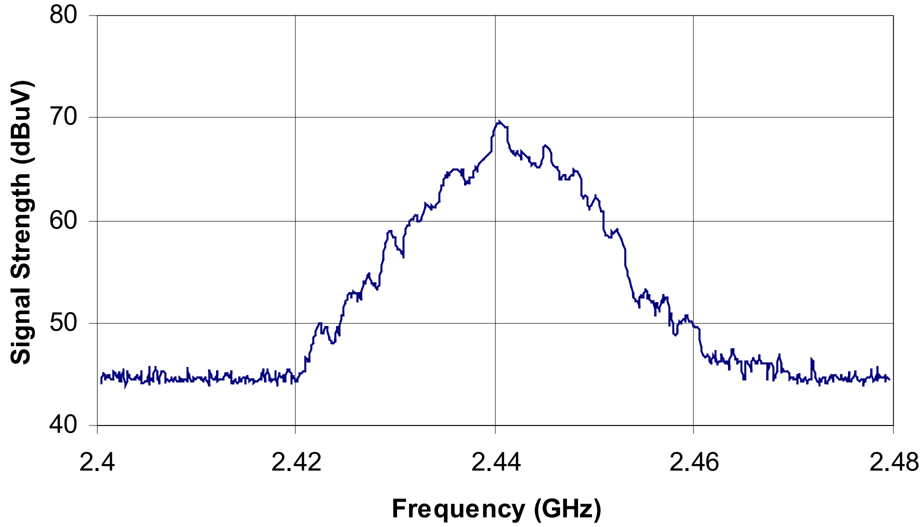


Figure A.5.2a. Envelope of Reader Transmissions

A representative time trace of the transmissions from the reader and seal are shown in Figure A.5.2b. Measured at 2.44 GHz, with a resolution bandwidth of 1 MHz, the sharp peaks are the responses detected from the seal. This is a typical example, as each peak is within ±0.2 dB of the average for all the peaks (some distortion of peak values occurred in the transfer of data from the analyzer to the graphing utility). The query signals from the reader are the seen as lower-strength bursts of about 0.5-second duration (the strength appears lower because the measuring antenna was directed at the seal and away from the reader).

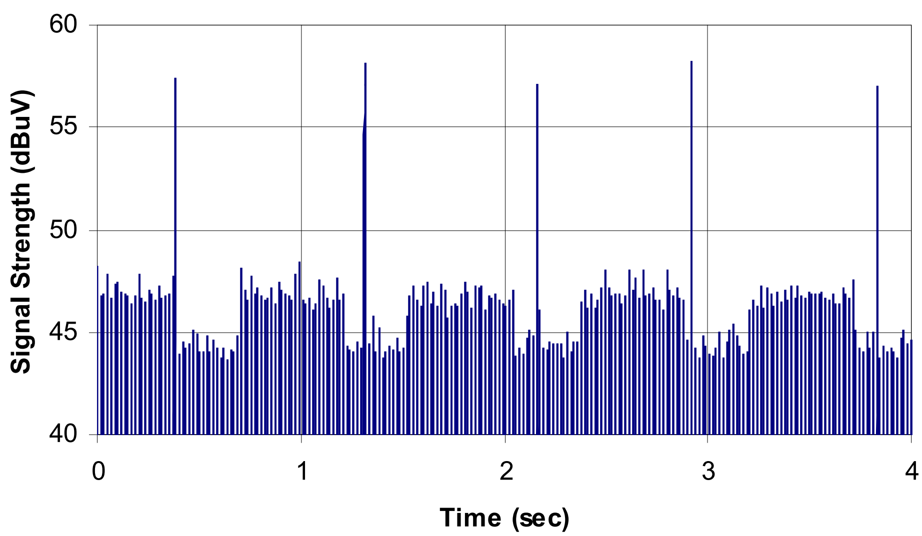


Figure A.5.2b. Trace of Reader Queries and Responses from Seal, at 2.44 GHz

When the reader detects a seal (or possibly just ambient signals in the frequency band of interest), the gap between reader transmissions is about 330 msec. When no seals are detected, the time between queries shortens to about 140 msec.

5.2.2 Seal Signal-Strength Maps

It is expected that, all else being equal, the RF field strength radiated by the ALL Seal in a given direction will correlate with the seal-to-reader range in that direction. The purpose of this test set is twofold:

- To generate data to support numerical modeling of the ALL Seal's radiation pattern.
- To generate RF signal-strength data that, together with the output of the numerical models, can be compared against seal-to-reader range measurements discussed later.

Tests were conducted both with and without a container door present. Without a container door present, the measured field pattern is attributable primarily to the ALL Seal's antenna and construction. These measurements provide data to help build and validate numerical models of the seal's RF characteristics. With a container door present, the measured field pattern includes the effects of reflections of RF waves. These reflections introduce the possibility of constructive and destructive interference, especially in the vicinity of the seal. Hence, the field-strength map may differ from that of the seal without the door.

Test Environment

All tests were conducted using a 2.44 GHz yagi antenna, co-axial cable, and an Advantest R3131A spectrum analyzer. Because the seal has broadband output over a 23 MHz bandwidth, different frequencies may have different radiation patterns from the seal antenna. It was not feasible to map the seal's signal strength over the continuum of the seal's 23MHz bandwidth. However, because the 23MHz bandwidth is only 1% of the center frequency, we do not expect the radiation patterns to vary much over the bandwidth. Also, depending on the seal's orientation, the peak signal detected at the yagi measuring-antenna would occur at slightly different frequencies over a range of about 10 MHz. It was also doubtful that the analyzer, with its 50 msec sweep time, was catching enough of the seal transmissions (which occur in a few milliseconds) to provide a meaningful signal value.

It was decided to measure the transmissions at 2.44 GHz, with the resolution bandwidth of the analyzer was set to 1 MHz with a sweep time of about 4 sec. This generated traces such as that shown in Figure A.5.2b. The peak value recorded out of four or five sequential peaks was used as the signal-strength value for that seal position. This approach provided very consistent and repeatable data.

Open-Air Testing

Description

The All Set seal was attached to a plastic mount, atop a leveled, rotary stage on a tripod. The tripod was adjusted so that the center of the ALL Seal was 1.52 m (5 ft) above ground level (Figure A.5.4).

Figure A.5.4. Rotary Mounting for All Set Seal

Two sets of measurements were made:

- one with the antenna axis in the same horizontal plane as the seal and aimed at the seal (Figure A.5.5.a), and
- one with the antenna elevated above the seal plane, with the antenna axis aimed downward at the seal at an angle of 30° (Figure A.5.5.b).

For both the at-level[19] and elevated configurations, measurements were made with the antenna rotated into two orthogonal positions: with the antenna elements in the vertical plane (Figure A.5.5.c), and with the elements in a plane that also contains the seal (Figure A.5.5.d). The antenna used for these measurements is shown in Figure A.5.6 and has a plastic radome covering it; the antenna of Figure A.5.5 is shown simply to illustrate the orientation of the elements inside the radome. For each set of measurements, the antenna was mounted on a mast and located so that its center element was nominally 3 m from the seal. Temperatures for these tests were around 21°C (70°F).

[19] At-level means that the antenna is in the same xy-plane (constant z) as the seal

(a) Level, horizontal (b) Elevated, "vertical" (c) Vertical
elements (d) Elevated, "horizontal"

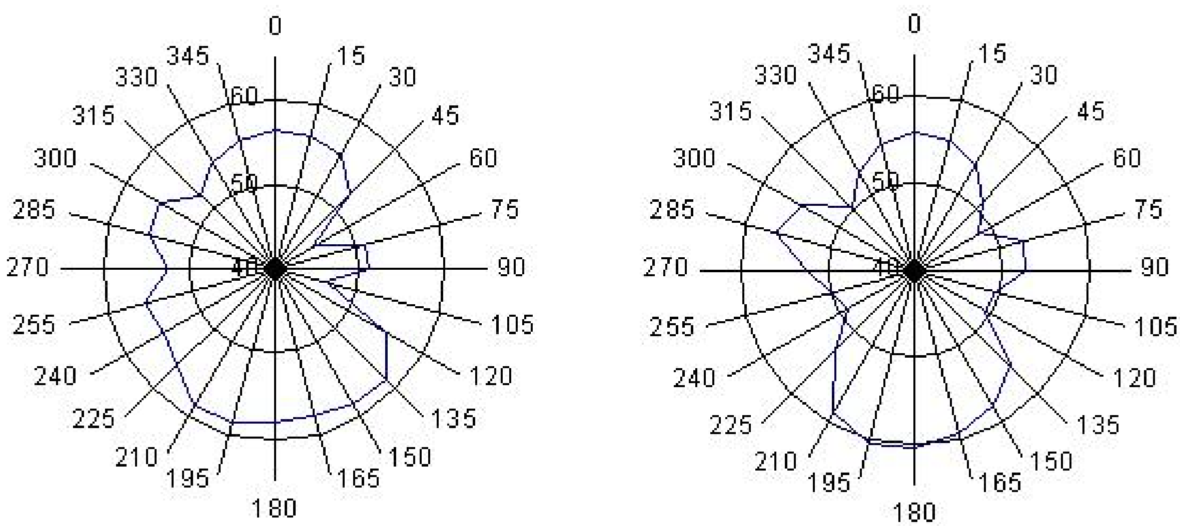
Figure A.5.5. Four Orientations of the Elements in the Measuring Antenna

Figure A.5.6. 2.44 GHz Yagi Antenna (with radome) Used to Measure Signal Strengths

Using the rotary stage, the seal was rotated through 360° (around z-axis), in 15° increments. Measurements were made with the seal tripod at the nominal 3 m distance from the antenna. The measurements were repeated with the seal tripod moved one-half wavelength (about 6 cm) further from the antenna. In the results presented below these measurements, after applying correction factors to each, were used to calculate the average.

Open-Air Test Results

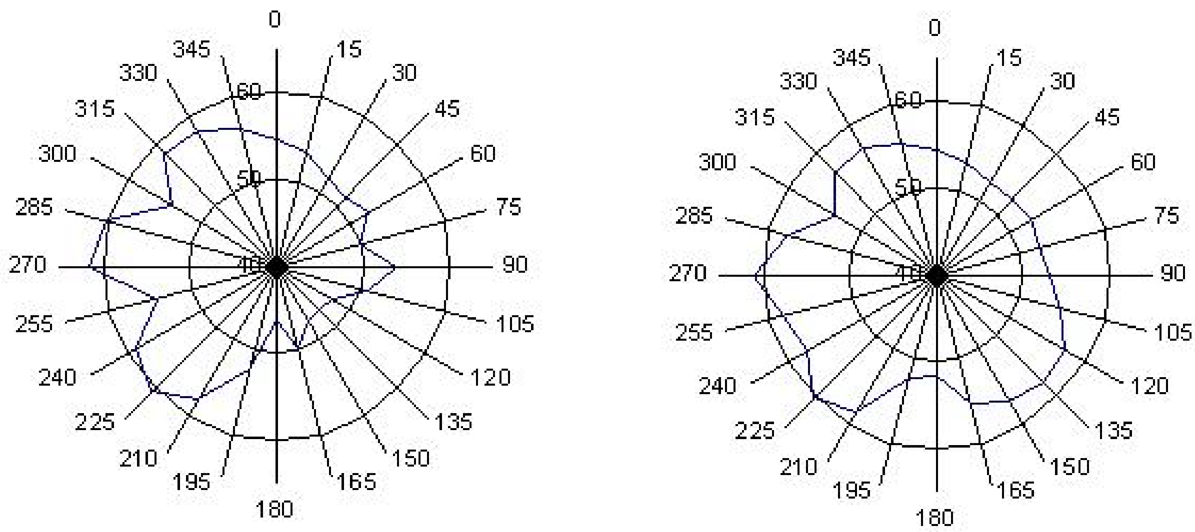
Figure A.5.6 shows the averaged signal strengths measured with the elements of the measuring antenna in a vertical plane. Both sets of raw data (at the nominal position and at one-half wavelength away in the horizontal plane) showed this same pattern, indicating that the low- and high-intensity features of the patterns were not generated by reflections from the surroundings.



(a) At Seal Level (b) At 30° Inclination

Figure A.5.6. Measured Signal Strength (relative dBμV), Horizontal Plane Pattern (Vertical Polarizaton)

Figure A.5.7 shows the signal strengths measured with the elements of the measuring antenna normal to the vertical plane. In Figure A.5.7.a, the antenna axis and elements are in the same horizontal plane as the seal, as in Figure A.5.5.a. In Figure A.5.7.b, the antenna axis is aimed at the seal from above, and the antenna elements are horizontal, as in Figure A.5.5.d.



(a) At Seal Level (b) At 30° Inclination

Figure A.5.7. Measured Signal Strength (relative dBμV), Horizontal Plane Pattern (Horizontal Polarizaton)

On-Door Testing

Description

Photos of the hinge area of an actual container are shown in Figure A.5.8. A half-height, full-width simulation of a container door was built, including keep bars, as shown in Figure A.5.9. A simulated hinge was added to it and the All Seal was attached, as shown in Figure A.5.10. This structure was intended to replicate the small features found around the hinge area. On an ISO container, the slot ahead of the hinge pivot rod provides a possible patch for signals to be transmitted to the starboard side of the container, so it was important to include it in the simulated hinge. The lab tests were performed after the tests at the cargo terminal. Since the seal was installed just below the hinge at the terminal, the simulated hinge region was modified to allow the seal to be placed below the hinge.

Figure A.5.8. Hinge Region of ISO Cargo Containers

Figure A.5.9. Simulated Container Door, Before Addition of Hinge Structure

Figure A.5.10. Simulated Hinge Region and Seal Mounting for Lab Tests

The antenna was mounted on a mast, its axis aimed at the seal. The mast and antenna were moved into seven angular positions in a 180° arc around the seal (Figure A.5.11).

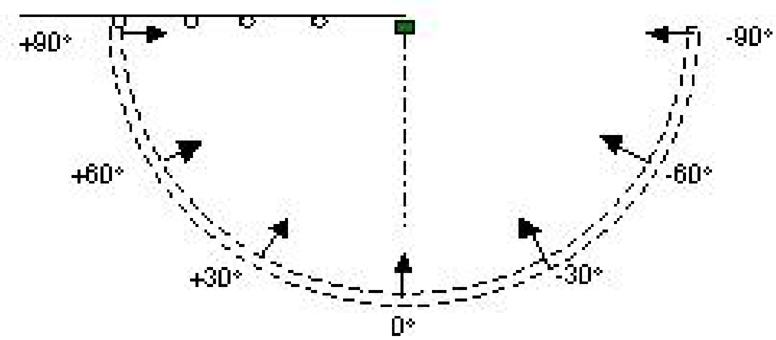


Figure A.5.11. Diagram of Nominal Antenna Positions Around Seal on Container Door

At the level of the seal, the yagi antenna was rotated into two orthogonal positions, to measure the vertical and horizontal polarization of the RF field. Also at each angular position, measurements were made with the antenna located so that its center element was approximately 3 m from the seal, and again with the antenna moved one-half wavelength (6 cm) away from the seal, along the same angular path from the seal. After the corrections discussed earlier, these two measurements were averaged to calculate a representative field strength for that position.

In a second set of measurements, the reader was placed at the same seven positions around the seal, aimed at the seal, and the RSSI values (signal strength returned from the seal) were measured.

On-Door Test Results

The on-door test results were measured with the monitoring antenna at the level of the seal. The results are plotted in A.5.12 through A.5.14. Figure A.5.12 shows the vertical polarization measurements using the yagi antenna.

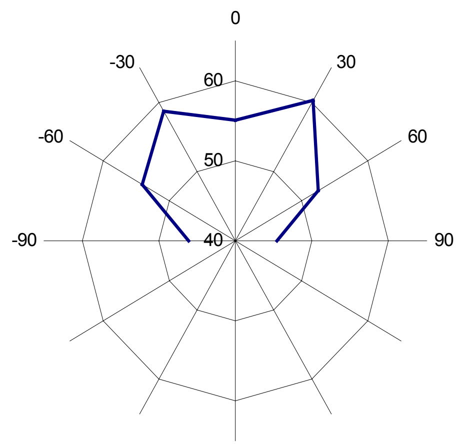


Figure A.5.12. Measured On-Door Signal Strength (dBμV) at Seal Level, Vertical Polarization

A definite strong point was detected in the –30° direction. The strength measurements were less consistent in the +30° direction, but peak values were measured as shown in the plot. At the –90° and +90° directions, signals were barely, if at all, distinguishable above the noise. So, the value of the noise floor was used in the plot.

Figure A.5.13 shows the horizontal polarization measurements at the seal level obtained using the yagi antenna. There is a definite signal drop-off in the –60° direction.

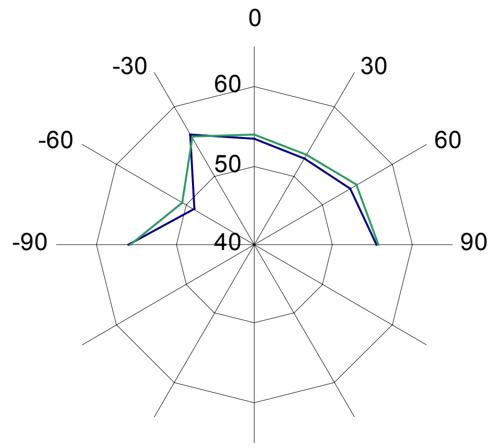


Figure A.5.13. Measured Signal Strength (dBμV/m) On-Door at Seal Level, Horizontal Polarization, Horizontal Plane Pattern

Figure A.5.14 shows the RSSI measurements at the seal level obtained using the reader's integrated patch antenna. Note that the RSSI value reported by the software may be based on signals received at the strongest frequency, or from a combination of frequencies; that was not determined. From the −60° viewing angle, the reads were variable and infrequent. The RSSI value shown is that measured when a read was successful. No reads were achieved in the 0° position[20], despite moving the reader away and returning it.

[20] No signals were received in 0 position, another graphical representation for no-signal received, would be to a data point down to "150". Unlike Figure A.5.14, Figures A.5.12 and A.5.13 were signal strengths measured with a separate yagi antenna connected to spectrum analyzer.

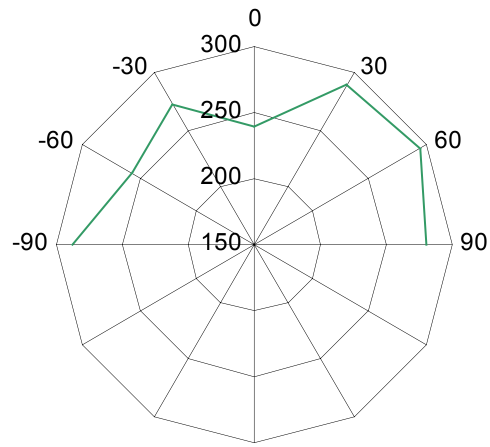


Figure A.5.14. Measured On-Door Signal Strength (RSSI) at Seal Level

5.2.3 Reader-to-Seal Range Maps

In the lab, when testing at ranges of 7 m or more, reflections from the boundaries of the test area became a concern. So, this test was performed in conjunction with the on-road testing described in section D of this report. The on-road testing was performed using a rental truck with a roll-up door. Most of the door (the region around the seal) was covered in conductive metal sheeting to provide a large back-plane similar to that of a cargo container. The All Set seal was positioned behind a small gusset plate in the lower corner of the door. This area provided structures that were similar (though not identical) to those of an ISO container: a vertical "lip" that blocks the line of sight of the seal from the starboard side of the container, and a gusset plate that provides a some shielding of signals directly rearward of the seal. The roll-up door was opened slightly to allow the seal to be placed in its intended orientation, and then the gap beneath the door was covered with metal sheeting, to restore the reflective back-plane. This construction is shown in Figure A.5.15. For All Set, the height of the reader antenna was only about 1.5 feet above the height of the installed seal.

Figure A.5.15. Views of ALL Seal During and After Installation in Door Seam

The reader, with its integrated antenna, was placed on the side of the road, about 10 feet from the center of the lane. It was aimed at the back of the truck. The truck was incrementally moved away from the reader. Reads were consistent out to a distance of about 310 to 340 feet (~100 m). Readability (defined as the ability to read the seal's ID) remained intermittent out to about 500 to 550 feet (~150 m), not reading at some locations, but reading again at a slightly longer distance. After this limit, reads largely ceased.

<u>5.3.4 Seal-to-Reader Range Maps</u>

The ALL Set radio is TDD (time division duplex) type and peer-to-peer (symmetric, i.e. equal power levels and half duplex communication), hence we expected the two links to be of equal strength.[21].

With a single reader, it was not possible to determine whether the read limit was caused by the reader-to-seal link or the seal-to-reader link. Multiple power sources over a hundred meters apart would be required to perform such a test, sensing near the seal whether it had responded to a query from the reader. Such facilities were not available at the remote site used for the on-road testing. Only if one component were sending more power to its antenna would it be the source end for the stronger link, and that reportedly is not the case.

<u>5.2.5 Data Capabilities</u>

As discussed earlier in this report, the seal has the ability to record internally:

- a log of the time and type of events (tamper events, reads, writes, sealing, unsealing),
- container ID and its own seal ID, and
- a bill of lading

[21] This test is realy designed to evaluate systems with asymmetric links, i.e., FDD(frequency-division duplex) and power amplifiers and LNA in the reader.

Figure A.5.16 shows one of the two user-interface windows that are always present when using All Set's demo software. In this case, it list two seals that were detected locally after scanning for seals. We had entered a Container ID to the memory of Seal #35, and this data was returned, along with the seal and alarm status, when the seal was detected.

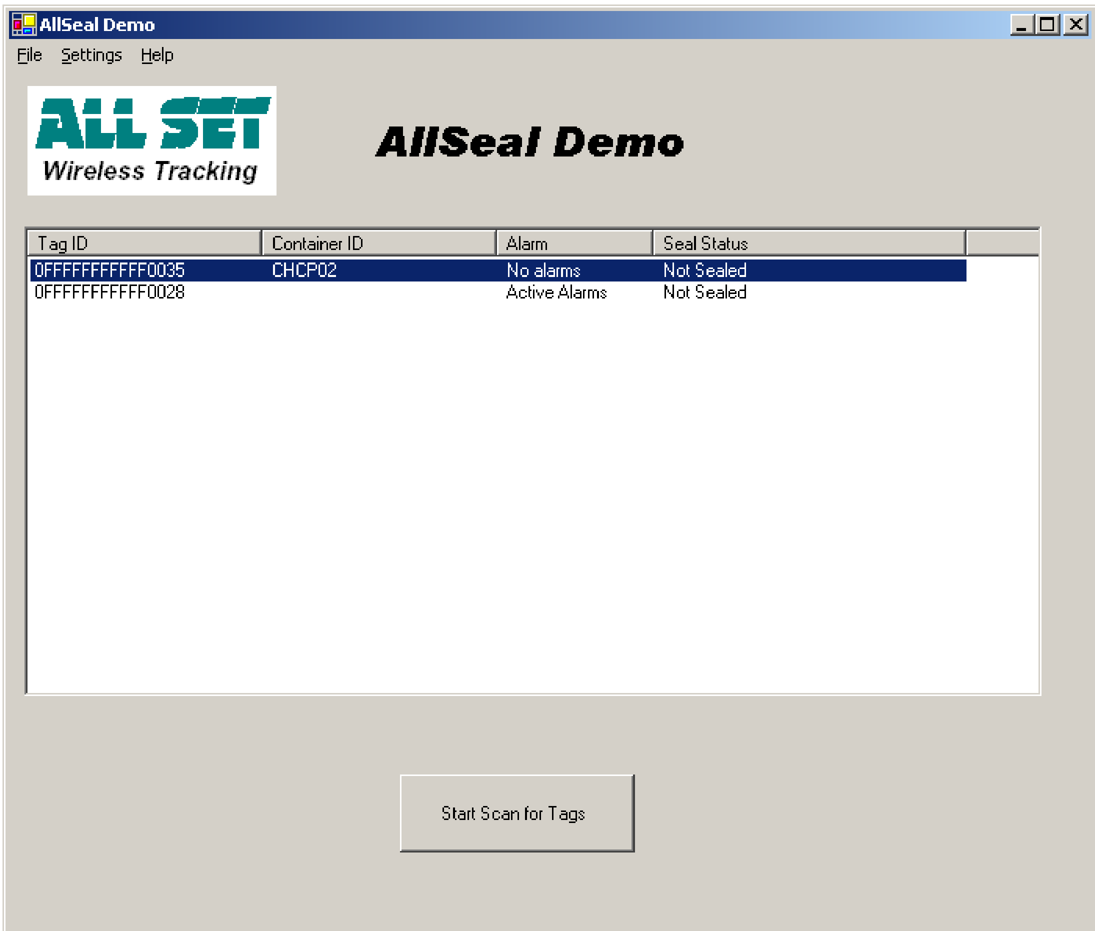


Figure A.5.16. User Interface Window of All Set Demo Software

Figure A.5.17 shows the activity log that can be accessed through the main window of Figure A.5.16. We have successfully applied and removed the "sealed" setting from a seal on a closed container, i.e., put the seal in the container; closed the door; used the demo software to "seal" the door. Demo software indicated status as "sealed". Then opened the door; used software to "unseal" the container.

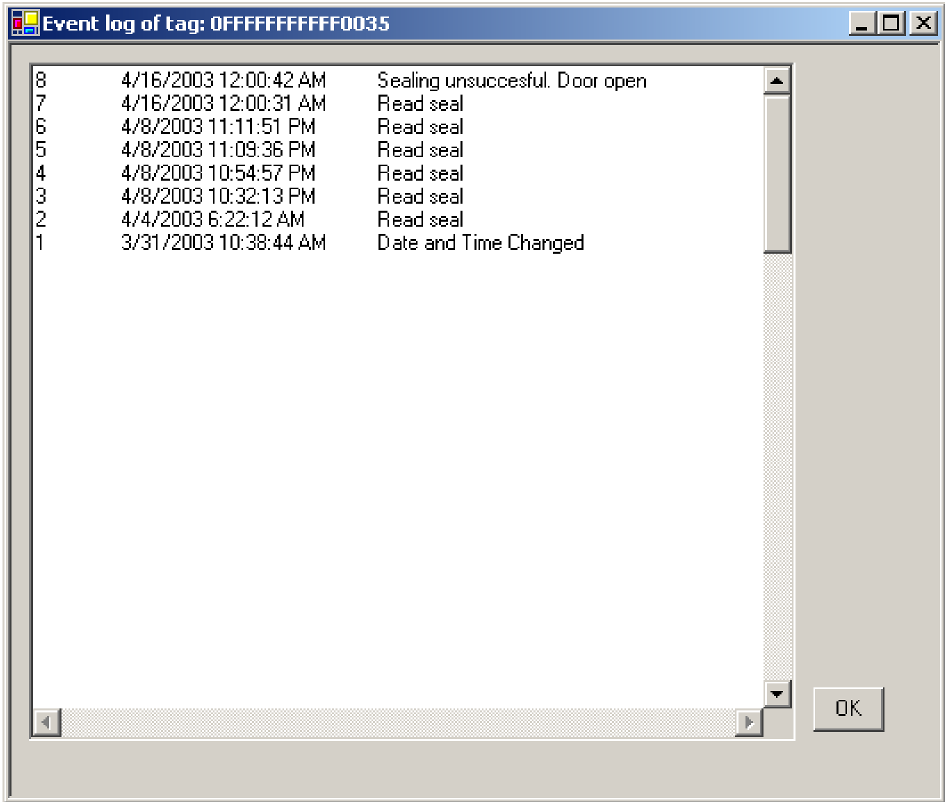


Figure A.5.17. Activity Log for Seal #35

We also added a bill of lading to Seal #35, and retrieved it as shown Figure A.5.18. When a bill of lading is requested via the software, the specific seal is queried, and the data is presented in a window such as that shown in Figure A.5.18.

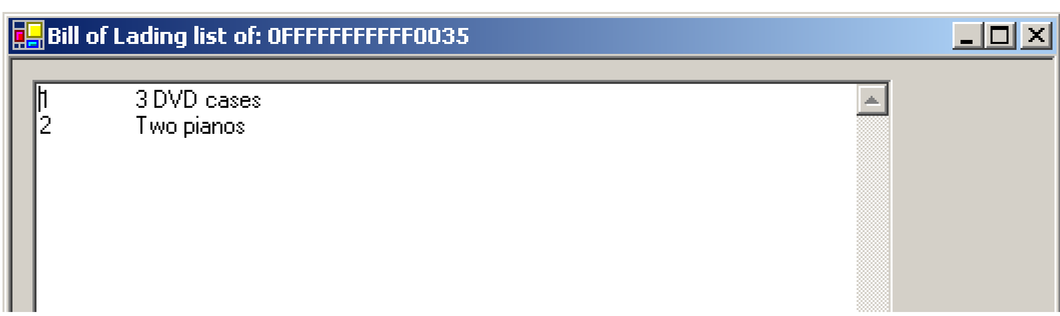


Figure A.5.18. Detail of Bill of Lading Window, with Two Entries Saved in Seal Memory

Finally, Figure A.5.19 shows the other window that is always available when the demo software is running. Of note in this example, the RSSI value is presented (the seal was only a few feet from the reader, providing a high value of 346). Also, the door switch value (1020 is high) indicates that there is essentially no pressure on the switch, as would be the case if the door were open. We observed the variations in this value upon squeezing the seal by hand and when installed in a container.

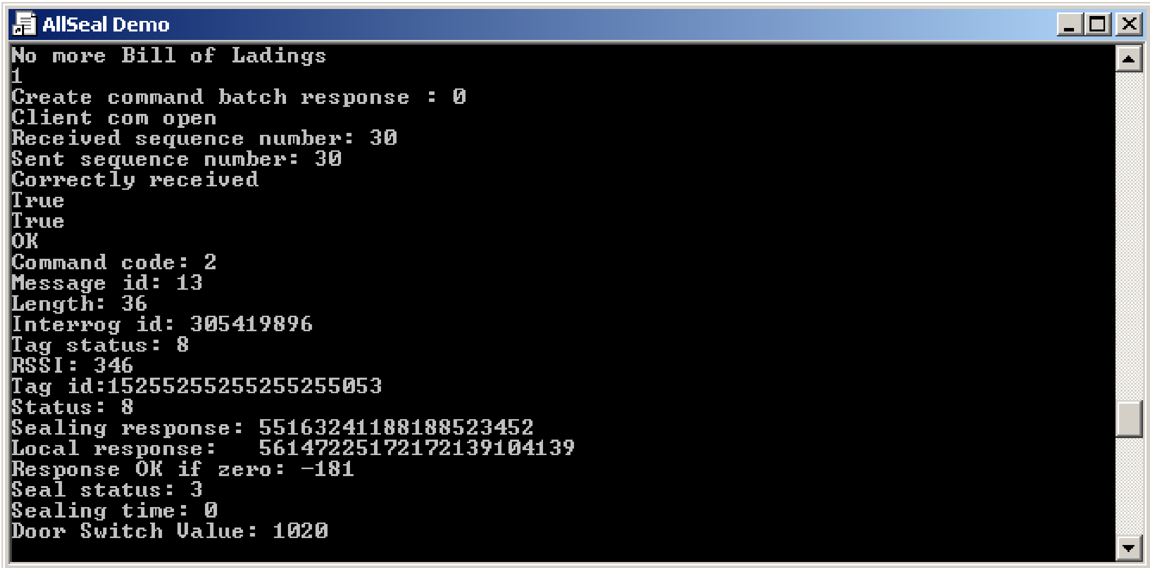


Figure A.5.19. Scrolling Data Window in User Interface of Demo Software

A.6 CGM: MACSEMA+NAVALINK

In this section we present results and observations of our laboratory evaluation of the “MiniButton” contact memory product, manufactured by MacSema, Inc., and provided by CGM Security Solutions. The CGM product is a mechanical container-seal system that provides small recesses into which MacSema’s memory buttons are bonded. This combination allows electronic data to be stored on the container and seal.

Since the MiniButton is not an RF seal, most of the laboratory tests from our test plan were not applicable. Testing of the MiniButton focused only on its capability to record and retrieve electronic data.

A.6.1 CGM / MacSema System Description

CGM offers numerous products for cargo security, including single-use cable and bar seals for cargo container applications, as well as some re-usable versions of these. These barrier seals require manual inspection to identify signs of tampering. The components of a typical single-use system are shown in Figures

A.6.1 and A.6.2. One end of the cable, or of a bolt through a bar seal, can be inserted into a locking head to complete the sealing of the container. The internal construction of the head prevents the cable from being pulled back out.

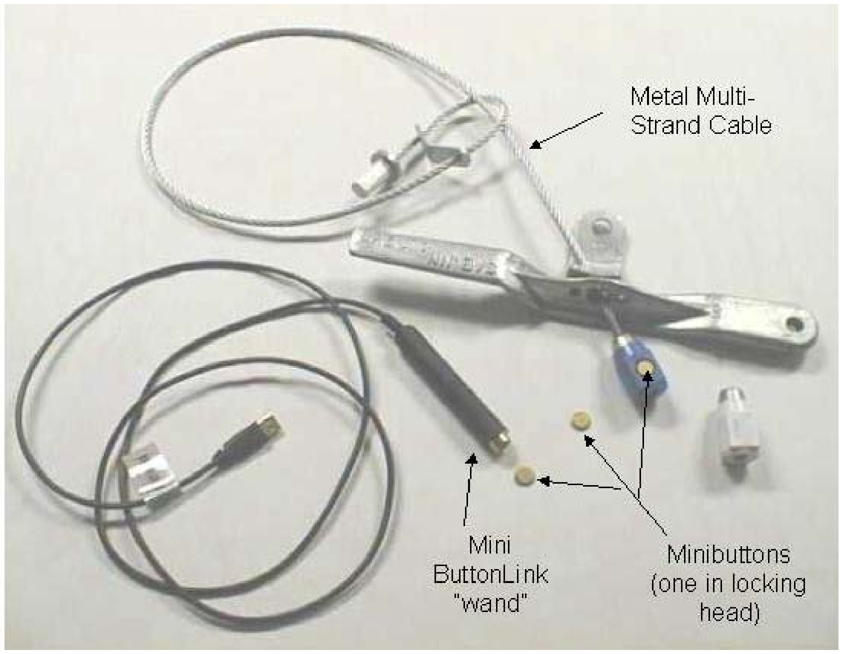


Figure A.6.1. System Components with Cable through Door Hasp

CGM offers locking heads that have small recesses in them. A memory button can be epoxied into the recess to protect against accidental or malicious removal. Alternatively, the button could be epoxied on a surface of the locking system. A second button can be bonded to the container itself. The ID of the seal button can be written to the container button, and vice versa. Operators can then read both buttons to see if the one of the buttons has been exchanged, a sign of tampering.

CGM offers the MacSema Minibutton contact-memory device in these systems. The Minibutton has no internal power source; all power is provided by the reader when it is in contact with the button (requires 6 V at 10 mA). The reader consists of MacSema's Mini ButtonLink wand, with either a serial or USB connector, and software that resides on the user's PDA or other computer. The buttons are available with from 128 bytes to 64 kB of memory. Larger MegaButtons (1.1" diameter) offer up to 8 MB of memory. At a 115.2K baud rate, MacSema reports that a 32 kB button can be read in 2.9 sec.

Figure A.6.2. Close-Up of Memory Button Epoxied into a Locking Head

Although we did not perform environmental testing, the following performance specifications are some of what MacSema provided. Where applicable, testing was reportedly done per MIL STD-810E.

Parameter	Rating	Notes
Storage Temp.	-85°F to 302°F	
Operating Temp.	-85°F to 257°F	
Electrostatic discharge	15 kV	20 pps, human model
EMI	Non-susceptible to RF to 200 V/m	2 - 4000 MHz, 18.5 – 19.5 GHz
EMP	5.8, 26.7, 55.0 kV/m	
Vibration	Worked after vibration equiv. to jet aircraft fuselage, for 15 min.	Vibrated at –85°F and 275°F
Salt Fog	Per STD-810E	Performed normally after
Saltwater	Submerged > 1 month	Performed normally after
Abrasion	80 psi glass beads, AlO(OH)	Performed normally after
Magnetic field	1500 gauss	Performed normally during

For reading and writing, the button and wand must be in electrically conductive contact, so at the time of reading, the seal cannot covered in paint, thick grime, etc. There are distinct contact points on the wand and button, so the they cannot be immersed in water during reading, as this may short the contacts together.

Multiple commercial and DoD customers use the MiniButtons. The MiniButton has been manufactured in its current form factor since 1995.

CGM and MacSema provided several contact memory buttons (8 kB capacity) and a contact wand with a USB connector. They also provided software applications that had been written to demonstrate the features of the button-memory products in various industrial applications. The “Shipping Container” demonstration was used for evaluation of the product. A laptop PC running Windows 2000 was used for these tests; no PDA-based applications were tested.

This evaluation was not intended to find flaws in demonstration software. Our testing primarily showed the typical operations envisioned by MacSema for their memory device in the container shipping industry. The GUI screens, encryption technique, data fields, and use of passwords are currently selected on a custom, application-specific basis.

The demonstration allows three user types: Administrative, Typical, and View-Only. The following example of the MiniButton operation shows the graphical user interface (GUI) for the Administrative user.

One button bonded to a seal we designated as “CHCPSEAL01.” Another button was designated “CHCPCONT02” and represented a button that would be attached to a container. In the GUI shown in A.6.3, this was done by entering the desired name in the “Seal ID (with button)” field. We clicked on “Add Seal ID to Button,” touched the wand to the button, and confirmed our intention when asked by the software. At the top toolbar, we selected “ButtonLink >> Read Button,” and touched the wand to the button. The seal status, transaction date, and serial number then appeared as shown at the bottom of Figure A.6.3.

The Seal ID might typically be initially written to the seal at the factory. Either way, it is simply an alias to help the user classify the seal. The software identifies a seal based on its serial number, which is permanent, not its Seal ID, which can be changed.

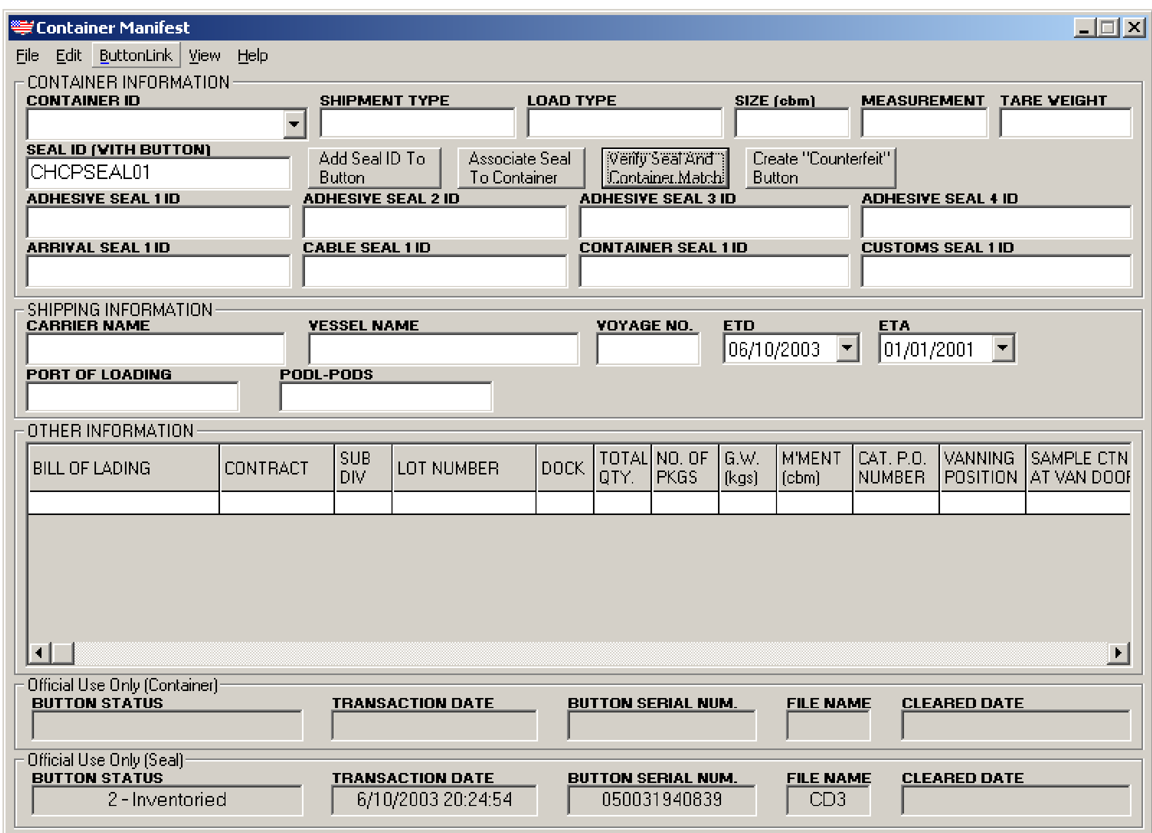


Figure A.6.3. GUI Showing Seal Parameters

We selected a container profile (manifest, carrier, size, etc.) from a pre-defined database (for this demo), and entered the "CHCPCONT02" seal ID. By clicking on "ButtonLink >> Read Button" on touching the blank (no data) container button, the software gave the option of "adding component data" to the button. We were thus able to store the container info to the button.

Upon clicking on "Associate Seal to Container", the software instructs the user touch the wand to the seal button. It then reads the seal-button data (serial number, seal ID, other background data) and instructs the user to touch the container button. The seal-button data is downloaded to the container button, and the computer captures the container data from the container button. The software then instructs the user touch the seal button again. It then downloads the container data to the seal button. Now when either seal is read, the same container data is available.

The buttons' serial numbers are generally encrypted, and MacSema offers different types of encryption depending on the customer's needs.

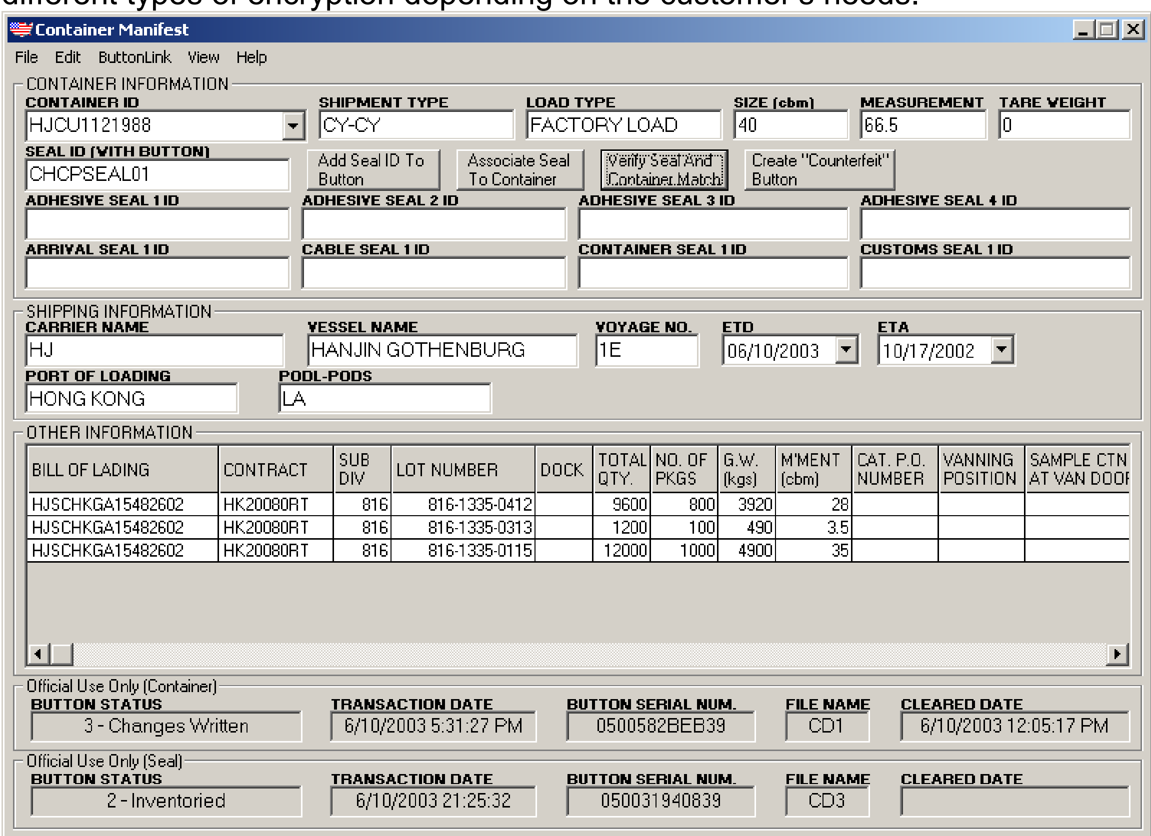


Figure A.6.4. Container and Seal Data After Association of Seal to Container

Upon clicking on "Verify Seal and Container Match," the user is instructed to touch the wand to each button. The software checks to make sure that the container button serial number is what the seal button expects, and that the seal button serial number is what the container button expects.

The software can generate time stamps and audit trails of each read and wrte attempt and store that log on a button. We observed this feature in a separate demo application that incorporated it.

In addition to encryption, the buttons we tested were also reportedly password protected (by and within the software), so that only a software application with the proper password could communicate with these buttons via a wand.

In this demo, the Administrative User had the following authorities that the Typical User did not:

- Clear button status and seal ID's from the container info in the software database
- Add a seal ID to a button
- Delete a file (i.e., all data) from a button
- Add new users
- Create a "Counterfeit" Button, to demonstrate success of encryption

For the Typical User, the GUI is looks the same, except that a couple of buttons are removed.

Also in this demo, the Typical User had the following authorities that the View-Only User did not:

- Save data to the local database
- Associate a Seal to a Container

For the View-Only User, the GUI appears as:

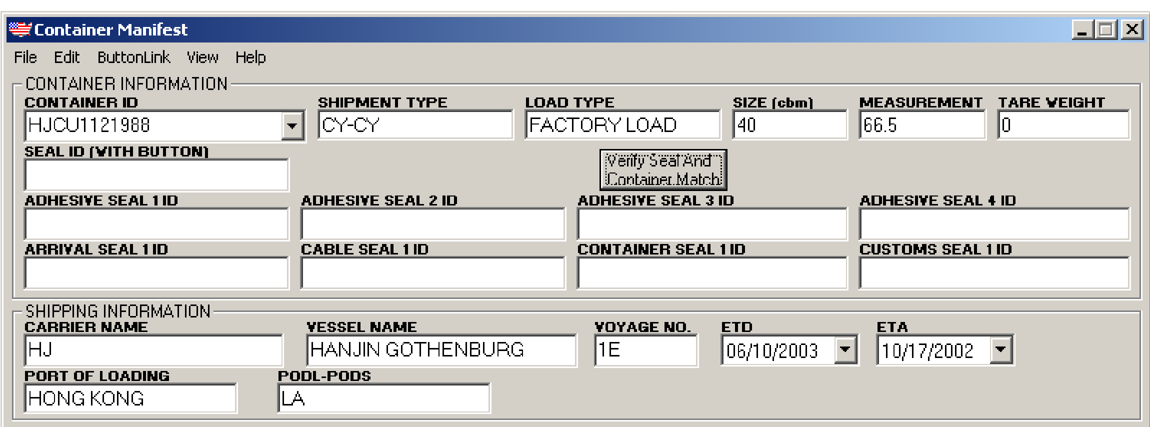


Figure A.6.4. GUI for a View-Only User

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APPENDIX B: GATE-AREA TESTING

B.1 INTRODUCTION

The In-gate area at the terminal is a crowded environment with a lot of structures, most of the time with very heavy traffic, where checking-in and checking-out operation takes about 6-10 minutes, and each lane queue is typically 3-4 trucks deep. It is not clear how well would e-seals perform in this kind of environment. Will gate structures and vehicles be an obstacle? How will it effect readability at different e-seal frequencies? What is the reader range under the described circumstances?

To answer those and other questions the in-gate testing focused on

- Establishing how far out can the reader detect the e-seal (establish the e-seal read –zone) and e-seal readability as the truck is approaching the booth - this is the point when e-seal can be first processed, and
- Testing readers' ability to detect e-seals across different lanes. In a crowded gate environment, the farther the lane from the reader, the more obstacles and interference there are between a reader and e-seal.

The key objective of those tests was to gain understanding about the reader range and e-seal readability in the in-gate environment, with the purpose of evaluating optimum placement of e-seals on containers, as well as placement of reader antennas and readers to achieve their optimum use.

The in-gate tests were performed at the Howland Hook Marine Terminal in Staten Island, NY. Site survey was conducted on January 9, 2003. First part of in gate testing was conducted on January 27-28, 2003, second part was conducted on March 26-28, 2003. Testing was completed on June 2, 2003.

Appendix B presents results and observations from the in-gate testing.

In-Gate Environment

Figures B.1.a- B.1.d show the layout and structures in the in-gate area. Figure B.1a shows the Howland Hook Terminal Gate. Figure B.1.b and B.1.c provide a closer look at the entrance to the gate, and specify the dimensions for booths, islands and lanes. Finally, figure B.1.d provides the view of the ceiling area.

Only 1 to 2 feet between gate ceiling and container roof.

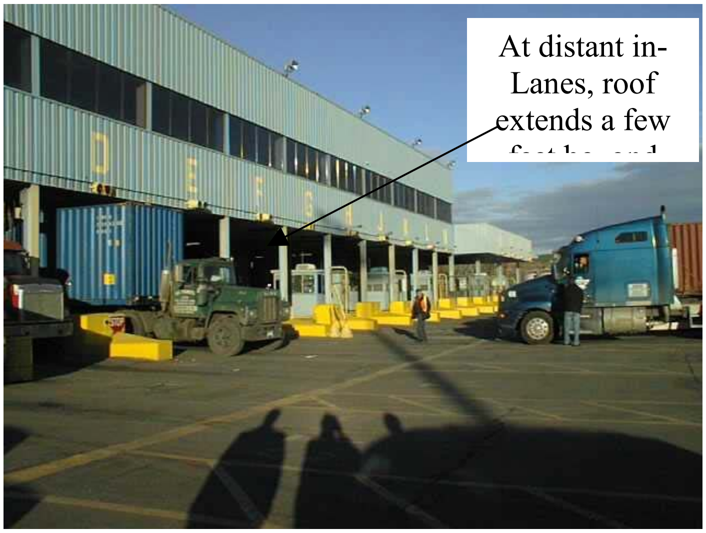

Figure B.1a Howland Hook Terminal Gate

Three I-beam pillars between each Lane (one at each end, one in middle). One booth near entrance side of each island. Some islands serve reversible Lanes; these have a booth at each end.

With truck at rest, rear of container will be 20 ft to 45 ft (6 m to 14 m) from edge of ceiling.

Figure B.1b Howland Hook Terminal Gate – Lane views

Lanes: 10-ft wide (3.05 m)
Islands: 6-ft wide (1.83 m)
Lane center-to-center: 16 ft (4.88 m)

Booth: 8ft long (2.44 m).
Metal base and roof, glass/plastic windows.

Figure B.1c Howland Hook Terminal gate –Booth views

The “ceiling” is 15 feet above the road surface and consists of a metal grid (2-ft x 4-ft) that supports non-metallic acoustic tiles (many missing). Above the islands between Lanes C, D, E, and F are piping and blowers that are suspended from the ceiling Figure B.1d. Between Lanes L and M there is an island-to-ceiling masonry structure (possibly a stairwell housing). Between Lanes M and N is a metal-covered wall, with a mixture of chain-link fencing and equipment at the in-bound side.

Figure B.1d. Details of Piping and Blowers in Gate Area

Gate Geometry and Traffic Flow

Figures B.2.a-c show the in-gate geometry and traffic flow. There are total of 20 lanes, 12 of which are in-bound (Lanes E-S), 4 are reversible (Lanes A-D), and four are out-bound lanes in the uncovered area. The blue boxes (figure B.2b-c) represent the booths/clerk houses; the tops of their roofs are typically nine (9) feet above the road surface. The yellow shapes represent piping and blowers located in the ceiling. Yellow triangles mark the beginning of the island. Figure B.2.c shows a green 20-foot container in Lane F, with the e-seal on the back door of the container. In Lane G, there is another 20-foot container, with no e-seal, and is marked in gray.

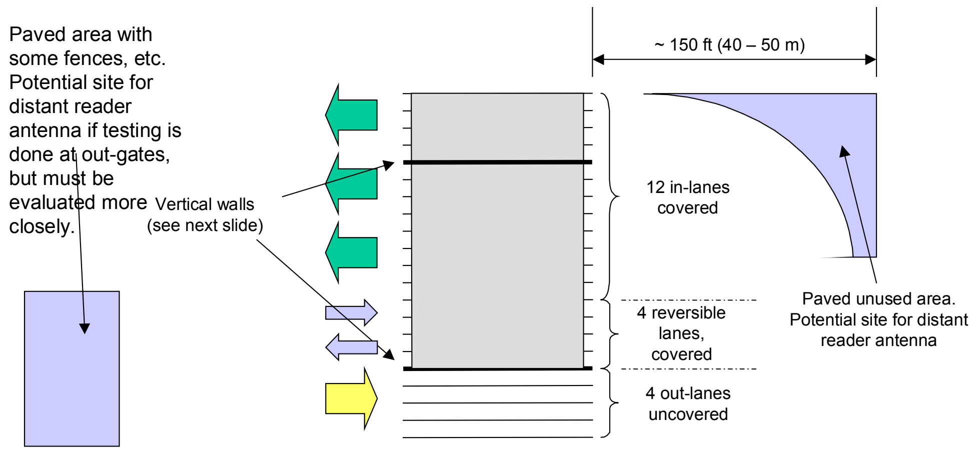

Figure B.2a View of In-gate Area with Traffic Flow

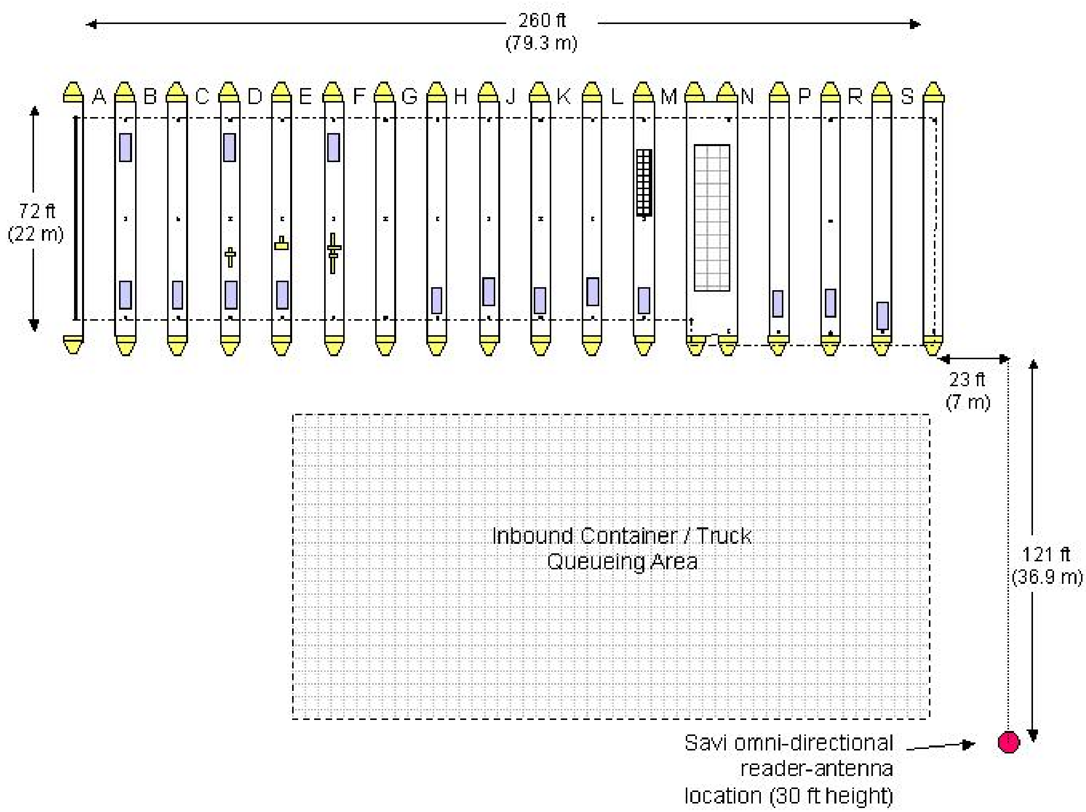

Figure B.2b. View of Gate area with marked position of the Savi Antenna/reader (Lanes A-B are out-lanes)

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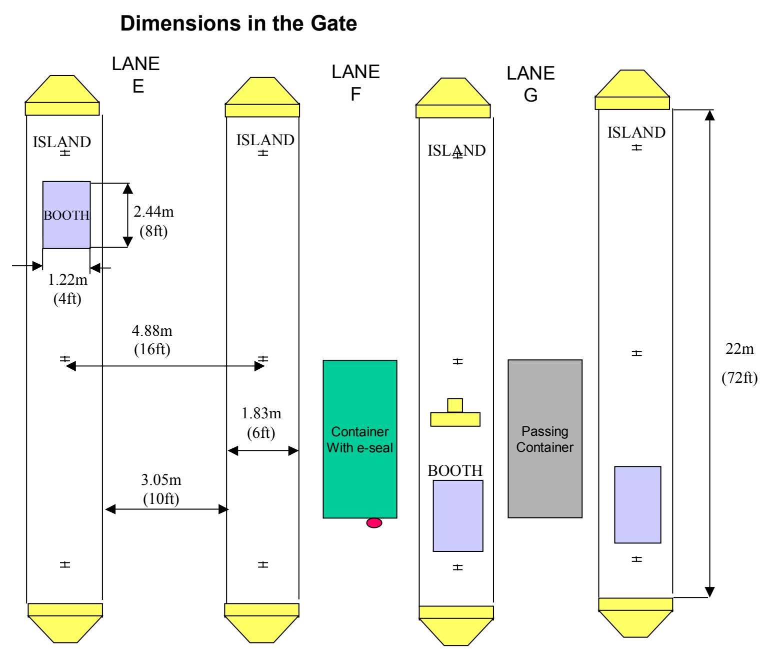


Figure B.2.c In-gate dimensions

Antenna Placement

A vertically-oriented, quarter-wave whip dipole antenna with a circular ground plane was positioned above the E/F island as shown in Figures 3a and 3b. It was placed about 14.5 feet above the road surface, so that its ground plane was slightly below the reflector of a nearby fluorescent lamp. The red circle in Figure B.3b indicates its location. Lanes E and F were selected because they were unused the day of the testing. The lack of clerk houses in islands E/F and F/G minimized large, nearby reflective surfaces. This antenna location was used for testing of Hi-G-Tek, e-Logicity and AllSet seals inside of the gate. Time constraints prevented attempts at optimizing antenna location, which could easily vary among the vendors' systems and would depend on the antenna choice, terminal process requirements, etc. Also, using a longer antenna with a higher gain conceivably could extend the read range. However, the low ceiling and the possible need to place an antenna over a Lane may limit that option. Directional antennae with higher gain are also an option.

Figure B.3a. Antenna Location for e-Logicity and Hi-G-Tek Range Tests

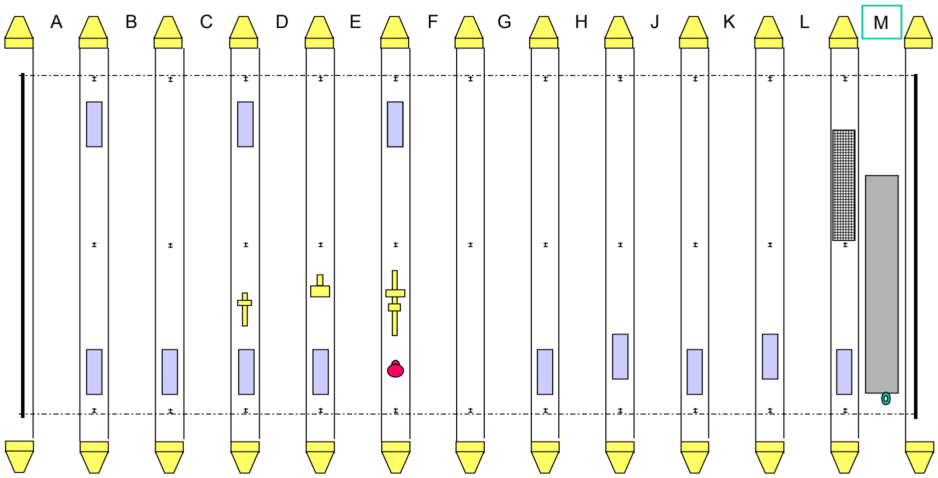


Figure B.3b. Antenna Location for e-Logicity and Hi-G-Tek Range Tests – between Lanes E and F

Savi recommended the external location for their system[1]. Figure B.2b depicts the location of the Savi reader (with integrated antennae) in the gate area – red circle.

[1] There were indications from the other vendors that ranges may be inadequate to reach the in-Lanes if the reader antennae were positioned behind the queuing area. Also, positioning reader antennae inside the gatehouse structure allowed us to examine qualitatively the ability of different wavelengths to travel in a relatively "crowded" environment

B.2 E-LOGICITY TEST RESULTS AND OBSERVATIONS

Gate-Area Readability

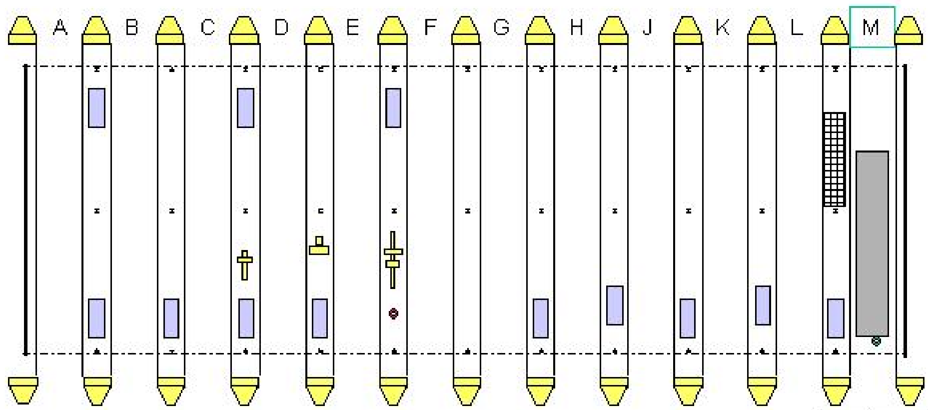
As discussed and illustrated in Laboratory test Report (section A.2), in many cases the e-Logicity seal can rotate about its bolt after installation, affecting signal strength and readability.

We tested the seal in three rotational orientations:

- Position 1: Seal face and barcode facing out from door
- Position 2: Seal rotated 90° so that its label faces the right side of the container
- Position 3: Seal rotated 180° so that its label faces the container.

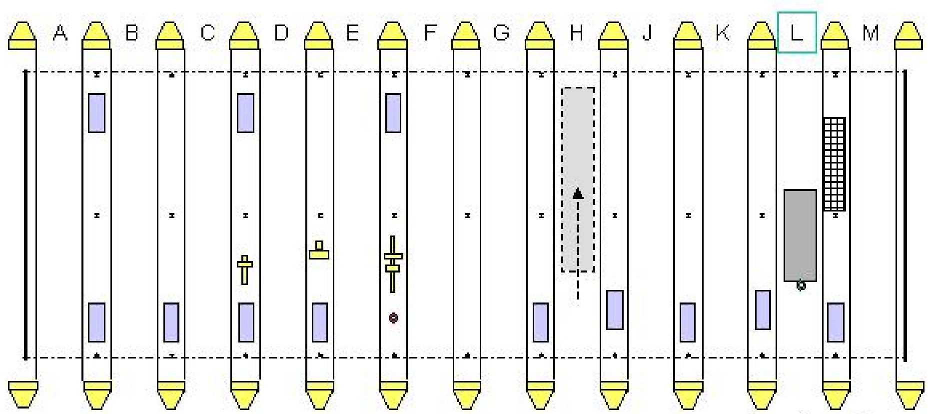
We activated the seal by placing a modified bolt into it. The modification allowed us to place the bolt through the door hasp as would typically be done, but a screw-in plug at the top allowed us to remove the seal and transfer it to another container. (Incidentally, the seal correctly transmitted to the reader that it was "Tampered.") The seal was typically placed on a container as it waited in the queue, and we attempted to read the beaconing seal as the container moved into the gatehouse. Since we were using functional containers during normal gate operations, the containers stopped at various locations. In the queue, the container doors face away from the reader antenna, and no e-Logicity seals were read while in the queue.

Figures 4 and 5 show the results obtained when containers stopped in Lanes M and L, respectively. Several readings (each 10 seconds apart because of the seal's beacon rate) were made with the seal in each rotational position. All readings (except one) for both Lane M and L were successful. For example in figure 4, with container in Lane M, and with the seal in position 1, 5-of-5 reads were successful. In figure 5, with container in Lane L, and seal in position 2, 3-of-3 reads were successful, as another container moved through Lane H. A possible reason that caused one missed read in position one maybe a refraction of the signal from the surrounding structures moving container.



Pos.	Rate
1	5/5
2	7/7
3	4/4

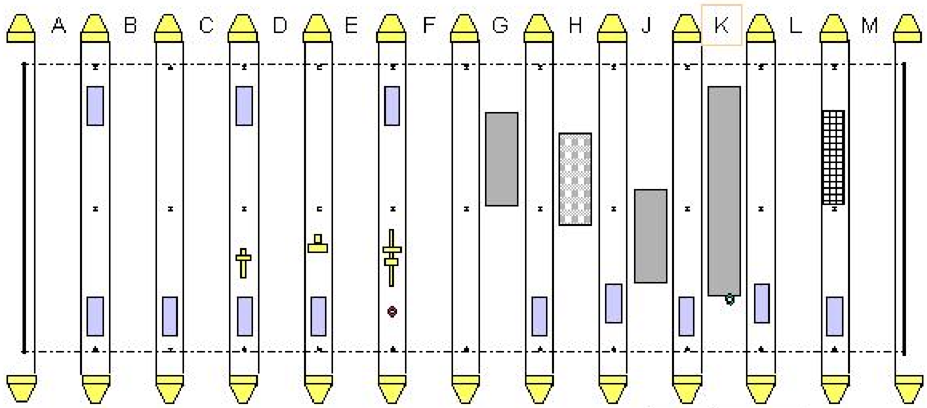
Figure B.4. e-Logicity Seal in Lane M



Pos.	Rate
1	12/13
2	3/3
3	3/3

Figure B.5. e-Logicity Seal in Lane L

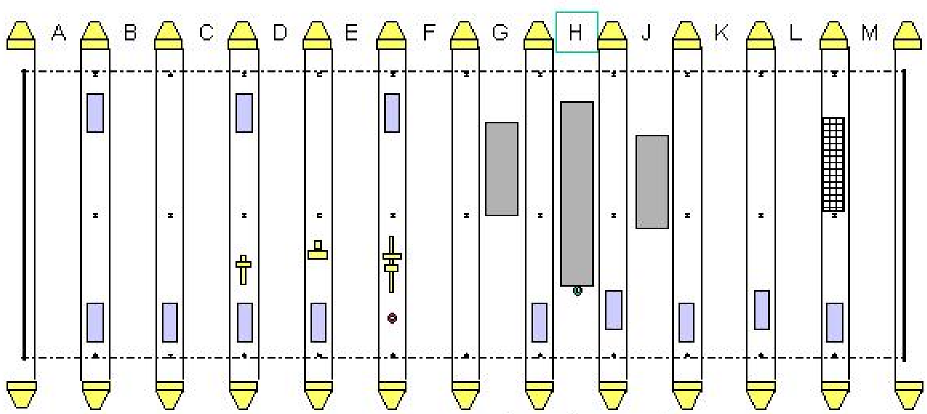
In Lane K, as shown in Figure B.6, with a container in Lane J and clerk house nearby, reads were only achieved with the seal in Position 2. Lane H contained only a chassis. Also, there was an existing bolt seal in the handle, so our seal was placed in the outboard latch on the right-side door.



Pos.	Rate
1	No reads
2	4/7
3	No reads

Figure B.6. e-Logicity Seal in Lane K (seal on outboard latch)

Figure B.7 shows consistent reads in all seal positions in Lane H. Because of the proximity to the two clerk houses, there were often drivers walking near the seal; this apparently had no adverse effect.



Pos.	Rate
1	3/4
2	4/4
3	6/6

Figure B.7. e-Logicity Seal in Lane H

Containers in Lanes A-D were outbound, so there was never a clear line of sight from the reader antenna to the doors. Figure B.8 shows a container in Lane D that had bolt seals in both right-door latches. So, we tested the seal on the inboard latch of the left-side door. Very good reads were obtained. We then taped the seal into place, hanging from the in-board latch of the right-side door.

No reads were obtained. For comparability, we taped the seal into position on the left-door latch; this still provided good read rates. This door is shown in Figure B.9. The left-door latch is about 27 inches (68 cm or about one wavelength) to the left of the inboard right-door latch.

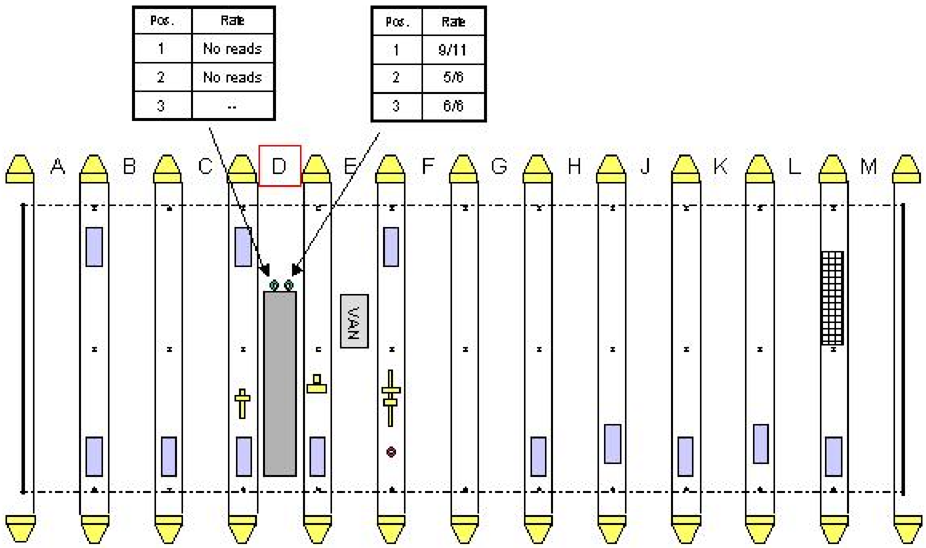


Figure B.8. e-Logicity Seal on Outbound Container in Lane D

Figure B.9. Container Door from Figure B.8 (Lane D)

With no other containers around, a seal in Lane C had to be placed in the outboard, right-door latch. As shown in Figure B.10, no reads were achieved.

When the container pulled forward, so that the seal was past the clerk house as shown in Figure B.11, good reads were achieved. Compared to the case in Figure B.8, the angle from the back left corner of the container to the reader antenna Figure B.11 is not as sharp. This may contribute to the readability from seals placed on the right door.

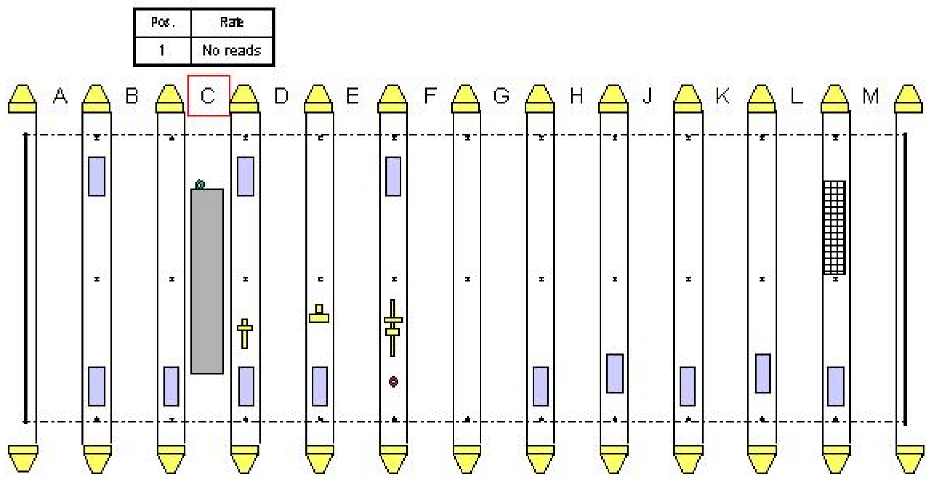


Figure B.10. e-Logicity Seal on Outbound Container in Lane C

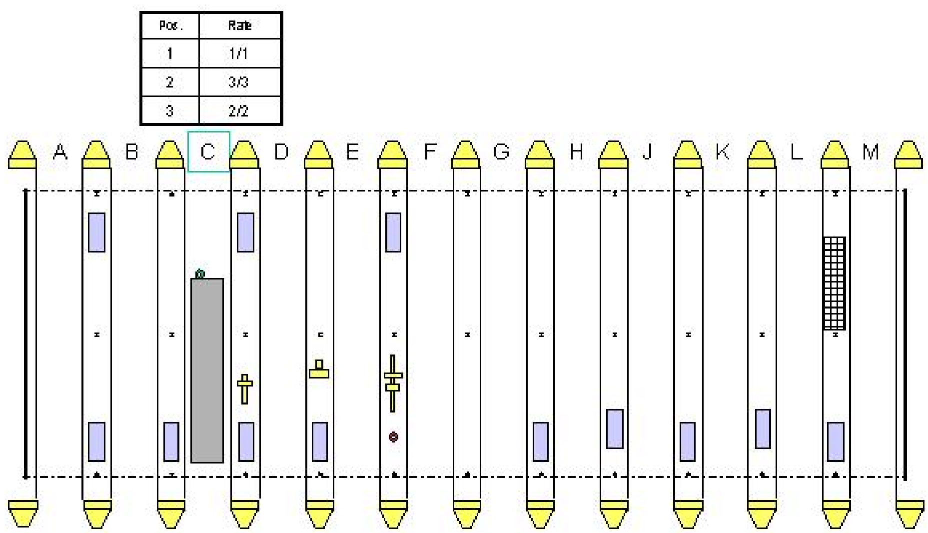


Figure B.11. e-Logicity Seal on Container Pulled Forward in Lane C

Figure B.12 shows a different container in Lane C, with the seal still on the outboard latch. With containers in Lane D and B, good reads were obtained in seal Positions 1 and 2, but reads were inconsistent in Position 3. Because of the proximity to the clerk house, drivers were walking and standing in the general vicinity, though not immediately next to the seal.

Pos.	Rate
1	3/3
2	3/3
3	3/10+

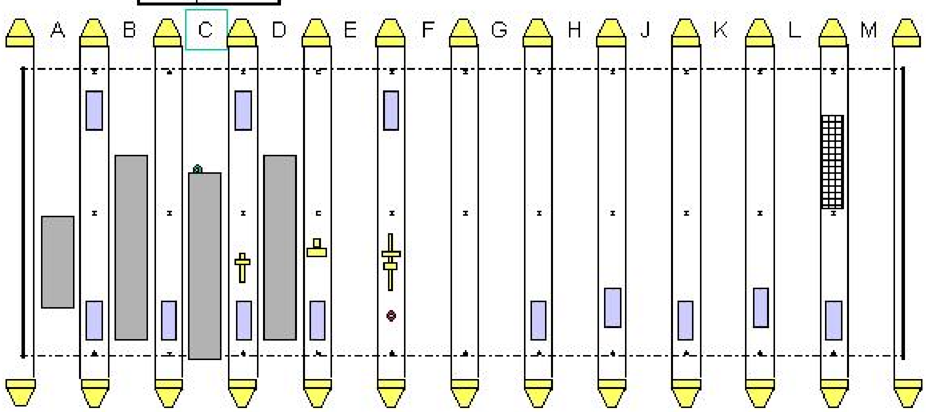
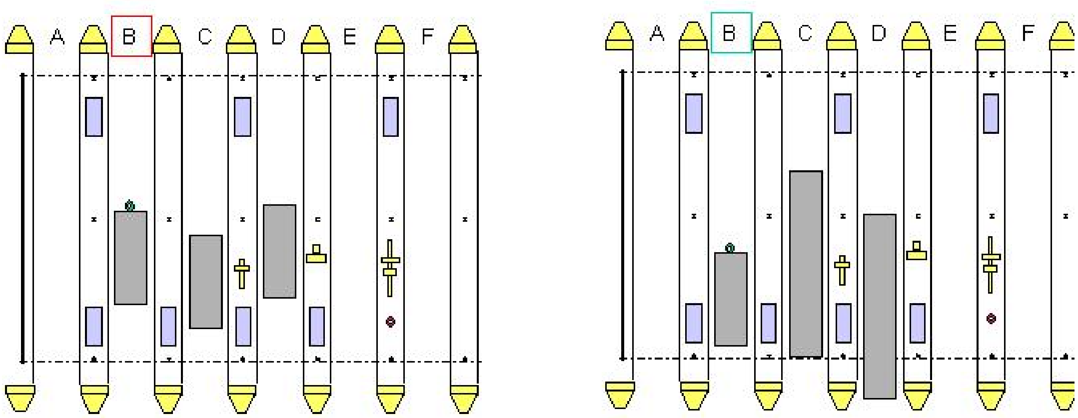


Figure B.12. Containers Surrounding e-Logicity Seal in Lane C

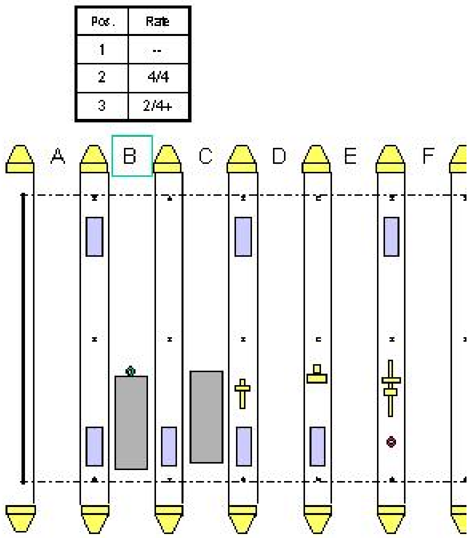
Numerous situations occurred while the seal was on containers in Lane B; these are shown in Figures 13(a) through (e). These results in 13(b) suggest that the presence of a container in Lane D (closer to the reader antenna than Lane C is) may have caused read problems when the seal was in rotational position 2. Also, at least for position 2, reading was more difficult when the container was further back in the Lane (i.e., signals must “turn” a greater amount around the container corner to reach the antenna). In that case (Fig. 13(a)), the I-beam support pillar in island B/C was also near the corner of the sealed container.

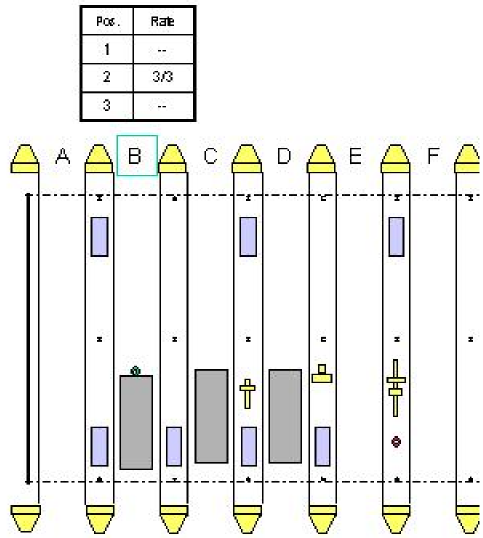
Pos.	Rate
2	No read

Pos.	Rate
1	4/4 (from entry to stop)
2	2/2, then missed several, even with Lane C vacated
3	--



Figures 13(a) and 13(b). Situations with e-Logicity Seal in Lane B





Figures 13(c) and 13(d). More Situations with -Logicity Seal in Lane B

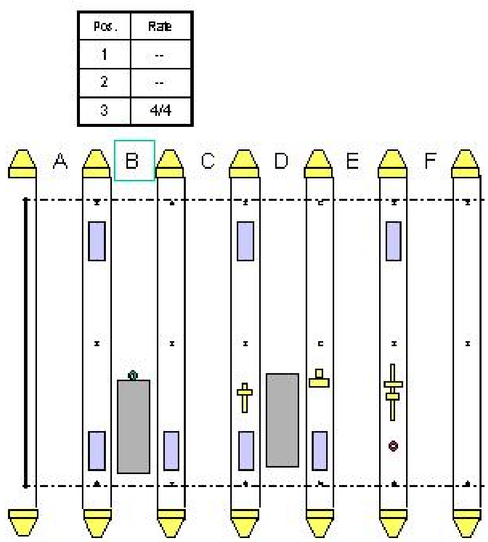


Figure B.13(e). Situation with e-Logicity Seal in Lane B.

Signal Strength

The same seal was placed on a parked container in Lane E, as illustrated in Figure B.14. Using the same antenna as above (quarter-wave dipole with a circular ground plane), field strength measurements were made at a number of lateral locations, at two heights, in two vertical planes, just outside of the gatehouse structure. Figure B.14 shows the locations of these planes (red lines) and locations (red circles).

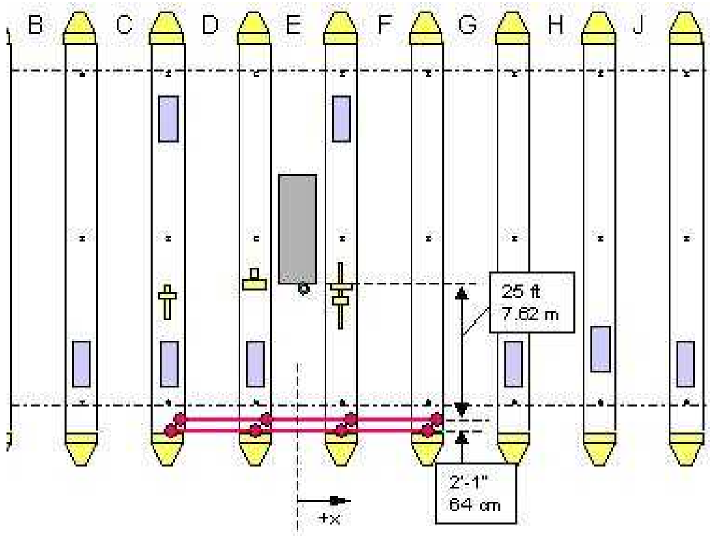


Figure B.14. Schematic of Sealed Container and Field Measurement Points

Figure B.15 shows the antenna in one of these locations. The data are presented in the Table below. They have been corrected for cable losses. Note that there is a different antenna-to-seal elevation angle associated with each measurement point. The antenna may have a somewhat different gain at each such orientation. This must be taken into account in the modeling and in further data reduction. In the Table, Corrected Strength values shown as "32.7" dBμV were actually at the noise floor of the instrumentation; no pulse from the seal was discernible at these points.

Figure B.15. Antenna Outside of Gatehouse Structure

Distance Along Lane (m)	Distance from ctr of Lane E (m)	Height (m)	Seal Orientation	Corrected Strength(dBμV)	Notes
7.62	-6.68	3.91	1	45	
7.62	-6.68	3.91	2	39.7	
7.62	-6.68	3.91	3	44.1	
8.26	-7.32	3.91	1	36.95	Truck in C
8.26	-7.32	3.91	2	32.7	
8.26	-7.32	3.91	3	44	
7.62	-6.68	2.16	1	38.9	
7.62	-6.68	2.16	2	36.7	
7.62	-6.68	2.16	3	42.1	
8.26	-7.32	2.16	1		Truck in the way (D). No data.
8.26	-7.32	2.16	2		Truck in the way (D). No data.
8.26	-7.32	2.16	3		Truck in the way (D). No data.
7.62	-1.802	3.91	1	48.8	53.1 with container 5' past in D
7.62	-1.802	3.91	2	48.8	
7.62	-1.802	3.91	3	49.6	53.2 with container 5' past in D
8.26	-2.442	3.91	1	51.4	
8.26	-2.442	3.91	2	42.4	
8.26	-2.442	3.91	3	32.7	
7.62	-1.802	2.16	1	49.1	
7.62	-1.802	2.16	2	43.2	
7.62	-1.802	2.16	3	51.9	
8.26	-2.442	2.16	1	42.1	
8.26	-2.442	2.16	2	37.2	
8.26	-2.442	2.16	3	39.7	
7.62	3.076	3.91	1	44	
7.62	3.076	3.91	2	43.5	
7.62	3.076	3.91	3	32.7	
8.26	2.436	3.91	1	40.6	
8.26	2.436	3.91	2	36.7	
8.26	2.436	3.91	3	32.7	
7.62	3.076	2.16	1	43.3	
7.62	3.076	2.16	2	42.3	
7.62	3.076	2.16	3	44.4	
8.26	2.436	2.16	1	46.3	
8.26	2.436	2.16	2	44.6	
8.26	2.436	2.16	3	38.5	
7.62	7.954	3.91	1	37.2	
7.62	7.954	3.91	2	38.1	
7.62	7.954	3.91	3	40.5	
8.26	7.314	3.91	1	38.3	
8.26	7.314	3.91	2	42.3	
8.26	7.314	3.91	3	32.7	
7.62	7.954	2.16	1	40.1	
7.62	7.954	2.16	2	40.3	
7.62	7.954	2.16	3	39.5	

8.26	7.314	2.16	1	39.7	
8.26	7.314	2.16	2	41.3	
8.26	7.314	2.16	3	44.3	

Table I. e-Logicity Seal Strength Measurements

B.3 HI-G-TEK TEST RESULTS AND OBSERVATIONS

Gate-Area Readability and Signal Strength

A vertically-oriented, quarter-wave whip dipole antenna with a circular ground plane was positioned above the E/F island as shown in Figures 3a and 16. It was placed about 14.5 feet above the road surface, so that its ground plane was slightly below the reflector of a nearby fluorescent lamp. The red circle in Figure B.16 indicates its location. Lanes E and F were selected because they were unused the day of the testing. The lack of clerk houses in islands E/F and F/G minimized large, nearby reflective surfaces. Time constraints prevented attempts at optimizing antenna location, which could easily vary among the vendors' systems and would depend on the antenna choice, terminal process requirements, etc.

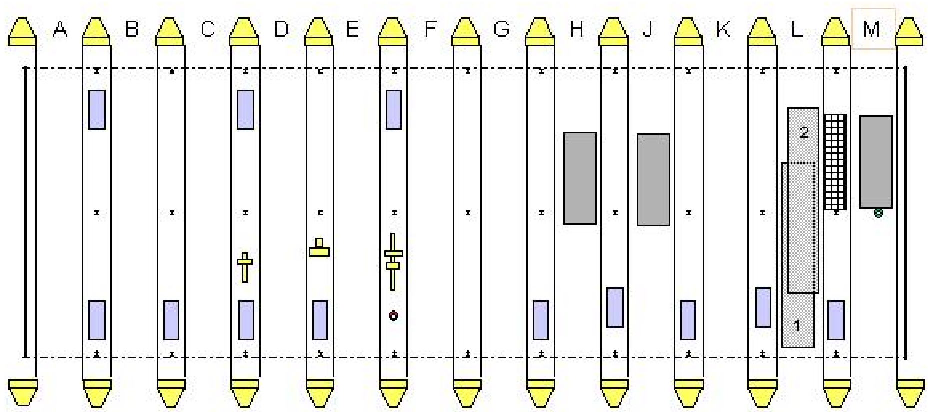
Also, using a longer antenna with a higher gain conceivably could extend the read range. However, the low ceiling and the possible need to place an antenna over a Lane may limit that option. Directional antennae with higher gain are also an option.

The first seal had not been previously used for any extensive testing, and its signal strength had not been measured. After testing with this first seal, we found that its output appeared to be several dB lower than that of the other two seals. So, we conducted additional testing with one of the stronger seals, which we had also used in our laboratory tests. The results with both seals are presented here.

Tests were performed by querying from the reader antenna and waiting for a response from the seal. The query instructed the seal to respond only once.

Immediately prior to testing, a change in the computer used to run the Hi-G-Tek software apparently resulted in losing the ability to vary the reader's output power. This made it difficult to confirm whether the limiting factor was the reader-to-seal link or the seal-to-reader link. Tests were conducted with the reader output power presumably at its default setting (65 on a scale of 0 to 100). Prior laboratory tests had shown that at a power setting of "1," a seal on a door responded at a head-on distance of at least 7 meters (and likely further). Also, a power setting of “60” was found to produce signals about 20 dBμV higher than a setting of “1.” This suggests a head-on range in excess of 70 meters in open space at the default setting; and Hi-G-Tek indicated an expected peak range of about 80 meters in open space.

Figure B.16 shows the seal in Lane M, and shows that the presence of a container in Lane L adversely affects readability. Figure B.17 shows the same seal in Lanes J and L, and indicates that proximity to the clerk houses in islands G/H and H/J may have hurt readability at one location in Lane J.



Condition	Rate
No container in L	19/28
Container in L (location 1)	No reads
Container in L (location 2)	No reads

Figure B.16. Hi-G-Tek Seal in Lane M

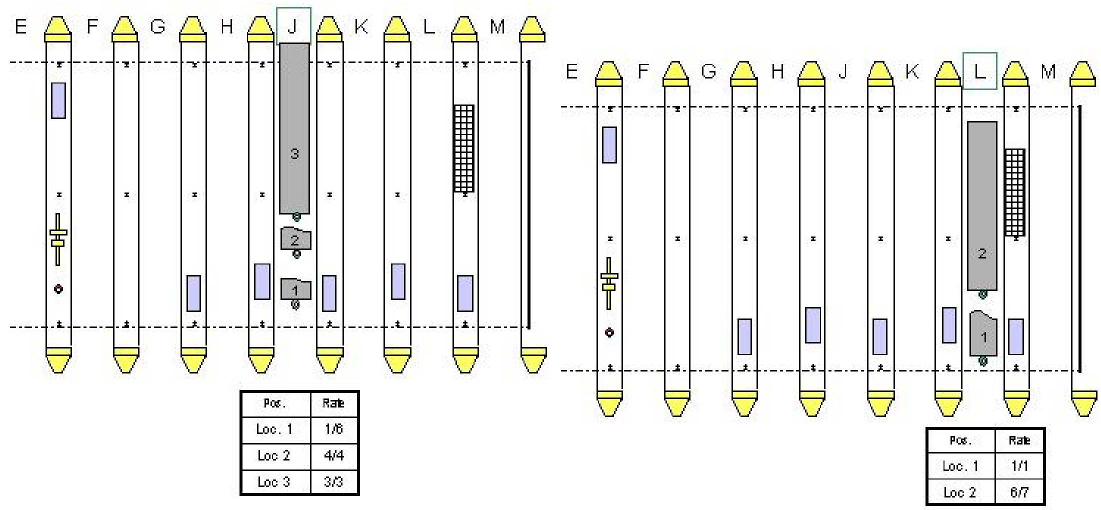


Figure B.17. Hi-G-Tek Seal in Lanes J & L (weaker seal)

Figure B.18 shows seal tested in Lane K. The seal is not in the line-of-site until it the back end of the container is in the gate, hence, there are no reads. Once the back end of the container is in the gate, the reads are registered.

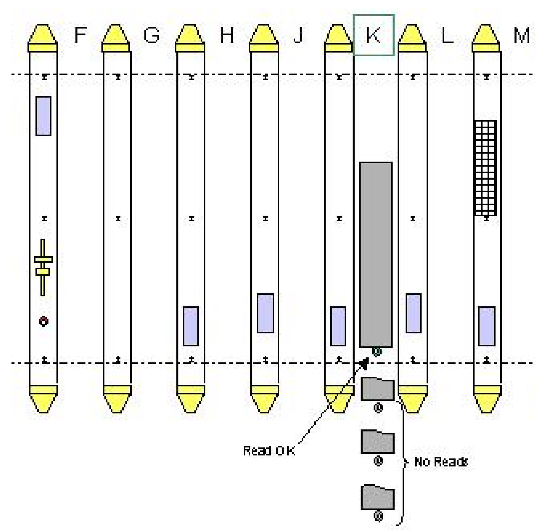
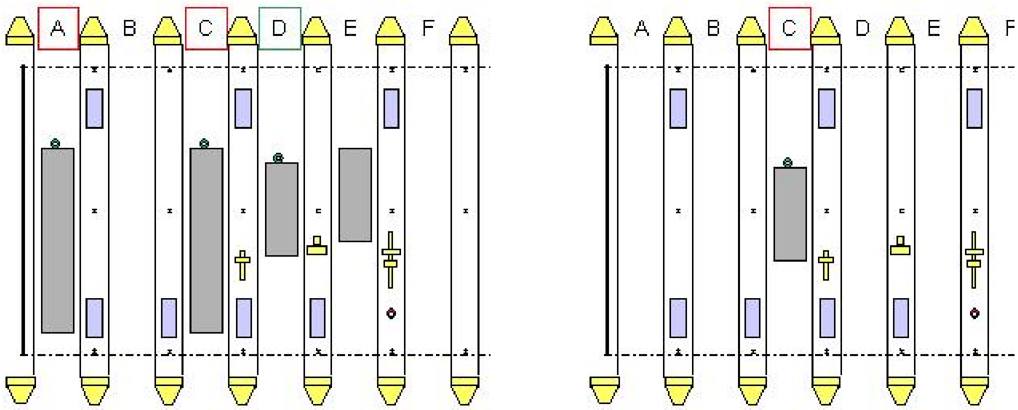


Figure B.18. Hi-G-Tek Seals in Lane K

For outbound containers, with the doors facing “away” from the reader antenna, success was only seen in Lane D with multiple containers arrayed as shown in Figure B.19. However, these tests were conducted with the “weaker” seal. In Lane C, no reads were achieved even with Lane D empty.



Seal Lane	Rate
A	0/8
B	--
C	0/15
D	9/11

Seal Lane	Rate
C	0/4

Figure B.19. Hi-G-Tek Weaker Seal in Lanes A, C, and D

Hi-G-Tek Updated Gate Testing

Because of the technical difficulties encountered in the earlier testing, we revisited the gate area of the Howland Hook terminal with the same Hi-G-Tek reader and seal. These new tests differed in that:

- The reader output power was better controlled.
- A dipole antenna was connected directly to the reader rather than via a coax cable.
- We located the antenna outside the gate structure. This was to demonstrate the performance of the system in a more likely configuration, rather than to test the performance of 916 MHz transmissions inside the crowded gate structure.

The DataReader, with the vendor-supplied dipole antenna attached, was suspended from a mast at a height of about 25 feet (7.5m). The reader was inverted with the antenna pointing down, so that the casing of the reader would not block signals from below. As shown on Figure B.20 the antenna was placed in Location “A2, ”about 61 feet (18.6 m) from the front of the lanes and adjacent to Lane A. Because of the narrow spacing between lanes and the traffic flow, it was not practical to place the antenna out in the queuing area. The A2 location allowed us to test over longer distances than if the antenna was in the middle of the queuing area.

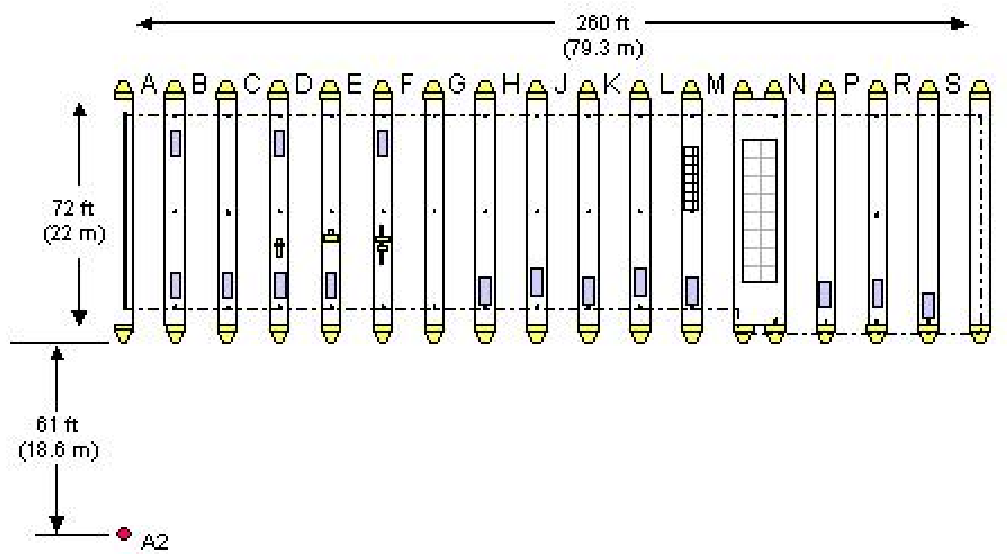


Figure B.20. Location ("A2") of Elevated Hi-G-Tek Antenna and Reader

The reader transmission power was set to "110," which Hi-G-Tek indicated would provide an output power of about 0.75 mW.

In this test, the seal was attached to active but empty containers as they sat in the gate queue and was queried as the containers moved into the gate. The reader interrogation time was set to its default value of 3.06 sec. (Shorter query times require the seals to wake-up and listen for queries more frequently, which reduces battery life proportionately.) The response window was set to a recommended value of 1.68 sec. In this roughly 5 sec period, a container moving at 5 mph (8 km/hr) moves 37 ft (11 m). During the 1.68 sec response window, it moves 12 ft (4 m). So, the moving seal generally receives the query at and transmits its response from different locations. Since the results of each query are displayed after all the seal responses are received, it was not possible to tell precisely where the seal was when it transmitted. It was also not determined whether a failure to read the seal was due to poor communications in the reader-to-seal link or the seal-to-return return link.

With each query, the seal was typically instructed to respond only once during the 1.68 second response window (the number of retries can apparently be set as high as 10 to overcome collisions when multiple seals are responding). If the re-try value were higher, and if there were output-power fluctuations from the seal, we would not know if the reader were detecting all responses or only the strongest. In a multi-seal environment, the stronger signals may be involved in collisions; therefore, one wants to be able to read all of the signals. In some cases, if read rates were low, the number of re-tries was increased to see if this improved performance.

Figure B.21.a shows the results of tests in three lanes, S, P, and M. A seal on a container in Lane S was read on three successive attempts (shown as green circles) as it moved from outside the gatehouse to inside. Trucks with containers were lined up in the queue in Lanes N and P. The seal was read on several more attempts as it sat stationary about halfway down the Lane, as shown. No missed reads occurred. At the furthest point, the distance between the seal and reader was about 280 feet (86 m).

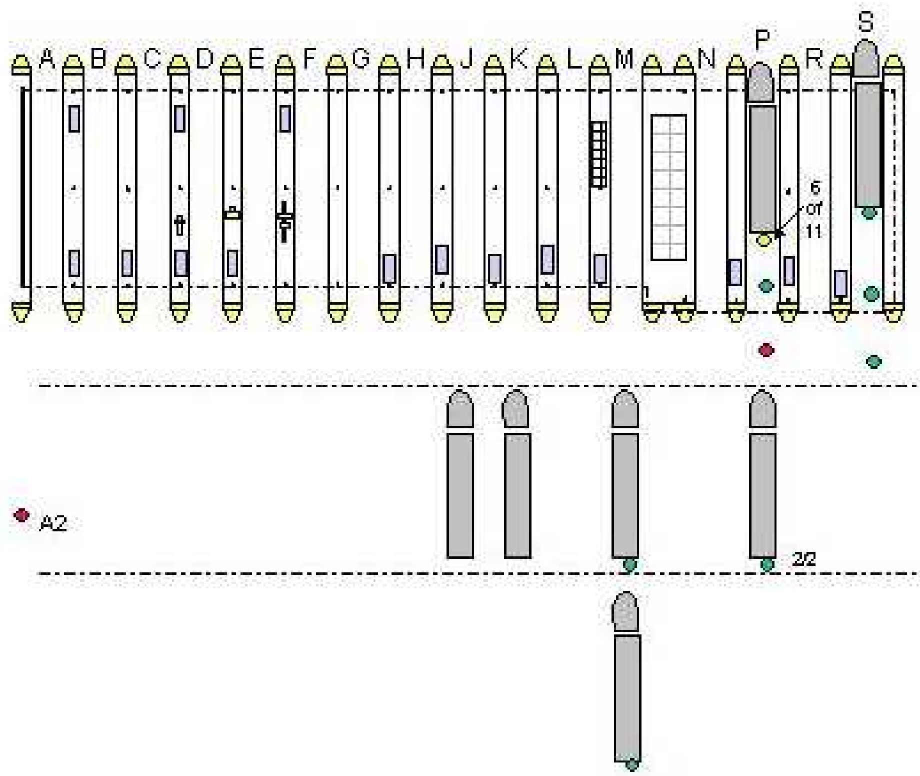


Figure B.21.a. Query Results with Seal in Lanes S, P, and M

In Lane P, the seal was read on two of two attempts as its container sat in the queue. Note that the reader antenna was "ahead" of the plane of the container doors; the signals were effectively wrapping around the container corner. As the seal moved forward into the gatehouse, one read was missed (noted by a red circle). Another truck with a 40' container sat in the queue in Lane M. It could have been blocking the line-of-sight during the query or response link. Inside the gatehouse, the seal was successfully read while moving. Once it stopped near the location shown, it was read on three of six successive attempts (yellow circle). With the seal and all other containers in the same locations, the seal was instructed to transmit four times for each query. The seal was then read on three of five queries. So, increasing the number of re-tries did not significantly improve the readability of the seal.

In the queue in front of Lane M, the seal was successfully read many times on a container that was next in line (no truck was in the number 2 position). It was also read on a 40' container that was second in line. The seal-to-reader distance in this position was about 200 feet (63 m), and the reader was about 20° "ahead" of the plane of the doors. The number of re-tries for these cases was set equal to one.

Figure B.21.b shows the results with the seal in Lanes R and L. In both of these cases, a container in the adjacent, intervening lane was also entering the gate, and lagging the sealed container by about one container length. So the front of the intervening container was close to the sealed doors.

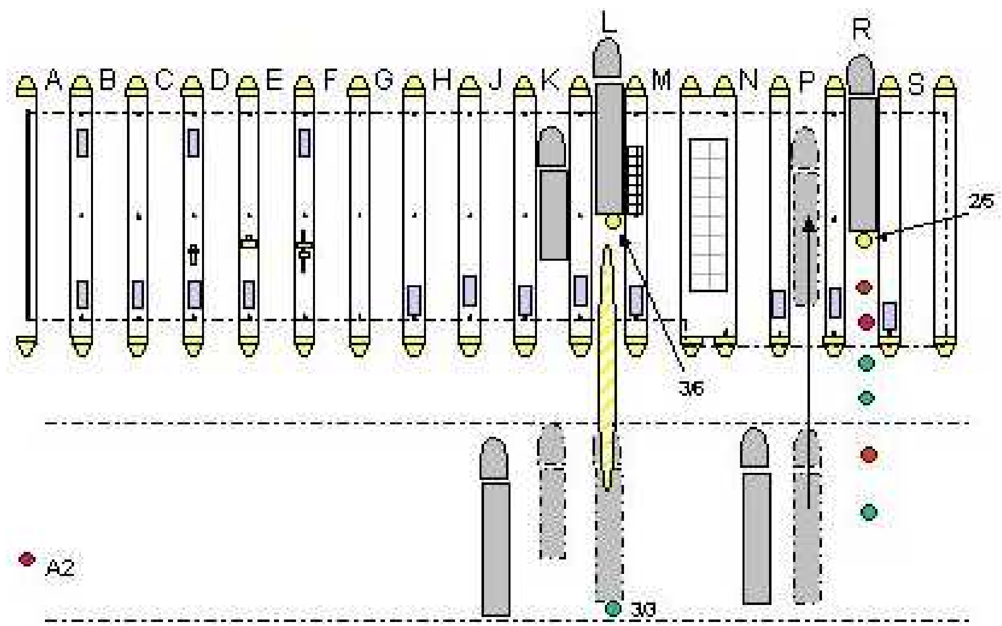


Figure B.21.b Query Results with Seal in Lanes S, P, and M

In Lane R, the seal was read on three of four attempts while it was moving outside the gatehouse. Once inside the gatehouse, and with the adjacent container probably blocking any line-of-sight, two reads failed. Only two of five reads were successful with the container stationary as shown.

With the seal in Lane L, reads were successful while the container sat in the queue. Containers were in Lanes J and K as shown. With the container in Lane K lagging the sealed container, reads were spotty. With the container parked as shown, three of six reads were successful.

Figure B.21.c shows a sealed container in Lane K, with a container in Lane J moving alongside it. A third container sat in the queue for Lane H. Although the seal was read as it sat in the queue, four attempts to read it as it moved toward the gate were unsuccessful (red circles). When it was near the gatehouse structure it was read, but the next attempt failed. The relative positions of the containers in K and J shuffled during this time. But, with the seal stopped in its lane, and with the container in Lane J stopped near the gate entrance as shown, the seal was read successfully on six of six attempts.

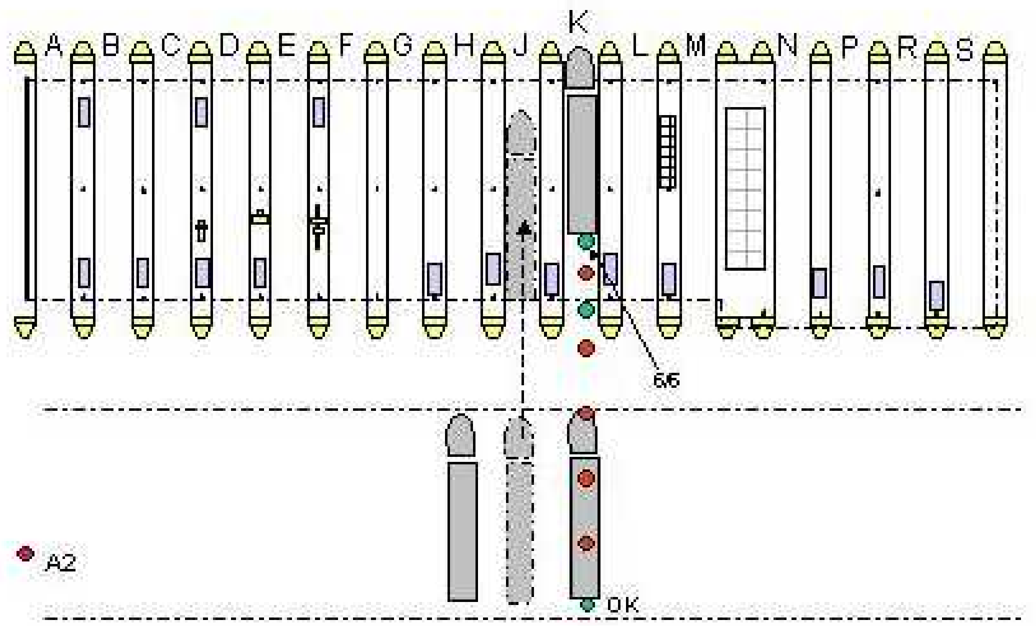


Figure B.21.c. Query Results with Seal in Lane K

When the seal was tested in Lanes E through H, there were no other containers between the seal and the reader antenna. When the seal was in the queue for Lane E, another 40’ container was in the queue for Lane F. Likewise, when the seal was in the queue for Lane F, another 40’ container was in the queue for Lane G. These adjacent containers may have provided surfaces for reflections as the sealed containers moved forward to the gate. Figure B.22 shows the results for these four lanes.

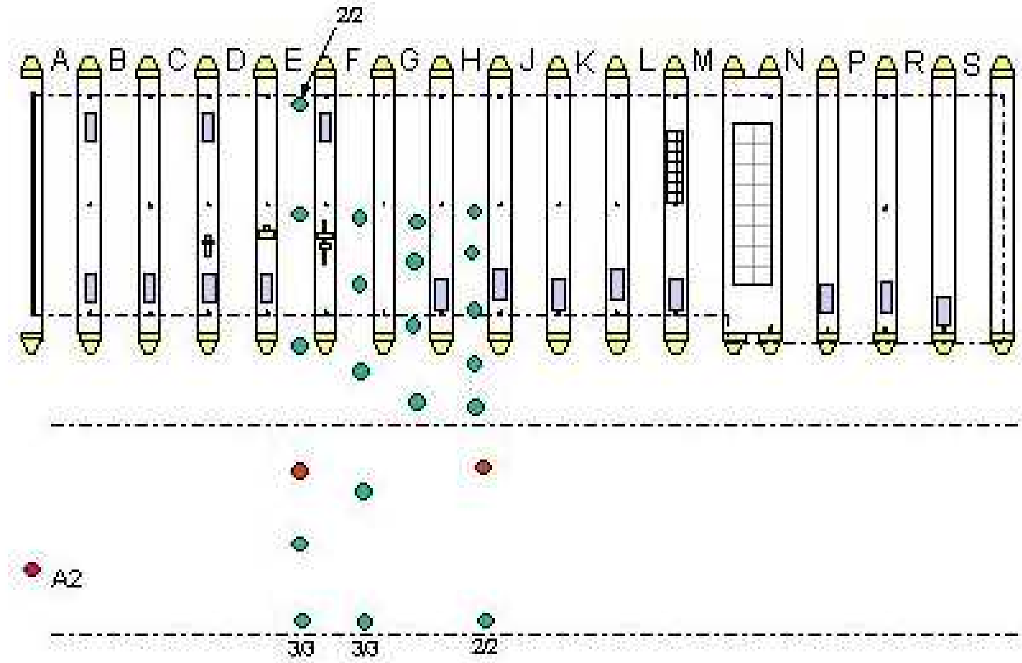


Figure 22. Query Results with Seal in Lanes E, F, G, and H

Of 28 seal locations, only in two positions (once in Lane E and once in H) was a read unsuccessful. Both of these occurred with the seal outside of the gatehouse and in clear view of the antenna. In each lane, the container was stationary for the final query or queries in the locations shown. In Lane E, the truck moved almost completely through the Lane before stopping, so we were able to determine that the seal was readable all the way to the back of the gatehouse.

Overall, the readability of the seals throughout the entire gate structure was good. Read failures usually seemed to be associated with the presence of another container near the sealed container and between the seal and the reader.

With the seal in the near lanes (E through H), there were 11 read attempts made when the seal had a clear line of sight to the reader antenna during both the query and response windows. Reads were unsuccessful in two of these 11 attempts. In one of these, there was a container in an adjacent, further lane; reflections off its surface could have caused a null in the reader or seal area. Reads were achieved at similar view angles from distances that were three times greater, so the read failures are apparently not due to lack of source signal strength.

B.4 SAVI TEST RESULTS AND OBSERVATIONS

Gate-Area Readability and Signal Strength

The location of the Savi reader was shown in Figure B.3. It was elevated about 30 feet above the road surface, within a few meters of a much taller light pole. Four seals with comparable power outputs were typically used simultaneously. Via the reader, we broadcasted a query for all seals in the area to respond. The reader software then reported the ID's and RSSI (received signal strength indicator) from each tag that it read. Since the reader contains two orthogonal antennae to create an omni-directional pattern, the software reported the greater of the two RSSI readings. Savi indicated that for RF-noisy areas, they prefer minimum RSSI values of 60 to 80 to have confidence that reads will be successful. In the low-noise environment of the test terminal, the background RSSI noise was in the range of 25 to 35. We read correct seal ID numbers with RSSI values as low as 51.

We conducted two types of range tests. First, the seals, with their magnetic backings, were attached to various metallic surfaces around the gate structure. To challenge the system, many of these placed on the opposite side of the gatehouse, on surfaces "facing" away from the reader. Many of these were on the flanges of ceiling-support I-beams (10 inches wide). Second, all fours seals were attached to the door of a stationary container being processed in the gate. No bolts were used, so they were not placed directly on the latches.

Figure B.23 shows 11 locations where seals were placed on surfaces other than containers. The results are shown in Table II. At Location 1, no seals were read on one query, an only three of the seals were read on a second query. Table II lists the average for RSSI for this second attempt. In all other cases, all four seals were read.

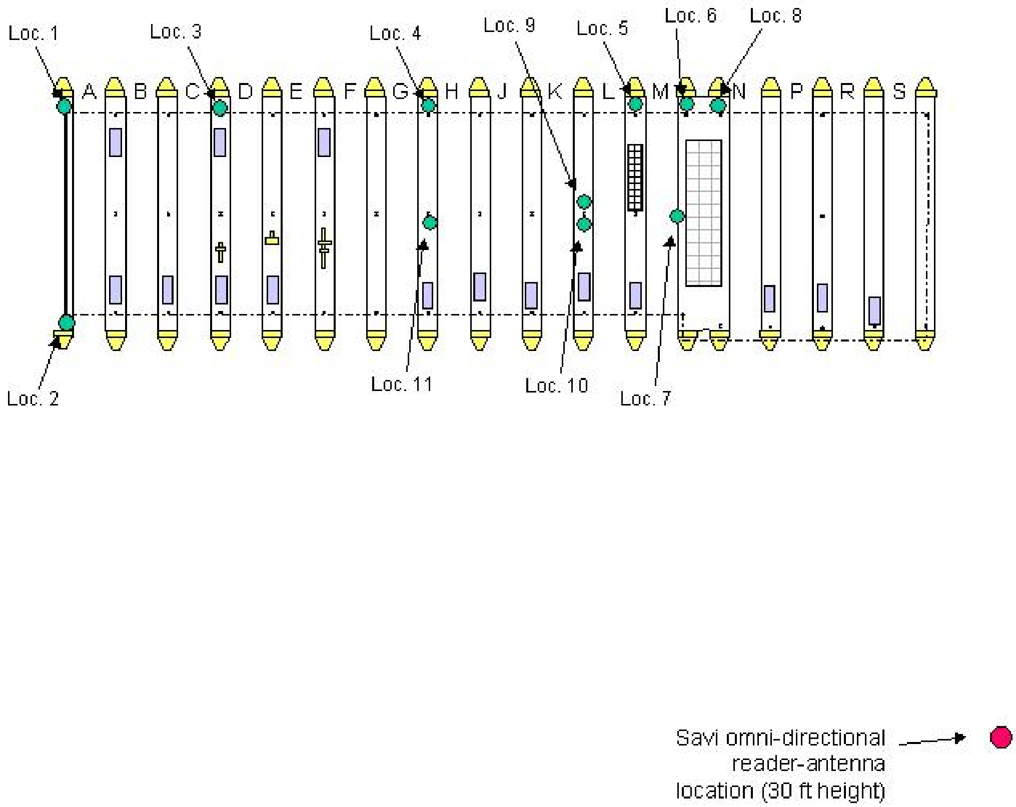


Figure B.23. Savi Seal Locations 1 through 11 in the Gate Area

Location	RSSI (avg)	dBm (avg)
1	52.4	-99.8
2	64.0	-95.2
3	74.1	-91.2
4	76.8	-90.1
5	75.9	-90.4
6	79.0	-89.2
7	78.5	-89.4
8	92.4	-83.9
9	73.3	-91.5
10	101.4	-80.3
11	100.0	-80.8

Table II. Average Signal Strength Measurements for Savi Seals

The average dBm values shown are based on a correlation provided by Savi.

Figure B.24 shows three on-container cases tested. In each case, all four seals were read. Note that this means that the reader-to-seal link and the seal-to-reader link both had an adequate combination of power and gain. The three cases were not simultaneous; they are shown in a single Figure B.for ease of comparison. The signals from the seals in Lane C have an average RSSI of only 65, which Savi may consider marginal in a terminal with higher RF noise at 434 MHz.

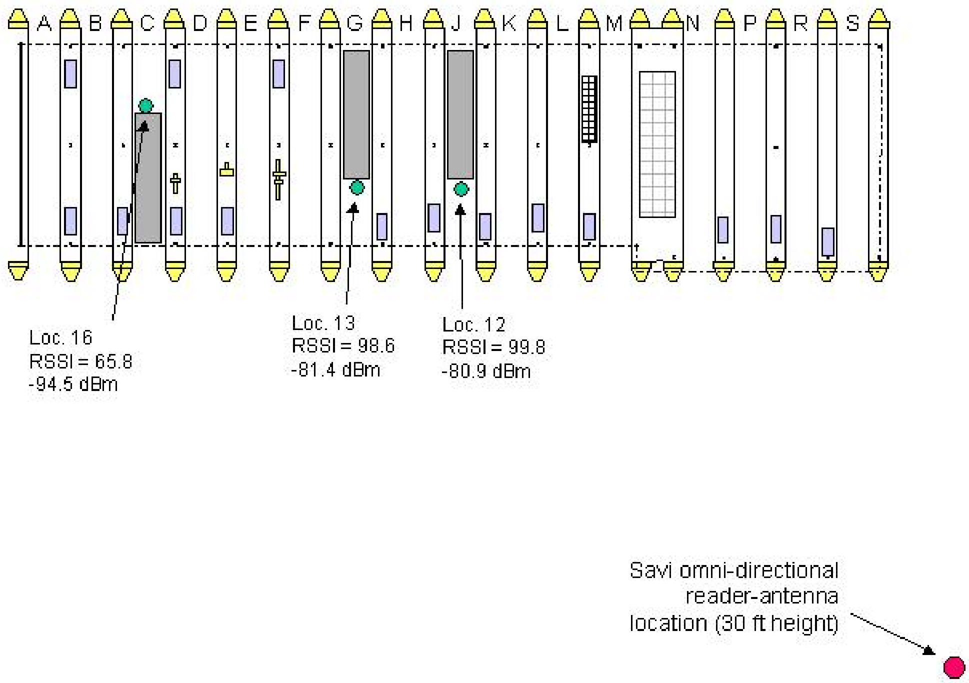


Figure B.24. Results with Savi Seals on Container Doors in Gate Lanes

Figure B.25 shows the other three cases tested. Seals were placed between two 20-ft containers on a single chassis in Lane D. The average signal was as strong as that received from Locations 10 and 11 in Figure B.23, where seals were also at the mid-point of the gatehouse, with a small back-plane (I-beam) but facing the reader antenna. (Note that because of all the containers in the queue and the long distances between the reader and the seals, test personnel were not in visual contact, and the positions of other containers in the gatehouse were not recorded.)

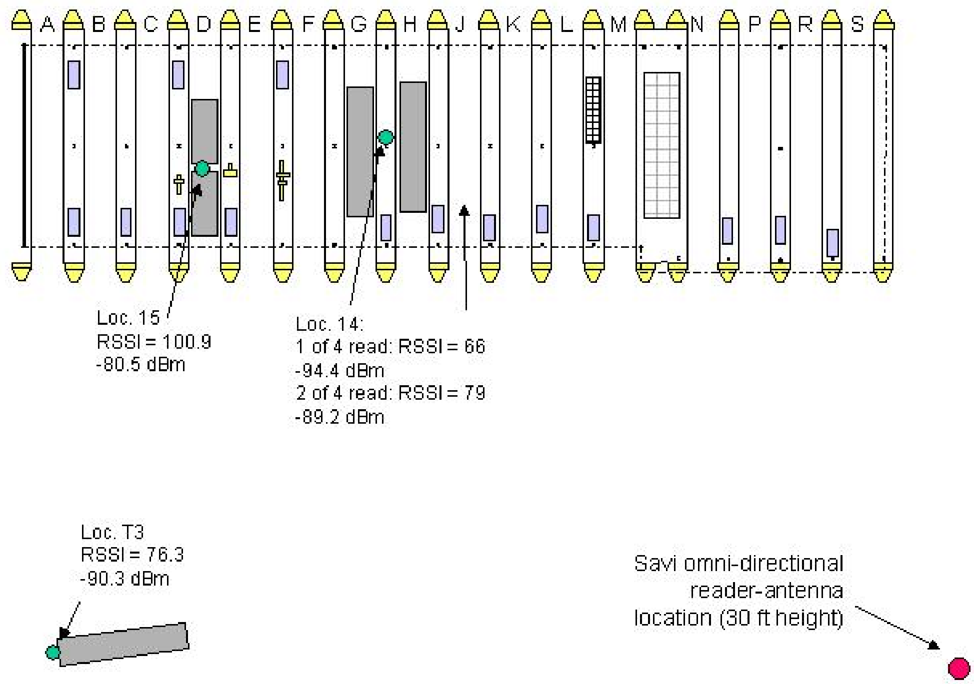


Figure B.25. More Results with Savi Seals in the Gate Area

As shown for Location 14, two containers shielding an away-facing seal reduced the read rate to 37% (these seals were not on a container).

Finally, at Location T3, the four seals were placed on container inside of an entrance tunnel, roughly 100m away from antenna. The seals were queried as the container doors exited the tunnel, with the tractor driving roughly towards the antenna. Four successful reads with an average RSSI of about 76 was recorded. Other measurements with the seals on a light post in that same area gave readings with average values within about 6 dBm of the on-container readings.

B.5 ALL SET TEST RESULTS AND OBSERVATIONS

Gate-Area Readability

For this test, it was impractical to use operating containers as they moved through the gate since the installation/removal of e-seal required opening of the right door of the container. Instead, we installed the seal on a single container and drove that container through various gates.

The reader was positioned above the island between Lanes E and F, as shown in Figure B.26.a, about 10 feet above the road surface. (The tops of the clerk houses were nine feet above the road surface.) The red semicircle and arrow in Figure B.26.a indicates its location and direction. Lanes E and F were selected because they were unused the day of the testing. The lack of clerk houses in islands E/F and F/G minimized large, nearby reflective surfaces. Time constraints prevented attempts at optimizing antenna location, which could easily vary among the vendors' systems and would depend on the antenna choice, terminal process requirements, etc.

The All Set high gain reader includes an integrated, directional, patch antenna with vertical polarization (the low gain reader is omni directional, -9dBd, similar to the AllSeal). Because of its directionality, we performed three sets of tests, each with the reader facing a different direction.

Tests were performed by continuously querying from the reader antenna (scan mode) and waiting for a response from the seal. The process can generate more than one read of the same seal per query. Success rates were measured as the fraction of queries that result in at least one successful read. Because read tests could be run continuously and with intervals of about one second, many of the test conditions allowed us to measure "read zones" as the container was moved slowly through the lanes. In the figures presented below, green-shaded areas mark the approximate regions where the door of the container was, when consistent valid readings were obtained.

In Figure B.26.a, with the reader directed toward Lane M, the seal was read as the container turned to become aligned with the Lane, was lost as the line-of-sight to the reader was blocked by the doors of the container, and was re-acquired as the plane of the doors entered the gatehouse. The read zone extended behind the clerk houses and the intervening containers in Lane L, but readability was lost behind the brick-and-metal, floor-to-ceiling structure between Lanes L and M.

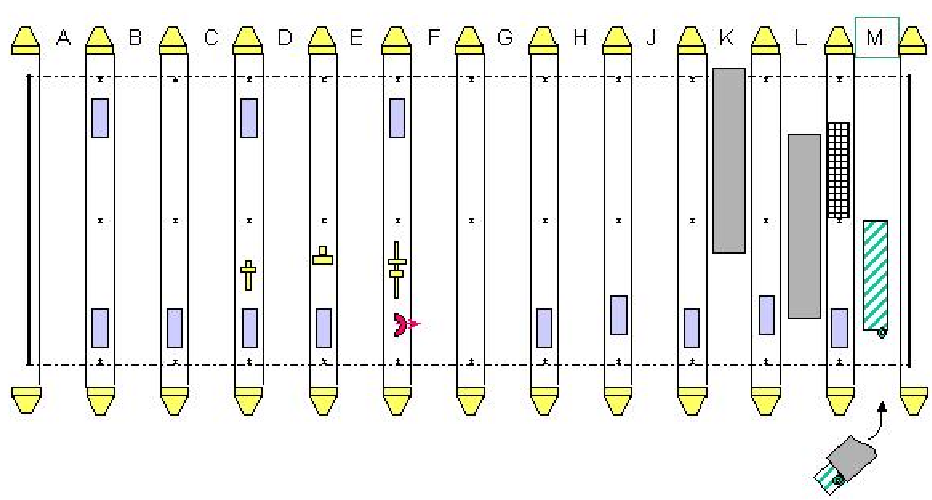


Figure B.26.a. Container with e-seal in Lane M; All Set Directional Reader Aimed Toward Lane M

Figure B.26.b shows the seal in Lane L. The seal was read as it approached the Lane, but once stationary inside, only one read was achieved out of 20 queries. There was no line-of-sight between the reader and seal at that point. Testing while leaving the lane was not performed in this scenario.

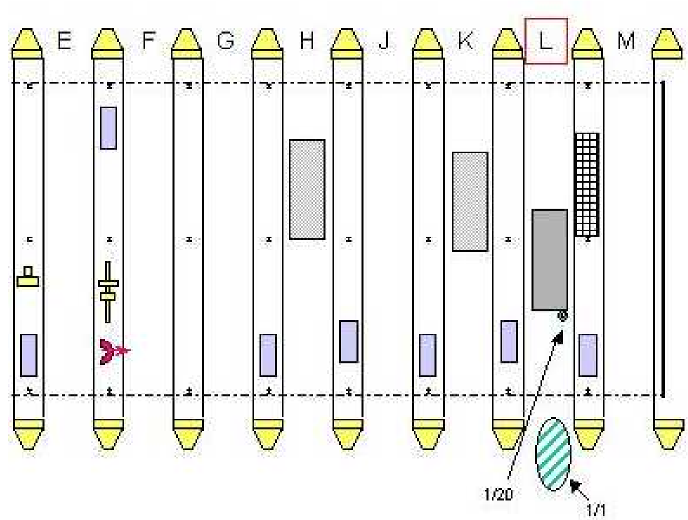


Figure B.26.b. All Set Seal in Lane L, Reader Aimed to Lane M

As shown in Figure B.26.c, the seal was only read in Lane K when it was still outside of the gate structure and approaching the lane. The intervening containers in Lanes G, H, and J, and/or the clerk houses, seem to have provided enough obstacles to prevent a read.

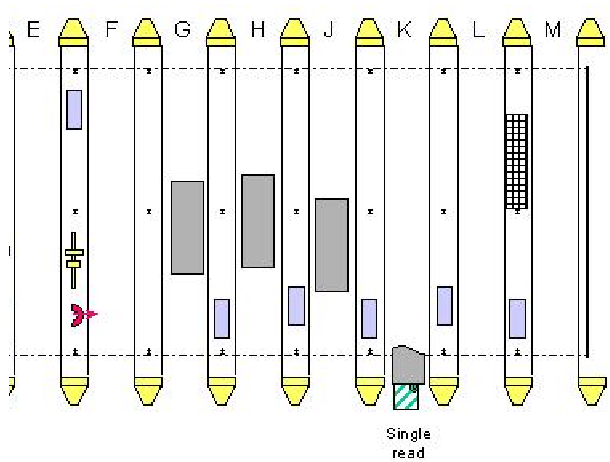


Figure B.26.c. All Set Seal in Lane K, Reader Aimed to Lane M

The seal could be read throughout most of Lane J, even with a container sitting in Lane H, as shown in Figure B.26.d. A container moving through Lane G did not adversely affect readability. A brief region of no reads was observed in the entrance (gap between the two green zones), although reads resumed before the seal moved past the clerk houses.

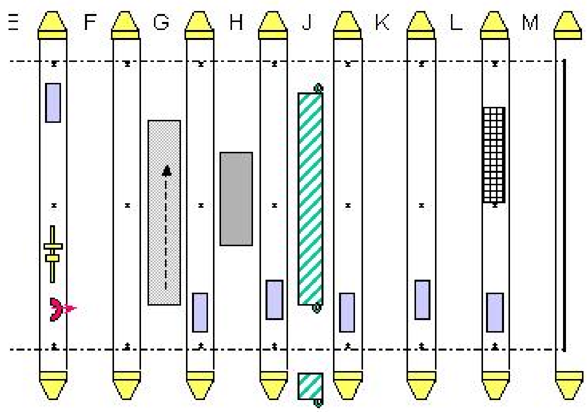


Figure B.26.d. All Set Seal in Lane J, Reader Aimed to Lane M (arrow indicates direction of the container in Lane G)

The results from passes through several lanes are illustrated in Figure B.27.a. In each case, there were no intervening containers between the seal and the reader. As with Lane J, Lane H exhibits a small no-read zone upon entry to the gatehouse structure, but reads resume stops before the seal clears the clerk houses. The reader has a good view of the seal in most of Lanes F, G, and H. The read zone extends further for the more distant Lanes; this is likely due to the sensitivity pattern of the reader patch antenna, which reportedly has a 3-dB full beamwidth of about 65° to 75°, depending on polarization.

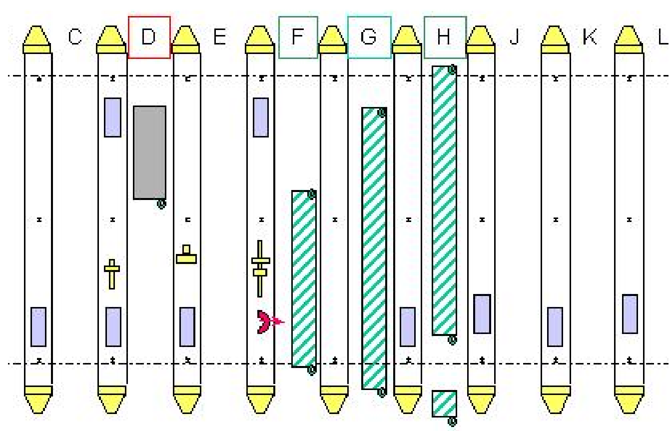


Figure B.27.a. All Set Seal in Lanes D, F, G and H (all inbound)

With the seal stationary in Lane D as shown, no read was achieved. This is to be expected, because of the directionality of the antenna.

Several cases were also tested with the reader antenna aimed toward the container yard, as shown in Figure B.27.b. Note that in Lane D, the seal was not read for most of the passage through the gatehouse, but there was a brief read zone as the seal left the gate. At this point, the seal-to-reader distance and angle appear to be about the same as in Figure B.27.a (seal in Lane D), where no reads were achieved. Three differences may explain these results. First, in Figure B.27.b, the seal has a more open path to the reader; the lip of the container hinge structure prevents line-of-sight from the seal antenna to any reader location on the starboard side of the container. Second, in Figure B.27.a, the seal was stationary, so there may have been a low-signal region that was overcome by moving the seal as in Figure B.27.b. Third, the blower piping and structure suspended from the ceiling may have provided some shielding in Figure B.27.a.

The results for Lanes F and L and Figure B.27.b might be expected based on the results shown for Lanes F, G, and H in Figure B.27.a. The Lane L is far to the side of the directional reader antenna. When the container was driving through Lane F[2], the reader antenna was turned as the container passed by. Good reads were achieved out to some distance beyond the gatehouse. As the container turned to cycle back through Lanes A through D, the seal became readable again, although the seal-to-reader range did not change significantly. This appears to be due to the directionality of the seal's output signal when installed in the hinge area.

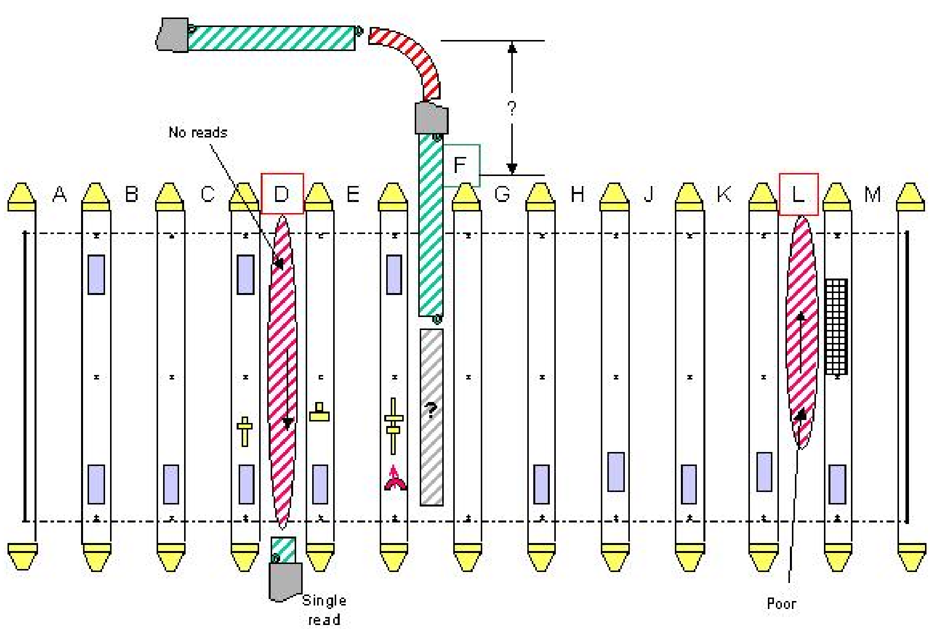
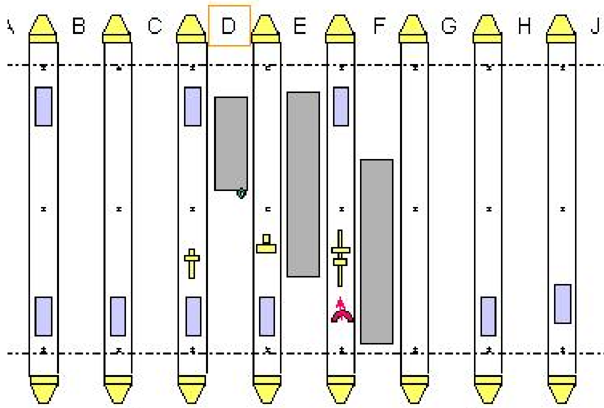


Figure B.27.b. All Set Seal in Lanes D, F, and L, Reader Aimed Toward Yard

[2] Note that the read/no-read measurements where not taken as the container was moving through the first half of Lane F, due to other activities. That period is marked as the grey zone.

Figure B.28.a shows the seal in Lane D, with a relatively short view to the reader, with some suspended piping structures in between. Very good readability is obtained until a container moves into Lane E and obstructs the line-of-sight completely. However, when a container is moved into Lane F, it apparently provides a beneficial reflective surface, and readability is restored, even with the container still in Lane E.



Condition	Readability
Lanes E, F empty	Very good
Container in E as shown	Poor (2/30)
Containers in E, F as shown	Very good

Figure B.28.a. All Set Seal in Lane D (inbound), Reader Aimed to Yard

Figure B.28.b shows the seal in Lane B. For most of its travel through Lane B, the container doors prevent a clear view of the reader. No reads are achieved, even with the intervening Lanes C and D empty. Once the doors were in line with the reader, the seal was behind the clerk house and at a 90° angle to the preferred direction of the reader antenna; no read was achieved. A truck and container pulled into Lane C. As the sealed container exited Lane B, a few reads were obtained. These coincided with a container pulling through Lane G, possibly providing a beneficial reflective surface. These reads were achieved even though the cab of the truck in Lane C blocked the direct line between the seal and the reader, and the reader-to-seal angle was roughly 120° away from the reader antenna's preferred direction.

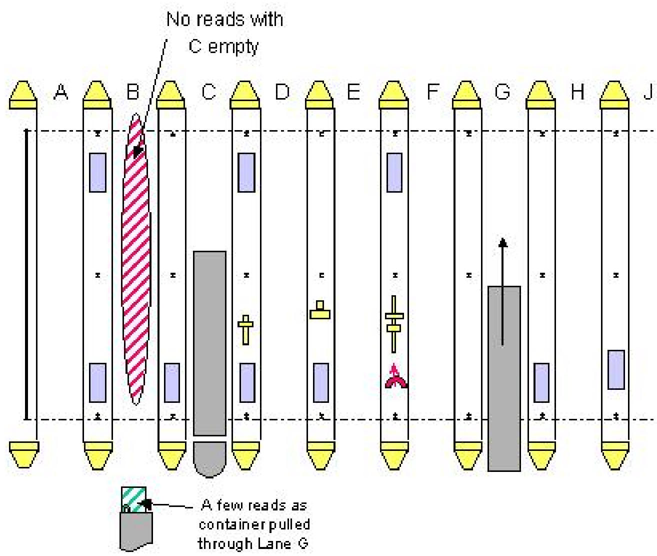


Figure B.28.b. All Set Seal in Lane B (outbound), Reader Aimed to Yard

A few cases were tested with the reader antenna aimed toward Lane A. As shown in Figure B.29.a, with the reader on the starboard side of a container in Lane E, reads begin once the seal is in line with the reader and continue for about 30 feet down the Lane. The stationary container in Lane D (with no container in Lane E) is not read. The angle from the rear left corner of the container to the reader may be too sharp.

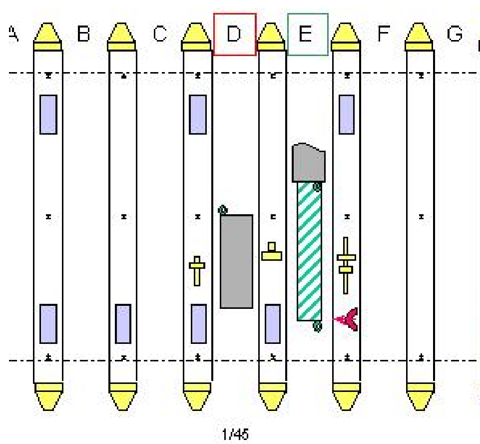


Figure B.29.a. All Set in Lanes D (outbound) and E (inbound), Reader Aimed at Lane A

Figure B.29.b shows the sealed container on two different passes outbound through Lane C. In both passes, there were no containers in Lanes D, E, or F. In the first pass, about two-thirds of the queries produced reads in the yellow[3]-shaded zone shown. In the second pass, reads were not achieved until the

[3]Yellow zone indicates, partial reads (e.g. two out of three queries)

doors had exited the Lane and there was a clear view from the reader antenna to the seal.

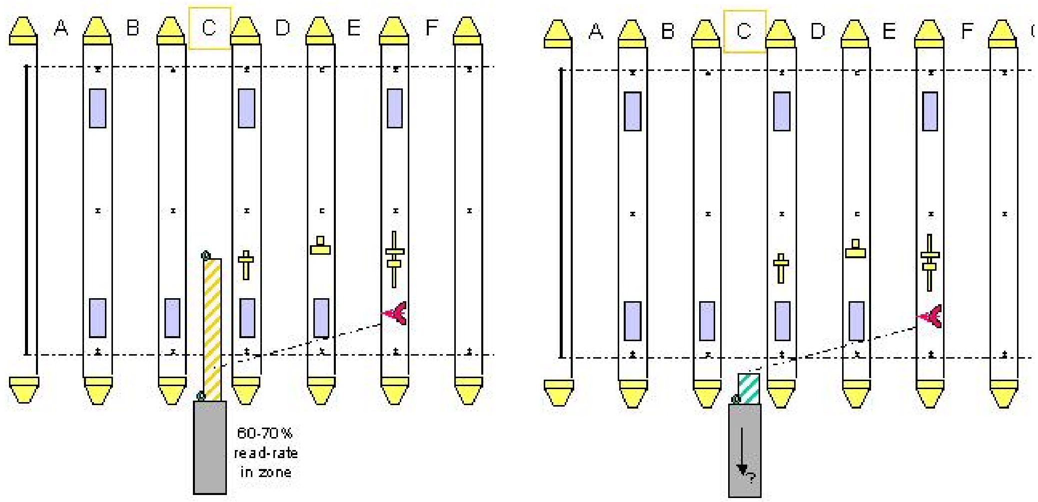


Figure B.29.b All Set in Lane C, Reader Aimed at Lane A

All Set Updated In-Gate Testing

In the initial gate testing, the distance from the All Set reader/antenna to the computer was limited to about 6 feet using RS-232 serial communication cables (this limit was not observe with the e-Logicity and Hi-G-Tek systems). All Set later provided a reader with Ethernet communications. This allowed the reader/antenna to be placed high on a mast, so we revisited the gate area of the Howland Hook terminal with the new reader and two new seals (#0011 and #0021). The antenna was the same as in the earlier tests.

The antenna was tested in three different locations outside the gate structure as shown in Figure B.30.a. In Locations A1 and A2, its height was about 23 feet. In Location F1, it was at about 28 feet. Because of the narrow spacing between lanes and the traffic flow, it was not practical to place the antenna out in the queuing area. Location F1 was as close as the antenna could be placed to the gate without impeding truck traffic. The A1 and A2 locations allowed us to test over longer distances than if the antenna were in the middle of the queuing area.

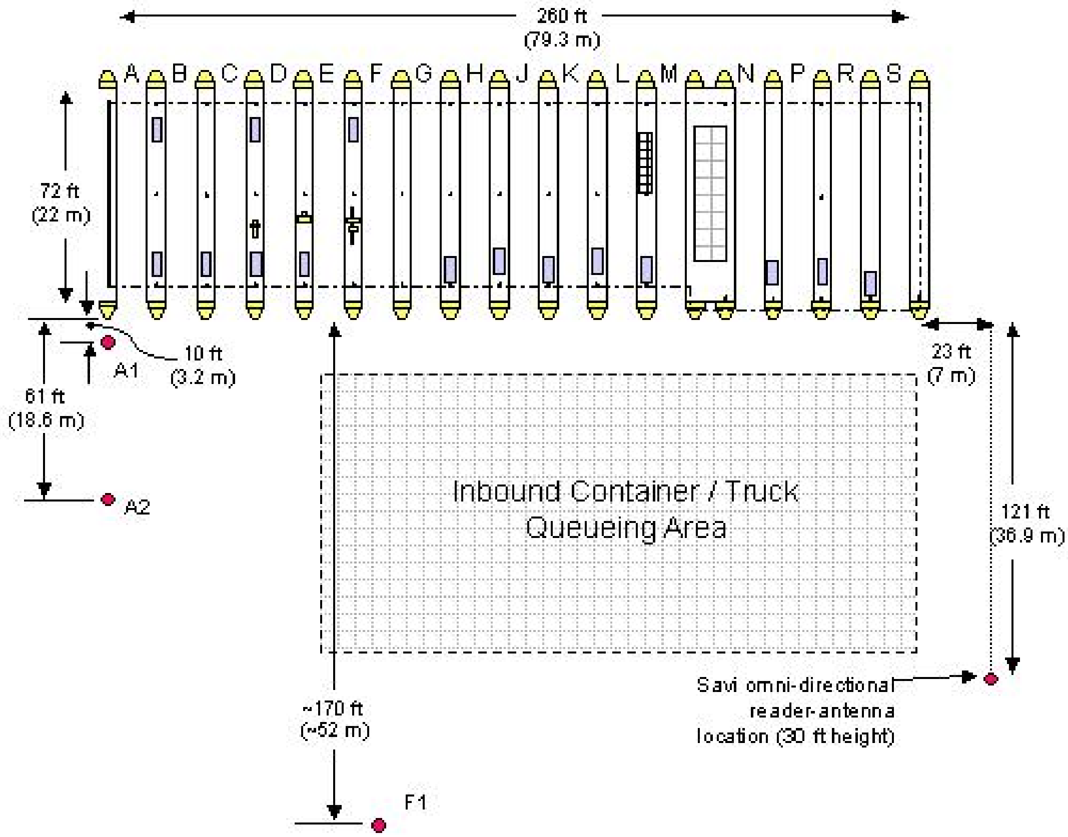
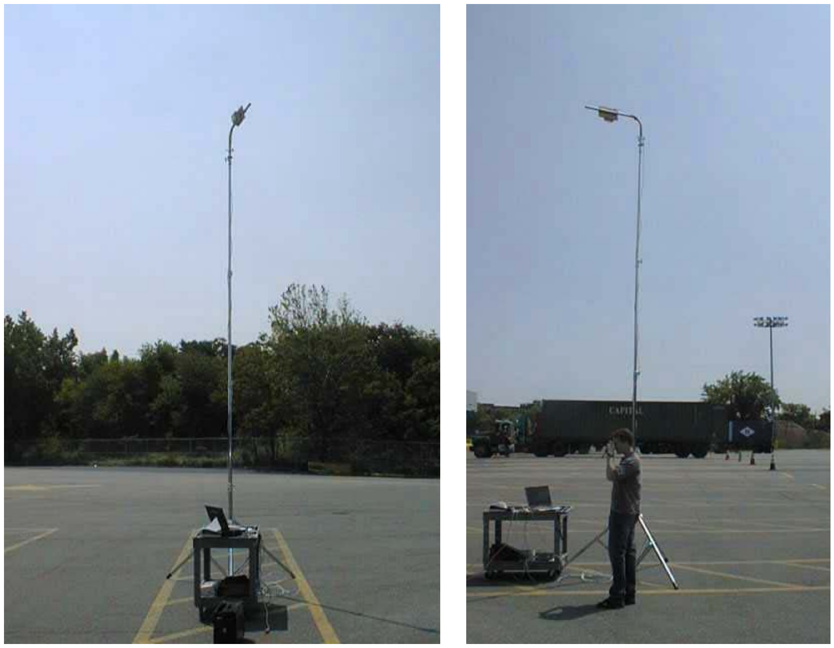


Figure B.30.a. Locations of Elevated All Set Antenna and Reader

The reader/antenna was mounted on a small wooden backing and could be rotated about a horizontal arm on the mast to change its elevation angle. This mounting is shown in Figure B.30.b The aximuthal direction of the antenna was controlled by rotating the mast about the vertical axis. For Location A2, the antenna direction was adjusted into the orientation shown in Figure B.30.c to get the best read performance when seals were held in front of Lanes N and R. The horizontal and vertical full-angle, 3dB beamwidths of this antenna are 75° and 65°, respectively, so we do not expect precise aiming to be critical. The reader was set at an angle of about 20° to the lanes, and given a downtilt of about 10°.



(a) (b)

Figure B.30.b All Set Reader Mounted to Point Down About 10° Below Horizontal

Two seals were installed in an empty 20’ container as shown in Figure B.30.c. These were placed in two locations: Seal #21 was placed immediately above the top right door hinge (to optimize line of site), and #11 was placed a few inches above the middle right door hinge.

Figure B.30.c. Seals Mounted on Container Frame

As in the earlier All Set tests, the container was driven slowly (5-10mph, i.e., speed the trucks would normally go through the gate) through various lanes. The demonstration software was run in scanning mode, so it continuously queried for the seals. Once per second, the software reported the last results from the reader, listing the seal ID's that had been read. The software and reader were not synchronized, so occasionally two successful reads by the reader appeared in the software as a "no read" followed by a "double read" of the same seal. Only if the software reported successive "no reads" of a particular seal ID could we be confident that the seal had actually been missed.

Antenna Location A2

Testing was started with the reader mast in Location A2, adjacent to Lane A and about 61 feet (18.6 m) from the lane entrances.

Figure B.31 shows the results of tests in Lanes S and R. The upper seal was read once (green circle) in Lane S but nowhere else inside or immediately outside the gatehouse. The lower (middle-hinge) seal was never read on this pass. Other nearby containers were located as shown. On the pass through Lane R, no containers were in the gatehouse in Lane P or S. The lower seal was read once, then the upper seal was read once. Numerous other attempts (roughly once a second) produced no other reads. It is important to note that the distance from the reader is about 80 meters, which is on the limit of the All Set range, hence, we can not be certain whether no-reads occurred because of obstacles, or because of the noise in the communication channel.

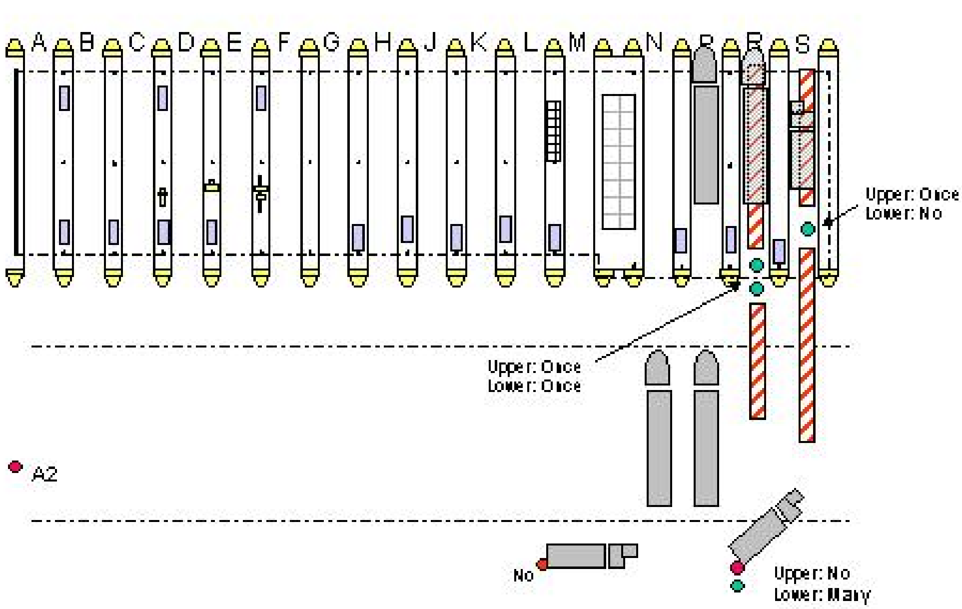


Figure B.31. Query Results with Seals in Lanes R and S

Still referring to Figure B.31, as the container moved behind the queue of trucks, no reads were achieved from the area in front of Lane L. This is expected since we were using directional antenna, and this might have been outside of the antenna lobe. This continued until the container turned to enter the queue for Lane R. At this location, the middle-hinge seal was read repeatedly, but the upper seal was never read. Again, this is most likely because the distance to the lane is at the limit of the All Set dynamic range. The reason why we were getting intermittent reads may have been the result of varying signal/noise levels. The view of the sealed container from the antenna location is shown in Figure B.32.

Figure B.32. Sealed Blue Container Entering Queue for Lane R

Figure B.33 shows the results with the seal in Lanes K, H, G, and F. With a 40' container in the queue for Lane J, the seals were not read outside the gatehouse in Lane K.

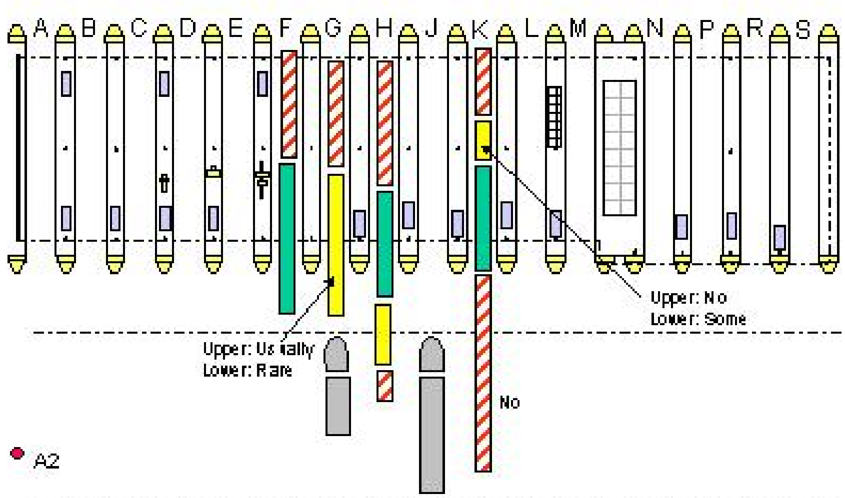


Figure B.33. Query Results with Seals in Lanes G through K

As the seals reached the entrance of the gatehouse in Lane K, each seal was read in roughly half of the query attempts: some queries detected one or both seals, others returned none. Given the short intervals between queries, this is probably satisfactory for determining the presence of the seals in practice. As the seals reached the midpoint of Lane K, the lower seal was still read occasionally – possibly due to random reflections. The upper seal was not read, most likely due to the interference from the ceiling. Therefore, this region is marked yellow instead of green.

In Lane H, the seal was not read in the queue until it moved beyond the 20' container that sat in the queue for Lane G. Results were still spotty, though, with perhaps one-third of the queries producing reads. In the entrance region of Lane H, both seals were read about half of the time, so this region is marked in green.

In Lane G, in the region marked in yellow, the lower seal was rarely read, but the upper seal was usually detected. Beyond this area, no reads were achieved. In front of this area, in the queue, some reads would be expected, but because of the angle at which the truck entered the queue, no data was recorded in this forward area.

For the same reason, no data is recorded in the queue area for Lane F. Outside of and for the first half of Lane F, both seals were read on most of the queries, but not on all. Beyond the midpoint of Lane F, reads stopped.

We estimate that at the entrance to Lane G, the range from the seals to the reader is about 125 feet (38 m), and the seals are off from the aim axis of the reader antenna by 10° or less in both the horizontal and vertical directions.

Lanes A through D are outbound lanes, so the containers move through from top to bottom in the figures shown here. With the antenna in Location A2, the sealed container was driven past in Lane B. With the seals tucked in next to the vertical plate of the container frame, we do not expect good reads to the right side of the container. The lower seal was not read until the doors of the container reached and passed the reader location. At that point, the distance between the seals and reader was about 20 feet (6 m) horizontally and 12 feet (3.6 m) vertically. As the container turned left towards the inbound queue a few seconds later, the upper seal was detected for the first time, and reads from the lower seal became less frequent.

<u>Antenna Location A1</u>

We considered that the poor reads at long distances (Lanes R, S) from Location A2 may have been attributable to poor signal-to-noise ration, i.e., RF-link operate at its limit . The antenna was moved, at the same height, to Location A1. From here, there is an open view to a container just entering the gatehouse as long as there are no intervening containers entering at the same time. The potential disadvantage of this location is that before the seal enters under the gatehouse ceiling, the direct line-of-sight from the seal to reader is at a sharper angle (near parallel with the container door) than for Location A2. The antenna was oriented with the same downtilt as at Location A2, but faced perpendicular to the lanes, parallel to the front face of the gatehouse.

With containers in the queue (but not entering) in Lanes N, P, and R, the sealed container was driven into Lane S. No successful reads of either seal were achieved.

As with the Lane B (out-going) test in Location A2, the sealed container was driven outbound through Lane C with the antenna in Location A1. Both of the seals were read some (< 50%) of the time. Unlike the Lane B test, successful reads were achieved before the doors of the container passed the antenna location.

Antenna Location F1

With Location A1 providing no obvious advantage, we relocated the antenna to Location F1. This, about 170 feet (52 m) from gatehouse, was as close as the antenna could be placed to the gate without impeding truck traffic. Still with a down-tilt of about 10°, the antenna was rotated to face toward the entrance of Lane J. The antenna was elevated to about 30 feet. Figure B.34 shows this placement, the approximate boundaries of the 3dB horizontal beamwidth (37° half-angle), and the test results. This antenna location was chosen because it provided a view of the back of the container as it lined up in the queue. The disadvantages were that:

- the container was usually at least 30 m away from the antenna, and
- with the container passed through the nearer lanes (closer to Lane G), the line-of-sight from the seal to the reader become more perpendicular from the container doors. The seal is partially shielded by the container-frame lip at these angles.

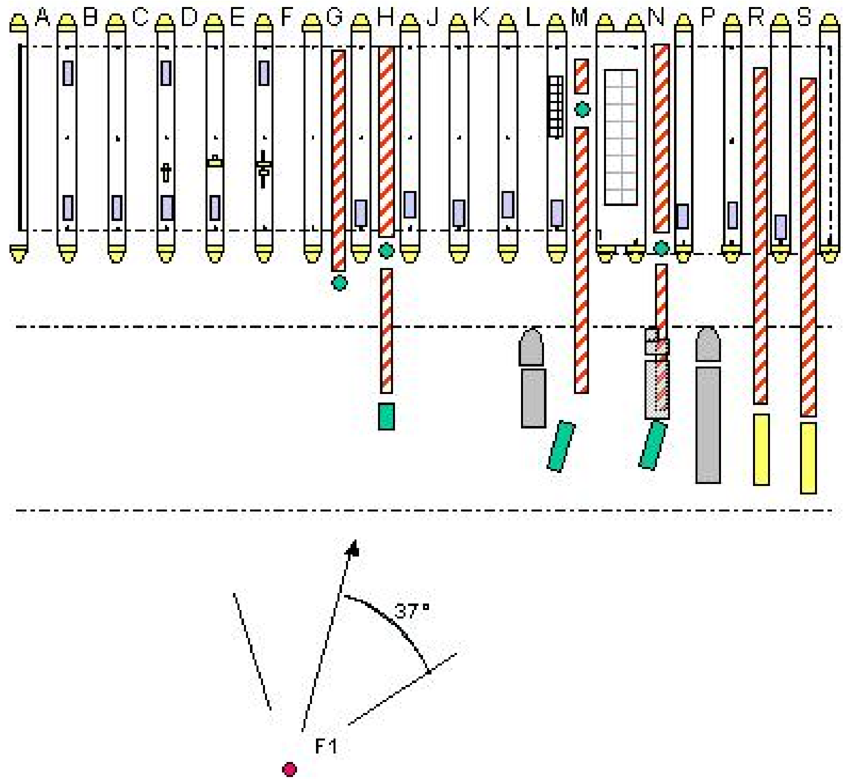


Figure B.34. Query Results with Antenna at Location F1

When the seals were entering the queue in Lane S, the lower seal was read several times in a row, but the upper seal was not read at all. This may again be the result of the RF link being close to its performance limit (76m). As the seals left the yellow-shaded region in Figure B.34 and moved alongside the container in Lane P, neither was read. The opposite was observed in the queue for Lane R: the upper seal was read repeatedly, but the lower seal was not. Moving the antenna slightly did not affect this one-sided behavior; the upper seal remained the only one that could be read.

Both seals were read most of the time as the container turned and entered the queue for Lanes M and N. The read zone was short-lived, however. For the rest of each pass through M and N, the upper seal was read once in each lane, in the approximate locations shown by the green circles. When the successful read of the upper seal in Lane M occurred, it was positioned in a 12-foot (4 m)-wide gap between masonry walls.

In the queue for Lane H, both seals were read most of the time in a brief region. As the container moved forward to the gate, neither seal was read until the seal were near the gate entrance, where the upper seal was read once. In Lane G, the upper seal was read once in a similar position near the gatehouse.

Signal Strength

Signal strengths received by the reader from the seal were measured at various locations using the reader's antenna and the RSSI values reported by the All Set demo software. (There is no firm correlation between RSSI and dBm, but All Set believes that a variation of 3 RSSI units corresponds to about 1 dB, i.e. 200 RSSI is approximately –80dBm but it is not completely linear.) At most measurement locations, the antenna direction was varied as was done for the gate readability tests; that is, it was aimed toward Lane M, Lane A, and/or inward toward the container yard. The reader-antenna height was maintained at 10 feet above the road surface. The 10 measurement locations are shown in Figure B.36.

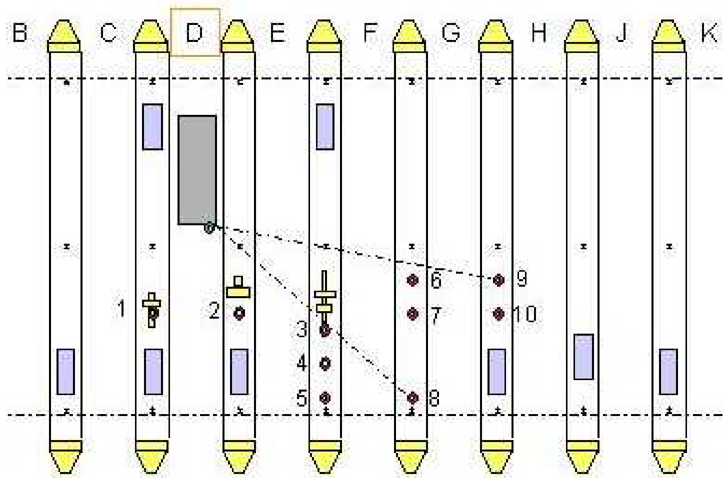


Figure B.36. All Set Measurement Locations in Gatehouse

Note that there is a different antenna-to-seal elevation and azimuthal angle associated with each measurement location and antenna direction. The antenna has a different gain at each such orientation and elevation (the elevation effect may be less for the measurement points selected)[4].

There was traffic in the surrounding Lanes during these measurements. These changes are noted in the following Table, with reference to the locations defined in Figure B.36.

Location	Reader Direction	RSSI values	Notes
1	to Lane A	253	Container in Lane C, many reads
1	" "	No reads	No container in Lane C; container in Lane B

[4] Also the environment will change between different locations. It is hard to make signal strength measurements without using an echo-free room.

1	to yard	242	
1	to Lane M	257	Container in Lane C
2	to Lane A	272	Container in Lane C
2	" "	Rare reads	No container in Lane C
2	to yard	278	Container in Lane C
3	to Lane A	261, 258	Container in Lane C
3	to yard	242	Container in Lane C
4	to Lane A	247, 248	Nothing in Lanes E or F
4	to yard	255	Nothing in Lanes E or F
4	to yard	261	Container moving through F
4	to yard	231	Container in E
4	to Lane M	No reads	Nothing in Lanes E or F
5	to Lane A	259, 250, 274, 272	Container in Lane C, nothing in Lane E. Possible reasons for RSSI changes not observed.
5	to yard	254	Container in Lane C, nothing in Lane E.
6	to Lane A	249	No containers near
7	" "	247, 247	Container in Lane G, rear corner 1-ft past reader, towards container yard
7	" "	247, 248	No container in Lane G
8	" "	233	I-beam on Island D/E is in-line between seal and reader. Intermittent (10%) read rate. As container moved through Lane E, read rate increased at some locations of the moving container, but not at others
9	" "	No reads	Containers in G and H creating "canyon" around reader.
9	" "	239, 244	Container in Lane H. I-beam on Island D/E is in-line between seal and reader.
9	to yard	No reads	Container in Lane H.
10	to Lane A	259	Container in Lane H.

Table III. All Seal Signal Strengths at Various Locations in Gatehouse

APPENDIX C: ON-RAIL TESTING

C.1 INTRODUCTION

The objective of the on-rail test was to determine e-seal readability in the on-rail environment. Testing of all e-seals, except for Savi SmartSeal, was conducted at the Howland Hook Terminal, during the week of March 31, 2003. The weather was fair, with the temperatures in the 40F. On-rail testing of the Savi SmartSeal was performed the week of January 27th, 2003. The temperatures on those days were in the 20F.

The test scenario addressed one of the worst-case scenarios for electronic seals on a railcar. In such a scenario, two twenty-foot containers are placed end-to-end with their doors facing each other. A forty-foot container is placed on top of them. If the containers were placed in a well car, the handle region of the doors may be below the sidewall of the railcar, and there would be a direct line-of-sight to the seal from only a narrow region on the sides of the car. In a slightly less severe scenario, the containers are on a flatcar rather than a well car.

Howland Hook Terminal does not have on-rail facility. Nevertheless, we were able to setup this test with resources available at Howland Hook, and have a test environment that will yield the answers we were looking for[5].

The test setup is shown in Figure C.1. Five empty containers were stacked up. These consisted of four, 20-foot, rag-top containers, with doors facing inward, and a 40-foot container across the top. The seals were applied to the door of one of the upper 20-foot containers (the "Genstar" container on the left of Figure C.1). This arrangement was intended to simulate a double-stack railcar configuration with a 40-foot container atop two 20-foot containers. The lower pair of containers that sat on the ground was used to elevate the sealed container above grade level, as if on a rail bed. A container sitting on a railcar platform is elevated about 4ft from the ground. In our test configuration, e-seal containers are elevated about 8.5ft from the ground, i.e. the height of the container. We

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[5] The key reasons for selecting Howland Hook Terminal for on-rail test, even though Howland Hook terminal does not have rail facility, were:

- The outlined on-rail test environment can be setup by using additional containers to serve as a railcar platform. Hence, we can achieve almost the same on-rail environment as when the railcar is in the stationary mode.
- Howland Hook management has offered full logistical support to enable this very challenging test setup.
- There was a concern that at the terminal with the rail facility, we will not be able to disrupt the on-rail operational to create the outlined scenario. In the unlikely case that the on-rail facility had additional resources to commit to this test, the cost required to support those resources would have exceed our available budget.

have mitigated the problem of the height difference by adjusting the height of the antenna post.

Figure C.1. Seal Locations on Simulated Rail-Car Double-Stack

The space between the container edges was about 4.5”; the surfaces of the container doors are set back from the container edge, so the distance between the door surfaces varied from about 9.5” to 12.5”. This variation is due to the corrugation features of the doors.

The primary focus of this test was to evaluate readability of e-seals, when they are placed deep between containers with obstructions on all ends, and only a narrow opening that provides line of sight. Therefore, for these tests, the goal was to map the read/write zone around the containers.

Test involving measurements when reader or e-seal platforms are moving where not conducted at this time due to time and resource constraints. The test setup would involve mounting the antenna, reader, and computer systems on a truck and driving past the containers at various speeds. More importantly, to test the velocity angle, it would also require driving at different distances from the container formation. However, based on the communication times for each e-seal system, we can still estimate the maximum speed allowed by these ranges.

C.2 E-LOGICITY TEST RESULTS AND OBSERVATIONS

On-Rail Readability and Signal Strength

Reads were attempted with a log-periodic (directional), low-gain (~ 4.7 dBi) antenna that was moved along a line 6 meters from the container walls at the height of the seal, as shown in Figure C.2. This distance was chosen to simulate a possible rail-side antenna location. At each position along the line, the antenna was aimed toward the gap between the 20-foot containers. This allowed us to maintain the calibrated gain of the antenna at each location.

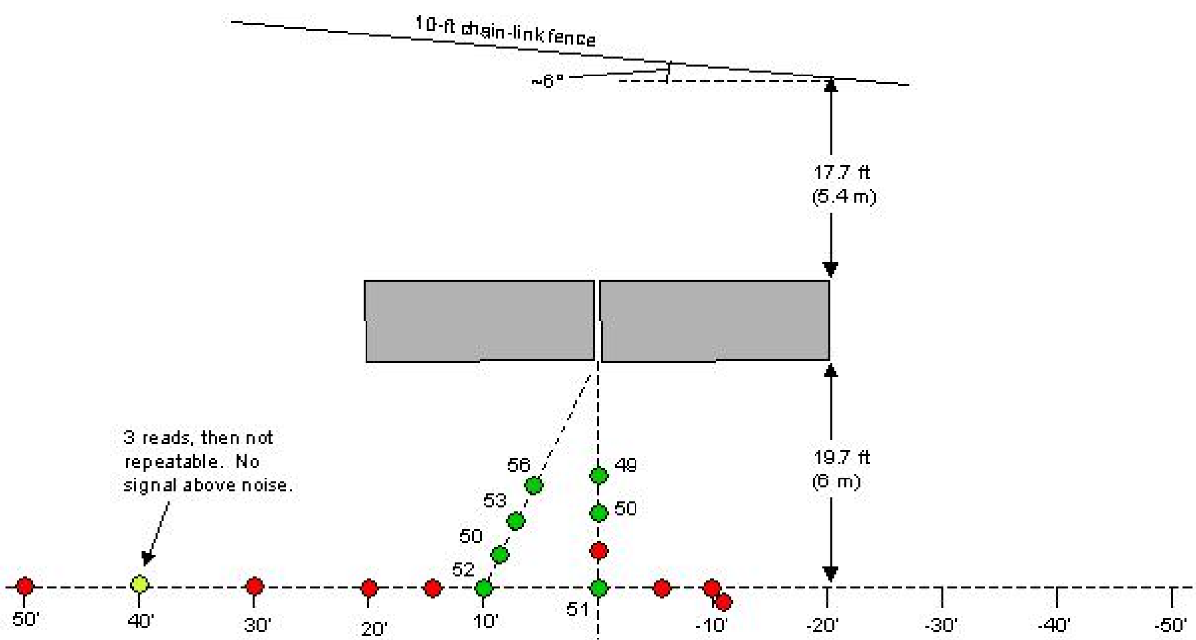


Figure C.2. Successful Read Locations and Signal Strengths (dBμV/m) for e-Seal

Green circles indicate locations where reads were successful and consistent, while red circles indicate locations where reads were non-existent or rare. Note from Figure C.2 that a few intermittent reads were achieved at 40 feet from the container gap, but no signal could be discerned above the noise using the spectrum analyzer, and the reads could not be repeated. The seal was readable in a 10- to 20-foot range near the gap between the containers.

Signal strengths were measured at 1-meter increments within the read zone, as shown in Figure C.2. All measurements were made with the reader antenna vertically polarized.

After testing was completed, it was noticed that the power level of this seal might have been unusually low during this test. The modification made to the bolt to allow it to be removable might have increased the power consumption of the tamper-detection circuit. This may have artificially reduced the read zone. This effect remains to be confirmed. Nonetheless, the output power from the seal was likely constant during this test, so the relative variations in field-strength at various locations should be valid.

C.3 HI-G-TEK TEST RESULTS AND OBSERVATIONS

On-Rail Readability and Signal Strength

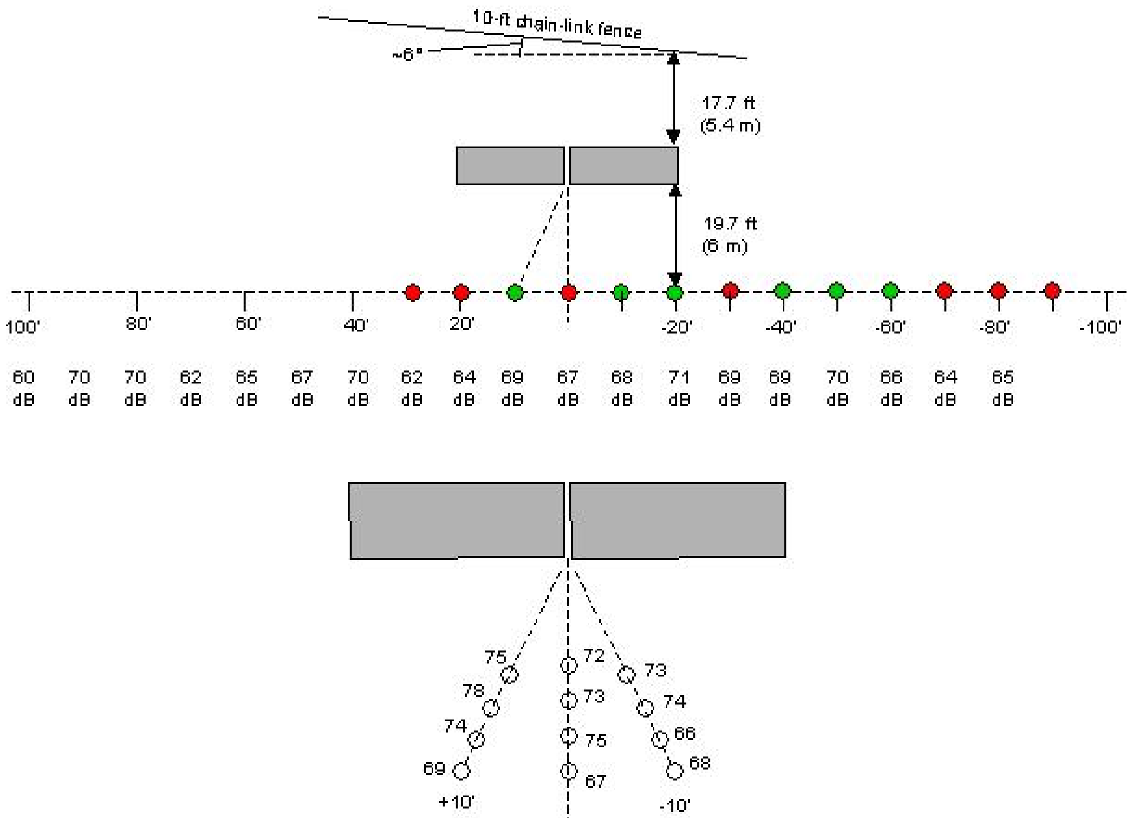


Figure C.3. Successful Read Locations and Signal Strengths (dBμV/m) for DataSeal

Reads were attempted with a log-periodic (directional), low-gain (~ 4.5 dBi) antenna that was moved along a line 6 meters from the container walls at the height of the seal, as shown in Figure C.3. This distance was chosen to simulate a possible rail-side antenna location. At each position along the line, the antenna was aimed toward the gap between the 20-foot containers. This allowed us to maintain the calibrated gain of the antenna at each location. Tests were conducted with the antenna vertically polarized.

Green circles indicate locations where reads were successful and consistent, while red circles indicate locations where reads were non-existent or rare. Figure C.3 shows that readability tends to drop off when the measured signal strength is below about 65 dBμV/m, although some reads were missed where signal strengths measured 67 and 69 dBμV/m. However, readability and signal strength measurements were not simultaneous; if there are strong signal nulls or peaks in these areas, small movements of the antenna could alter the received signal strength and readability.

The lower part of Figure C.3 shows signal strengths increasing by several dB towards the gap between the containers. These were measured at 1-meter increments.

The seal was readable at most measured locations over a 70-foot range, from the +10' to the –60' locations. The high signal strengths measured around the +40' and +90' locations suggest that those locations may have provided reads. However, the stretches of low-signal regions within these ranges indicates that uninterrupted communications may be a problem at some speeds. Moving the antenna closer to the rail line may raise the minimum signal above the required threshold. Modeling and analysis of specific antennae should provide more guidance.

C.4 SAVI TEST RESULTS AND OBSERVATIONS

On-Rail Readability

The seal was queried and read successfully from a distance of over 374 feet (114 m), with RSSI values in the range of 70 (around –93 dBm). The ultimate range of the Savi SmartSeal in the on-rail simulation was not reached. The distance of 374 feet (114m) was the practical limit for the test space available at the cargo terminal. However, for an environment with more RF noise around 434 MHz than the Howland Hook site exhibited, RSSI values of around 70 may represent a limit to the range at which readability is acceptable.

In this test, the reader was located at a height of about 15 feet. The seal on the container door was at a height of about 10 feet. The reader was moved along a line 6 meters away from, and parallel with, the "rail." At the long distances involved, the reader ended up being near other containers in the yard, as shown in Figure C.4.

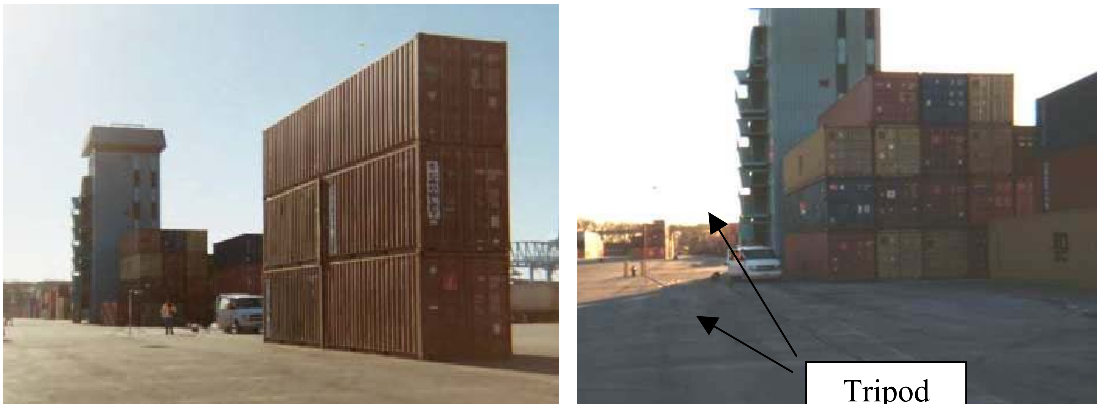


Figure C.4. Reader Antenna Nearing Other Containers (reader is about 200 ft from seal inn photo on right)

The seal was queried several times at each location. With software made available by Savi, we recorded the RSSI values received by both of the orthogonal antennae that are internal to the reader. These values are presented in Table C.1.

Range from Container Gap (ft)	View Angle	RSSI 1	RSSI 2
224	5.1°	79	96
		78	97
		76	97
		67	97
		51	97
		74	98
254	4.5°	89	91
		83	95
		*	*
		89	93
		88	90
		87	92
284	4.0°	89	101
		90	101
		86	104
		88	101
		79	103
314	3.6°	57	99
		61	99
		65	96
		36 / 51 **	99 / 99 **
		57	99
		63	99
		41	97

		49	95
344	3.3°	67	78
		71	82
		61	75
		64	69
		71	70
		70	81
374	3.1°	73	57
		72	52
		75	69
		74	61
		55	78
60	8.2°	120 ***	

* Possible failed query/read.

** RSSI-1 signal fluctuation corresponded to a top-lift driving by, parallel to the "rail," about 30 meters away.

*** See text.

Table C.1. RSSI values for Savi Seal in On-Rail Simulation

The Table also lists the view angle from the container gap back towards the reader. In all cases shown, the angle is very shallow, since the reader-to-seal distance is much greater than the stand-off distance from the reader to the "rail." The last row of data reports a reading taken at a closer point, about 60 feet from the container gap and along a line that was only 2.7 meters from the "rail" edge. This reading was taken with the reader at a height of about 30 feet, rather than 15 feet. In this case, the elevation angle from the seal height to the reader was about 18°, compared to about 1° for the other cases in the table. The measurement did not include a report of which of the two antennae in the reader detected the stronger (120 RSSI) signal.

Signal Strength

During a second set of tests, the Savi SmartSeal was set to beacon at 10-sec intervals. Signal-strength measurements were made with a log-periodic (directional), low-gain (~ 4.7 dBi) antenna that was moved along a line 6 meters from the container walls at the height of the seal, as shown in Figure C.5. This distance was chosen to simulate a possible rail-side antenna location. At each position along the line, the antenna was aimed toward the gap between the 20-foot containers. This allowed us to maintain the calibrated gain of the antenna at each location.

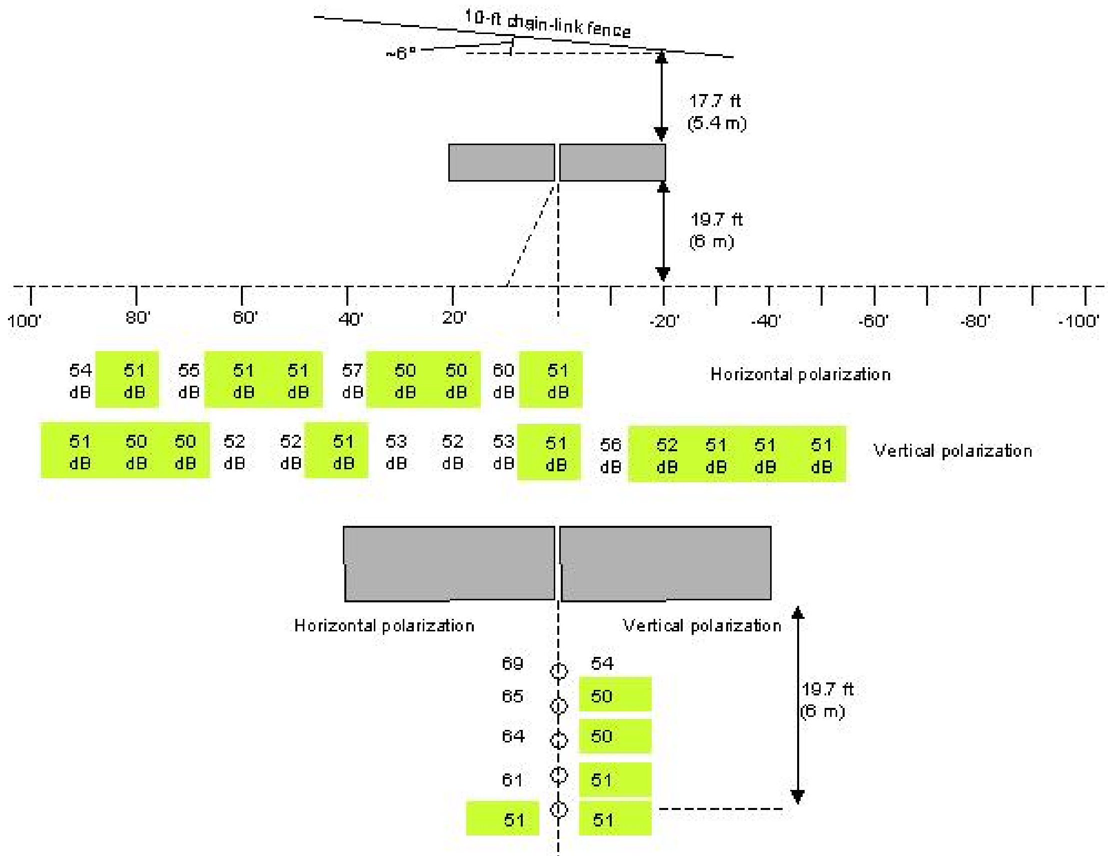


Figure C.5. Signal Strength (dBμV/m) Measured Along Rail Direction for Savi Seal

Two sets of measurements were taken, with the antenna horizontally and vertically polarized. In Figure C.5, signal values shown highlighted, listed at 50 or 51 dBμV/m, were not discernible in the spectrum above the ambient noise. (This does *not* imply that the reader, with its filtering and signal processing capability, could not successfully read or query the seal.) Note that, out to 50 feet along the “rail” direction, the vertical polarization measurements on the “negative” (right) side of Figure C.5 are lower than those on the positive side. A similar trend was seen in the readability of the e-Logicity seal, although its extent toward the positive direction was harder to discern because of the low signal levels.

C.5 ALL SET TEST RESULTS AND OBSERVATIONS

On-Rail Readability

The seal was positioned in the container door, just below the top hinge (a 1” gap between the hinge bottom plate and the top of the seal’s antenna unit). In the container stack, the seal was at a height of 16.5 feet. Reads were attempted by querying the seal from the reader, with its integrated, directional antenna (~ 8 dBi) that was moved along a line 6 meters from the container walls, as shown in Figure C.6. This distance was chosen to simulate a possible rail-side antenna location. The reader was at a height of 8.5’. Reader height was limited by the need to keep the RS-232 no longer than 6 feet for consistent communications between the PC and the reader. Two antenna orientations were used. In one, at each position along the “rail” line, the antenna was aimed toward the gap between the 20-foot containers. This allowed us to know that the gain was consistent at all locations. Because of the asymmetric positioning of the All Set seal (compared to other seals that are placed near the door handles), we also tested with the antenna on the opposite side of the rail, though again always pointing at the gap. The stand-off distance (3.1 m) and lateral extent (30 feet) were limited by the edge of the paved lot and the presence of other containers stacked nearby.

Green circles indicate locations where reads were successful and consistent, while red circles indicate locations where reads were non-existent or rare. Locations of intermittent readability are marked with yellow circles. Along the 6-meter line, consistent reads were obtained along a 55-foot range. After observing the variable performance at the +40’ and +50 locations, we conducted additional tests along a 4-meter line. Performance improved at the 40’ location, but the region of poor or inconsistent reads seemed to be shifted to the 20’ location. This indicates there may be a weak region centered along a line drawn from the gap towards the 35-foot x 6-meter point.

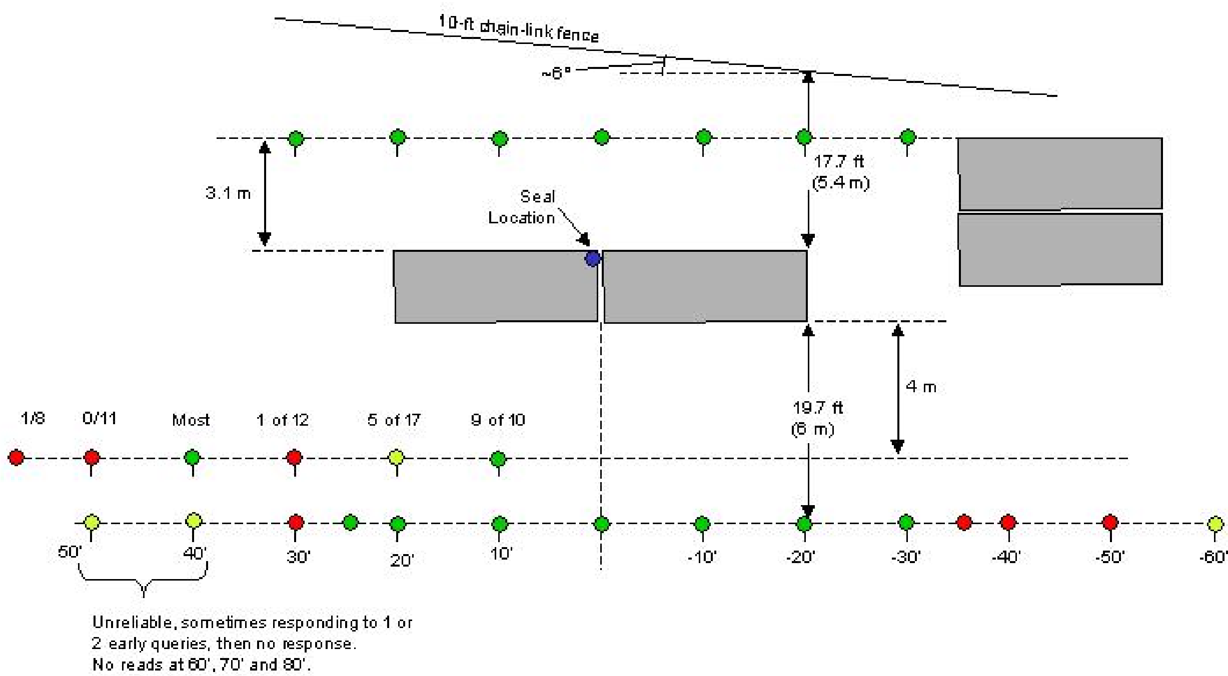


Figure C.6. All Set On-Rail Simulation Results with Reader Aimed at Gap

The second orientation kept the reader facing the lateral sides of the containers, perpendicular to the rail line. This replicates how the integrated antenna would be positioned in an actual application (i.e., fixed). Figure C.7 shows the results with the second reader orientation, perpendicular to the "rail" line. The zone of consistent reads at 6 meters is reduced to about 40', compared to the 55' seen when the antenna is always directed at the gap.

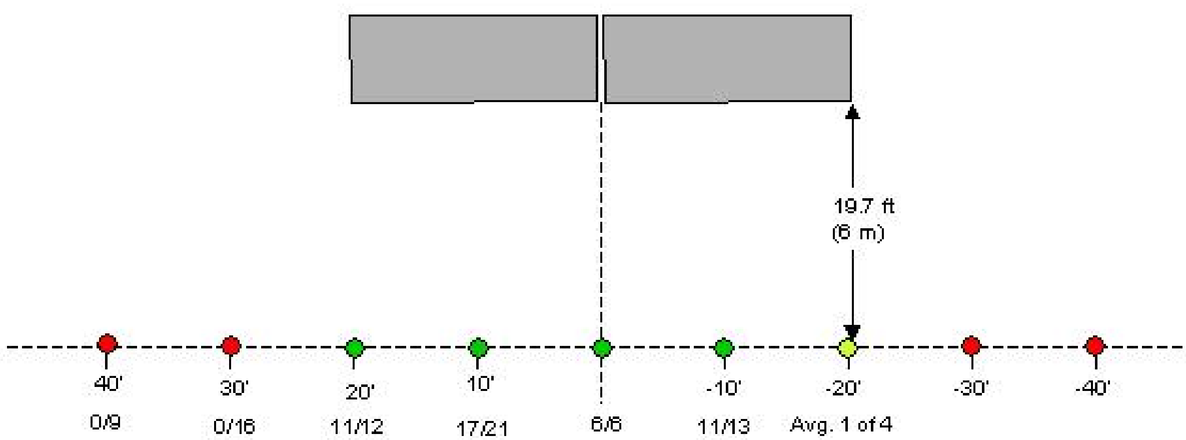


Figure C.7. All Set On-Rail Simulation Results with Reader Aimed Normal to Rail

Signal Strength

Attempts to measure signal strengths were unsuccessful due to ambient RF signals in a band around 2.44 GHz. The seals from the reader and seal could not be distinguished on the spectrum analyzer above the background signals. (Clearly, though, the reader, with its filtering and signal processing capability, could successfully read or query the seal.) These tests were also conducted with recently upgraded software from All Set, and the ability to read RSSI values with that software required the use of an upgraded reader. The new reader arrived the day of the testing, and was not integrated into the test set-ups until the following day. So, no RSSI values were measured in these tests.

APPENDIX D: ON-ROAD AT-SPEED TESTS

D.1 INTRODUCTION

The objective of the on-road tests was to determine e-seal readability and e-seal performance in the on-road environment. Specifically, when the truck is moving at speeds ranging from 5 mph to 30 mph. The findings would enable evaluating the feasibility of security screening of containers without having the trucks to slowdown or stop. If feasible, placing e-seal readers at various check points on the road will improve efficiency of container security checking at the approach to the terminal, boarded points, and various check points on the road.

This section of the report presents the results and observations gathered during the on-road test.

Test Environment

.The On-Road tests were conducted on April 12th, 2003 on the farm in Leesburg, Virginia. The day was partly sunny with the temperatures in the 60F. To simulated container, we had rented a U-Haul truck to simulate a container[6]

The seals were mounted, one at a time, on the roll-up door of the rented truck. Most of the door (the region around the seals) was covered in conductive metal sheeting to provide a large backplane similar to that of a cargo container. Efforts were made to install the seal with a stand-off from the door similar to that observed when installed on a cargo container. For the e-Logicity e-Seal, this involved passing the bolt through a small piece of Styrofoam, and taping the Styrofoam to the door. The e-Logicity seal was installed with its label facing outward from the doors. For the Savi SmartSeal, the backing magnet was held against the door, thereby setting the stand-off distance between the plastic seal housing and the door. This mounting is shown in Figure D.1(a). For the Hi-G-Tek DataSeal, the plastic mounting bracket was held against the door, and the seal inserted into the bracket. For these tests, the keeper-bar was not simulated. This mounting is shown in Figure D.1(b).

[6] Simulated "on-road" testing was initially attempted at the cargo terminal test site, but the data presented here were acquired off the terminal, on a lightly used public road, using a roll-door truck in lieu of a container. We opted not to continue these tests at the terminal for a number of reasons. First, in the container yard, there were very limited locations where trucks could be accelerated to 30 mph. Second, the trucks available fore this duty on the terminal had no speedometers, so it was necessary to employ a second "pace" vehicle leading the truck. The truck attempted to match the speed of the pace of the pace vehicle, whose driver radioed to the reader operator when a certain speed was reached. Third, the trucks could not maintain the approximate speed for very long because of space constraints. Finally, the road area available was also used by other two-way truck traffic, which limited the locations at which reader antennae and equipment could be set up.

(a) (b)

Figure D.1 Savi (a) and Hi-G-Tek (b) Seals Attached to Coated Roll-Up Door

The All Set seal was positioned behind a small gusset plate in the lower corner of the door. This area provided structures that were similar (though not identical) to those of an ISO container: a vertical "lip" that blocks the line of sight of the seal from the starboard side of the container, and a gusset plate that provides a some shielding of signals directly rearward of the seal. The roll-up door was opened slightly to allow the seal to be placed in its intended orientation, and then the gap beneath the door was covered with metal sheeting, to restore the reflective backplane. For All Set, the height of the reader antenna was only about 1.5 feet above the height of the installed seal. This is shown in Figure D.2.

Figure D.2. Views of All Set Seal During and After Installation in Door Seam

All the tests were conducted on a narrow, lightly-used, gravel and dirt road. Maximum safe speed was about 30 mph.

D.2 E-LOGICITY ON-ROAD TEST RESULTS AND OBSERVATIONS

Seal #21546 was newly activated by inserting the bolt with a hard push. (Although the bolt felt secure, it reported itself as "tampered," and was later removable with a hard pull.) This initiated the seal beaconing at 10-second intervals.

A directional log-periodic antenna, with a peak gain of about 4.7 dBi at 434 MHz, was aimed down the road at a height of 11 feet above the road surface. The antenna was aimed at about 15° off of parallel to the road (90° would have been looking directly across the road). With the truck traveling "left-to-right, " the reader is on the starboard side of the truck, as it would be if it were on the right shoulder of a U.S. road. With the truck traveling "right-to-left," it passes the reader on its port side, as it would if the reader were on the left shoulder of a U.S. road.

Summary of the e-Logicity on-road test results are shown in Table D.1

Direction of travel	Speed (mph)	Results
Stationary	0	Read range is 170ft
Right-to-left	30	One read
Right-to-left	30	No reads.

Beacon time interval =10sec (preset)

Table D.1. e-Logicity On-Road Summary results

In stationary tests, it was found that the range from the seal to the reader was about 170 feet.

Also, as was found in the gate tests with an omni-directional antenna, the seals are not read as the container is approaching the antenna location, but only once the container doors are nearly in line with the antenna

Multiple passes were made in each direction, at speeds of about 30 mph. Only one successful read was achieved at 30 mph, with the antenna horizontally polarized and the truck moving from right to left. In the 10-second interval between beacons, it is obvious that the seal would pass in less then 10 seconds through a 170-foot region at any speed above about 11 mph. Hence, at container speeds higher then 11mph, the read can be read only if the beacon signal occurs while the seal was in the read zone. As the speed increases, the probability of the beacon signal occurring while the seal is in the read zone is decreasing. During the testing, we were left relying on chance that this would occur, and it rarely did.

D.3 HI-G-TEK DATASEAL ON-ROAD TEST RESULTS AND OBSERVATIONS

A directional log-periodic antenna, with a peak gain of about 4.5 dBi at 916 MHz, was aimed down the road at a height of 11 feet above the road surface. The antenna was aimed at about 20° off of parallel to the road (90° would have been looking directly across the road), in the direction of truck travel so that it would point toward the rear door after the truck passed the antenna. The antenna was oriented with its elements in a vertical plane. With the truck traveling "left-to-right," the reader is on the starboard side of the truck, as it would be if it were on the right shoulder of a U.S. road. With the truck traveling "right-to-left," it passes the reader on its port side, as it would if the reader were on the left shoulder of a U.S. road. The reader transmission power was set to its maximum level (100 on a scale of 0 to 100).

The test results are summarized in table D.2. However, after the testing was completed we had found out from the vendor that the new reader software required different power settings then had been previously specified. Both vendor and testers felt that the incorrect power settings could have resulted in spurious readings. Hence, the obtained results are inconclusive.

Direction of travel	Speed (mph)	Results
Stationary	0	Not measured, 80m - vendor spec
Right-to-left	30	Multiple reads, all successful
Left-to-right	30	Multiple reads, all successful

beacon time interval= 3sec (manually set)

Table D.2. Summary of Hi-G-Tek On-Road Results (Inconclusive)

D.4 SAVI ON-ROAD TEST RESULTS AND OBSERVATIONS

Seal #4000109 was set into beacon mode. In a typical Savi application, a seal may be put into beacon mode by leaving a Signpost area, and read by a distance reader. The seal could then be taken out of beacon mode upon entering a later Signpost area. Querying from the reader and getting a response is not Savi's typical, recommended method for at-speed reading. The reader antenna was positioned on the side of the road, at a height of about 20 feet, and about 10 feet from the center of the lane (which is roughly the seal location).

On-road test results are summarized in Table D.3.

Direction of travel	Speed (mph)	Results
Right-to-left	30	No read
Right-to-left	30	One read, at about 10-15 feet before door reached antenna location
Right-to-left	30 & 25	Two reads. First about 100 feet before door reached antenna location; second about 250 feet beyond antenna. Speed at second read estimated as 25 mph.
Left-to-right	20	One read, about 50 feet before door reached antenna

		location
Left-to-right	30 & 25	Two reads. First about 25 feet before door reached antenna location; second about 400 feet beyond antenna, based on sustained speed of 30 mph.
Left-to-right	30	No read

Beacon interval = 10sec

Table D.3. Summary of Savi On-Road Results

Three passes were made in each direction, at speeds of 20 to 30 mph. With the truck traveling "left-to-right, " the reader is on the starboard side of the truck, as it would be if it were on the right shoulder of a U.S. road. With the truck traveling "right-to-left," it passes the reader on its port side, as it would if the reader were on the left shoulder of a U.S. road.

In the right-to-left direction, one pass resulted in two reads, which were 10 seconds apart (the beacon interval). At an average speed of 27 mph between these reads, the truck would have traveled about 400 feet between reads. This agrees relatively well with the estimated locations of the truck at the times of the two reads. A similar situation occurred in the final left-to-right pass. These results are consistent with the finding (discussed in the Lab Test report) that the seal-to-reader distance, when viewing the seal from the back of the container, is about 550 feet.

D.5 ALL SET ON-ROAD TEST RESULTS AND OBSERVATIONS

The reader, with its directional, integrated, patch antenna, with a peak gain of about 8 dBi at 2.44 GHz, was placed at a height of 4 feet above the road surface. The height of the antenna was limited because the seal was placed unusually low due to the limitations of the truck geometry; we did not want the reader to be artificially high above the seal location. The reader/antenna was located about 10 feet from the center of the lane. Tests were conducted with the reader antenna aimed directly across the lane (90° to the road) and with the antenna aimed at about 25° off of parallel to the road, so that it roughly faces the back of the truck after the truck passes the antenna.

With the truck traveling "left-to-right," the reader is on the starboard side of the truck, as it would be if it were on the right shoulder of a U.S. road. With the truck traveling "right-to-left," it passes the reader on its port side, as it would if the reader were on the left shoulder of a U.S. road.

Summary of the results is shown in table D.4.

Direction of travel	Speed (mph)	Results
Right-to-left	30	Multiple reads until 225 feet

Right-to-left	20	Intermittent as far as 500 feet (150 meters)
Left-to-right	20	
Left-to-right	30	Multiple reads until 70 feet (25m) from reader

Table D.4. Summary of All Set On-Road Results

Results with Reader Aimed Across Lane

The read zone is expected to be smallest with the reader aimed across the lane. The reader queries the seal about every 0.84 seconds. At 30 mph, the truck moves about 37 feet in this amount of time.

With the truck moving in the right-to-left direction at 30 mph, multiple reads were achieved. Some queries resulted in multiple reads. In this direction, the seal is “facing” the reader antenna as it passes, without the edge of the doorframe or the gusset blocking the view.

With the truck moving in the right-to-left direction at 30 mph, multiple reads were again achieved. Successful reads continued until the seal was at a distance of about 75 feet (20 – 25 m) from the reader antenna. When traveling in this direction, the edge of the doorframe is between the seal and the reader when the door is just passing the reader location.

Results with Reader Aimed Along Lane

With the truck moving in the right-to-left direction at 30 mph, multiple reads were achieved. Successful reads continued until the seal was at a distance of about 225 feet (70 m) from the reader antenna. Reads may have continued further except for the truck passing over a crest in the road. The truck travels 225 feet in about 5 seconds at 30 mph, and reads continued with each query during this time.

Some reads were achieved intermittently out to a distance of around 500 feet (150 m) as the truck continued and maintained speeds of over 20 mph.

APPENDIX E: SIMULATION RESULTS

E.1 INTRODUCTION

E.1.1 Purpose and Objective

The purpose of the e-seal field-testing was to collect and analyze e-seal performance data in the operational environment. However, some of the e-seal characteristics (e.g., frequency) and their impact on e-seal performance can be better understood by evaluating e-seal performance in the simulated environment. The primary focus of the e-seal simulation effort was to examine e-seal performance as a function of different frequencies. Of particular interest was evaluating signal patterns and their behavior around complex geometries. Hence, we have used a simulation tool that operates in a frequency domain and predicts resultant signal patterns from antenna sources around complex geometries.

E.1.2 Requirements

Evaluate signal patterns from antenna sources that operate at three frequencies:

- 433MHZ
- 916MHZ
- 2.44GHZ

E.1.3 Reference Documents

- CTLSS (Cold-Test and Large-Signal Simulator) – An Advanced Electromagnetic Simulation Tool for Designing High-Power Microwave Sources, Cook, Mondelli, *et al*, IEEE Transactions On Plasma Science, June 2000
- CTLSS User Manual V 1.1, April 2002, SAIC

E.2 SIMULATION PROCESS & TOOLS

The e-seal simulation was performed using the Cold-Test and Large-Signal Simulator (CTLSS) Tool. The use of CTLSS has been validated for RFID-type devices through past CCDoTT efforts. The Tool was hosted on a PC with a 1.4 GHz AMD Athlon processor. The operating system was Windows 2000.

This section describes in more detail the CTLSS Tool as well as the process used to setup the CTLSS environment and perform simulations.

E.2.1 CTLSS[7] Tool

The CTLSS code is an integrated three-dimensional, large-signal simulation program. It is a general-geometry, frequency-domain, electromagnetic code that predicts resultant signal patterns from antenna sources around complex geometries. CTLSS handles both resonant problems and non-resonant driven-frequency problems. CTLSS models static environments. To examine RF field patterns as components are moving relative to each other, separate simulations must be run, each one representing a “snap-shot” in time.

[7] The CTLSS code was created under funding from the Office of Naval Research Modeling and Simulation Program by Science Applications International Corporation (SAIC), and is released through the Vacuum Electronics Branch (Code 6840) at the Naval Research Laboratory.

The CTLSS code has been designed as a coupled cold-test and large-signal model. The entire model is three dimensional (3D), and is intended to handle arbitrary device geometry. The 3D cold-test module is volumetric and operates entirely in the frequency domain. It includes both a resonant (eigen-mode) electromagnetic solver and a non-resonant (driven-frequency) electromagnetic solver. Both solvers are designed to handle complex material properties (permittivity and permeability) with large loss tangents. The driven-frequency solver in this version of CTLSS does not include the capability to process S parameters between ports and between modes. This version is a single-block solver.

CTLSS is an object-oriented program that offers the CTLSS Graphical User Interface (GUI) to write the input file. In addition, CTLSS offers Templates for specific types of devices. Templates are higher-level interfaces that automatically populate the GUI (and hence the CTLSS input file). Often the user will start with a Template that is close to the problem, then edit the problem in the GUI before saving the CTLSS input file. In addition to the setup GUI that creates input files, CTLSS has a run-time GUI that helps to start runs and export data to the viewer and/or the post-processor. After saving the CTLSS input file, the user can call either the CTLSS run-time GUI or the CTLSS viewer interface from the setup GUI and do a setup run to examine the structure in an interactive 3D rendering. When the run is completed, the user can view 3D structures and fields using the either the VTK viewer or the Voyager post-processor. The post-processor creates an ASCII text file of results for import into spreadsheets or other tools.

To set up the simulation environment, CTLSS uses an orthogonal structured grid in either Cartesian or cylindrical coordinates. Structures are automatically broken into discrete elements on the grid using a stair-step representation. The grid is set up separately along each coordinate axis, and may be specified either as a piecewise uniform grid or as a piecewise stretched grid. In both types of setup, the user specifies "critical planes" (usually where the grid needs to align with a structure or feature).

Geometrical structures are placed on the grid using the Boolean combinatorial procedure. The code has a library of basic shapes, or "primitives," with which the user can build up complex structures. When a primitive object is selected, the user specifies its location, its orientation, and its size. The user also specifies the material type (conductor, dielectric, or permeable) and material properties (relative permittivity or relative permeability). The material properties can be specified as complex numbers (i.e., can model loss) and can be diagonal 3x3 tensors. The code then scans the entire grid to determine whether each cell centroid lies inside or outside the primitive object that was selected. The process of filling and carving primitive shapes can generate any geometry on the grid.

E.2.2 Simulation Process

E.2.2.1 Building the Model From a Template

The simulation process starts by selecting from the CTLLS toolbox a template that best models the type of device or problem to be solved. In our case, the problem was to evaluate radiation patterns of e-seal antennas. During the laboratory testing, we had measured antenna patterns for each of the e-seals. Those empirical results served as a guide to select the template that best fits the simulated e-seal antenna.

In general, one needs to perform several simulation runs to identify which template is the best approximation of the modeled e-seal antenna (e.g. vertical dipole antenna, perpendicular dipole, etc). After the first simulation, a new template is selected, and the results are superimposed over those from the first run. This process continues until we develop an e-seal antenna model with a pattern that is almost identical to the empirical results obtained in the lab. This e-seal antenna model is then used in simulation runs. It is important to note that developing an e-seal antenna model can be very time consuming when one wants to have a model that is almost identical to empirical results. In our case, that kind of precision is not necessary, since our objective is not to focus on specific vendor e-seals and their design, but on patterns as results of different frequencies. Hence, a first approximation of the e-seal antenna using a single template is sufficient.

E.2.2.2 Develop Scenarios and Structures

The next step is to develop simulation scenarios and, based on those scenarios, identify the simulation region and develop structures that appear in that region. Again, structure templates are found in the CTLLS toolbox.

E.2.2.3 Simulation Run

The next step is to run the simulation scenario. Note that for this simulation effort the CTLLS code was hosted on a PC with a 1.4 GHz AMD Athlon processor and Windows 2000 operating system. This is a very computationally-intensive simulation, with a run taking roughly 8 to 12 hours of CPU time. However, in the scenarios with the 2.44 GHz e-seal model and a region large enough to contain the structures, the simulation run was almost three times longer, e.g., 31 hours of CPU time. This was because more nodes were needed to handle a simulation with the shorter wavelength.

E.2.2.4 Data Scaling & Methodology

The CTLLS Tool provides as output "energy density (ED)" data. While this output serves as a good starting point to analyze signal strength patterns across different frequencies, one can also further refine these results by calibrating them using signal strength maps obtained during lab testing. This subsection describes the methodology used to calibrate ED data.

First, the locations at which the lab data points were measured must be converted into the coordinate system of the simulation (or vice versa). During e-seal lab testing, seven data points were measured, all at 3m distances from the seal. In the coordinate system of the seal and of the simulation, their locations are:

In the X-Y-Z Plane of the Seal:

	Coordinate System Centered at Seal			Coordinate System of Simulation		
Angular position	X	Y	Z	X	Y	Z
0	3	0	0	3.02	0.20	0.23
30	2.60	-1.50	0	2.62	-1.30	0.23
60	1.50	-2.60	0	1.52	-2.40	0.23
90	0	-3	0	0.02	-2.80	0.23
-90	0	3	0	0.02	3.20	0.23
-60	1.50	2.60	0	1.52	2.80	0.23
-30	2.60	1.50	0	2.62	1.70	0.23

At the 30-degree elevation:

	Coordinate System Centered at Seal			Coordinate System of Simulation		
Angular position	X	Y	Z	X	Y	Z
0	2.60	0	1.50	2.62	0.20	1.73
30	2.25	-1.30	1.50	2.27	-1.10	1.73
60	1.30	-2.25	1.50	1.32	-2.05	1.73
90	0	-2.60	1.50	0.02	-2.40	1.73
-90	0	2.60	1.50	0.02	2.80	1.73
-60	1.30	2.25	1.50	1.32	2.45	1.73
-30	2.25	1.30	1.50	2.27	1.50	1.73

Second, energy density is a scalar value, but field-strength lab data (in dBμV/m) was obtained using a polarized receiving antenna in two orthogonal directions, with its central axis directed at the seal. We make the assumption that the component of the electric field vector along the antenna axis direction was small compared to the other two orthogonal polarizations. Since the antenna was aimed at the seal from four to 24 wavelengths away, this seems reasonable. We perform vector addition on the two orthogonal field-strength values. The square of the resultant vector magnitude is proportional to the local energy density. We perform this conversion for each data point.

Third, we select one point in each data set (the simulation and the lab data) and determine a scaling factor that makes this point the same in each set.

As an example, assume that the selected angular position point is "0" at the seal level and its value from the lab data is 2.111e9 (uV/m)^2 (or 93.24 dBuV/m). In the simulation results, we select the ED value at a point closest to X = 3.02 m, Y = 0.20, Z = 0.23, which for our case is 0.0003879.

To scale the lab data to match the simulation, we multiply all of the lab data points by (0.0003879 / 2.111e9) = x 1.837e-13. (Such a large negative exponent is not surprising, since one has to convert from μV^2 to V^2, which alone requires a factor of 1e-12.) We apply this factor to all of the lab data points. Alternately, to scale the simulation data to match the lab data, we divide the simulation data by 1.837e-13, and apply this factor to all of the simulation points of interest. An equivalent procedure can be performed if it is desired to work in dB units.

E.2.2.5 Post Processing

When the run is completed, CTLLS will produce output in the form of ASCII data files and a 3D graphical representation of the simulated region. The results in the data file can be scaled using the methodology outlined above, and scaled results graphically presented using CTLSS graphics tool.

E.3 SIMULATION RESULTS

The simulation effort investigated e-seal signal propagation and radiation patterns in in-gate, on-rail and on-road environments. This section presents the results of that investigation.

E.3.1 Modeling

To produce simulations at these frequencies, the modeling tool discretized the simulation region into spatial elements that were only a few centimeters on a side. Memory and processing-time constraints limited the size of the simulation region to about 36 m^3 for the lower frequencies, and about half that for the 2.44-GHz cases. Because of the large dimensions of the containers and gate-structures, the longest dimension of any simulation was about 4.5 m, or about 15 feet.

The seal-antenna location and size was kept the same in all simulations, rather than relocating it to correspond to a particular vendor's seal at a particular frequency. This allowed comparison among frequencies without the added variable of seal location. The size of the antenna was 12cmx10cmx1cm.

E-seal Modeling

Our first step in the modeling and simulation of the selected e-seals was to examine the radiation patterns obtained in the laboratory environment[8] and select the template from the CTLLS toolbox that was closest to the empirical results. For each e-seal/frequency, a dipole antenna appeared to be the best starting point. Next, to determine dipole direction and orientation, we conducted a number of CTLLS simulation runs, each time changing the direction of the dipole antenna:

- vertical dipole (in Z direction), parallel to the backplane (i.e., container door),
- dipole perpendicular to the plane (in X direction), and
- parallel to the plane but in the horizontal (Y) direction.

For all frequencies and seals, orienting the dipole in the Z direction produced a pattern that fit the lab data better than did the other two orientations. This was mainly because the X- and Y-oriented dipoles each produced stronger variations with elevation (above the x-y plane) than was observed in the data. We further investigated representing each seal as a linear combination of all three dipole orientations, with each dipole contributing in a different proportion in each seal. The results suggest that a well-tuned e-seal model is a superposition of three dipole antennae generated by CTLSS. Additionally, our investigation suggests that the internal structure of the seals and the detailed features of their mounting on the door handles may also need to be modeled to better match the lab data.

However, to converge to this model, one would require finer grid resolution, which would shrink the practical simulation region. Considering that our primary focus was on investigating e-seal performance at different frequencies, rather then particular vendor product, a z-oriented vertical dipole was an adequate representation of an e-seal. Hence, a z-oriented vertical dipole was used for all simulations that follow.

E.3.2 In-Gate Simulation

E.3.2.1 Scenarios and Geometry

<u>In-Gate Scenarios</u>

The objective of the in-gate simulation was to investigate signal propagation and radiation patterns, especially when signals reach obstacles commonly found in the in-gate area, such as booths and other containers.

To accomplish this, we constructed two sets of scenarios. The first set simulated an e-seal on the back of the container with no obstructions in the region.

[8] We used the laboratory data that we measured with the seals mounted on a mock-up of a container door.

For each of the three e-seal frequencies, we performed simulation runs in the space with no obstructions. We performed several simulation runs, each time maximizing the X, Y or Z dimension of the simulated space. This approach was needed because of the practical constraints on the size of the simulation region for a single run. The purpose of these runs was to obtain radiation patterns for each of the frequencies and compare them with each other.

The next set of scenarios investigated signal propagation in the environment with obstacles. The objective was to determine how well different frequency signals traveled around objects and the potential impact from signal diffractions. We performed several simulation runs, applying the same structure setup for each e-seal frequency. The structures and regions used for these simulation runs are described below.

Because of the limited simulation region for each run, the results may be more useful when selecting antenna placements within a lane for lane-specific seal reading, rather than when determining the range or antenna placement to read across multiple lanes.

In-Gate Geometry

The key elements that we wanted to investigate in the simulated environment were radiation patterns from the e-seal when there are no obstructions, and changes in those patterns when there are structures in the way. We had setup the simulated region to reflect the e-seal in the in-gate environment. The in-gate geometry and dimensions are shown in Figure 3.2.1a-b. Figure 3.2.1.a shows lanes and islands, and positions of booths and containers. The e-seal that is being simulated is mounted on the container in lane F. There is a booth between lanes F and G, and another container in lane G. Figure 3.2.1.b shows container and booth geometry. The glass windows of the booth are modeled as transparent to RF. For the purpose of the simulation, the e-seal is placed in the lower end of the back door of the container.

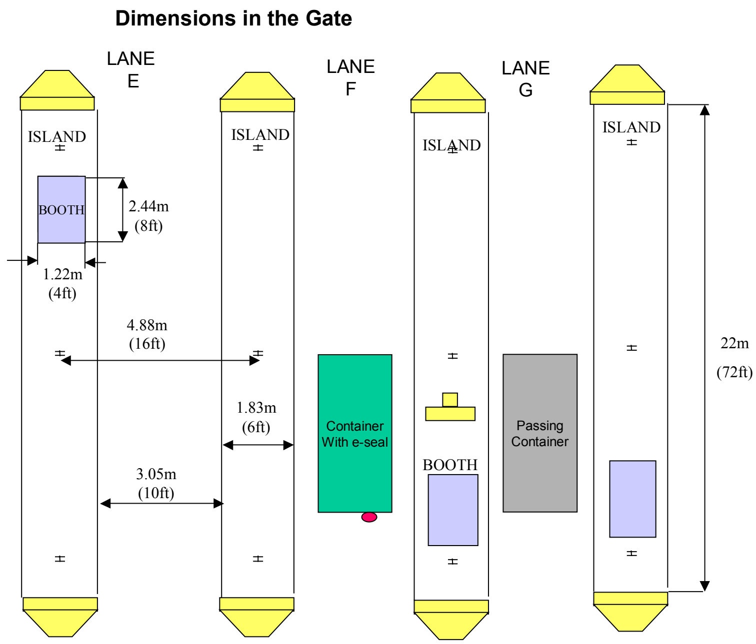


Figure E.3.2.1.a In-gate dimensions and configuration

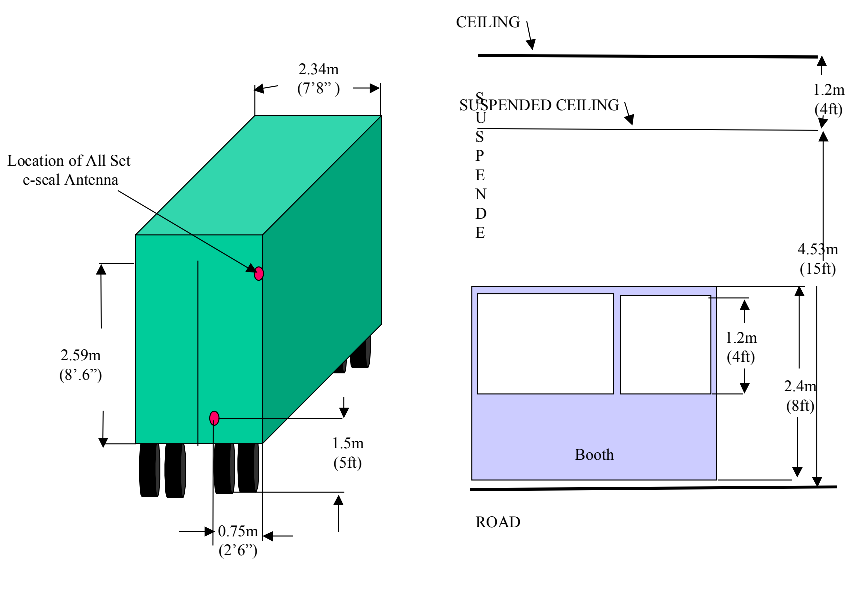


Figure E.3.2.1.b Container and booth dimensions

Simulation Region and Structures

Figure 3.2.1.c is a visual representation of the CTLSS simulation results. All simulation results in this report are presented in this manner. We will use the graphics in Figure 3.2.1.c to show how to interpret each figure.

Each simulation is run in the X-Y-Z space. The typical size of the region that CTLSS can simulate is 2mx3mx6m, and it is dependent on the amount of structures that need to be packed into the region, the wavelength, and the amount of time it will take to run the simulation. Larger regions will require longer times, as will smaller wavelengths. Also, if there are more structures that need to be simulated, those will take up more cells, and reduce the simulation region.

Since the CTLSS simulation region is limited in size, we have limited our simulation runs to only the area immediately around the e-seal. The tower structure shown in the figure below represents a slice of the container around the back door. Further, the structure simulates only the right half of the back door. The region to the left is largely free of reflecting structures; by not simulating that direction, we are able to extend the simulation region further in the other directions.

The figure also shows the radiation pattern in one plane. In this particular case, the selected plane is at a fixed Z coordinate, at the e-seal level, or 1.5m from the lane surface. The color contours show the radiation patterns: areas with the highest electric energy density are shown in red, and areas with the lowest electric density are shown in dark blue. The red dot represents the location of the e-seal. The polygon boundary represents the simulation boundary. It is important to note two items regarding the boundary:

- First, structures cannot be placed right at the simulation boundary, hence, there is an area to the left and behind the tower structure that is not of interest to us. It appears as an open space, when in reality, it should be occupied by a container.

Second, the numerical boundary conditions cause the output graphics to show contour lines that converge near the boundary. This is an artifact of the simulation technique. To avoid RF reflection from the boundary (i.e. to simulate an “open” boundary of RF propagation, boundary layers are constructed with heavy loss properties to absorb the incoming RF energy. As such, energy density of RF decreases exponentially in the boundary layers, which is shown by the concentration of color contours. For practical purpose, values in this thin boundary region near the simulation border should be ignore.
Other notes regarding interpretation of the figures are:

- The energy density values cannot be compared across frequencies, as the values are not normalized to a common power output.
- Instead, it is valid to consider the drop in energy density within a set of figures at the same frequency and with the same structural geometry.

- The values shown are derived from the formula "20*log(energy density)." This makes them proportional to dB (V/m). Note that they are not normalized to a common field strength.
- All seals are modeled at the same location on the container. The 2.44-GHz seal is not located in the upper hinge region where All Set's 2.44-GHz seal is typically placed.
- From the seal to the region boundary in the X (perpendicular) direction is only about 1 meter. This is less than two wavelengths for the 433-MHz seal and about twice as much for the 916-MHz seal. Therefore, the RF pattern in front of the seal may include near-field effects in its structure.

Figure 3.2.1.d shows various structures used in in-gate simulation runs to represent obstacles to signal propagation, such as a booth and a container in another lane. Again we have simulated only the sections of those structures that are within the simulation region. In the 2.44 GHz case, i.e., short wavelength, we have reduced the size of the region by half, and correspondingly, only the upper portions of the booth and container structures are modeled. This was necessary to fit the computational requirements of a very short wavelength. Hence, the bottom two pictures in Figure 3.2.1.d show structures used for 2.44GHz simulation runs, and represent only the top portion of structures used for 433MHz and 916MHz simulation runs (top two pictures).

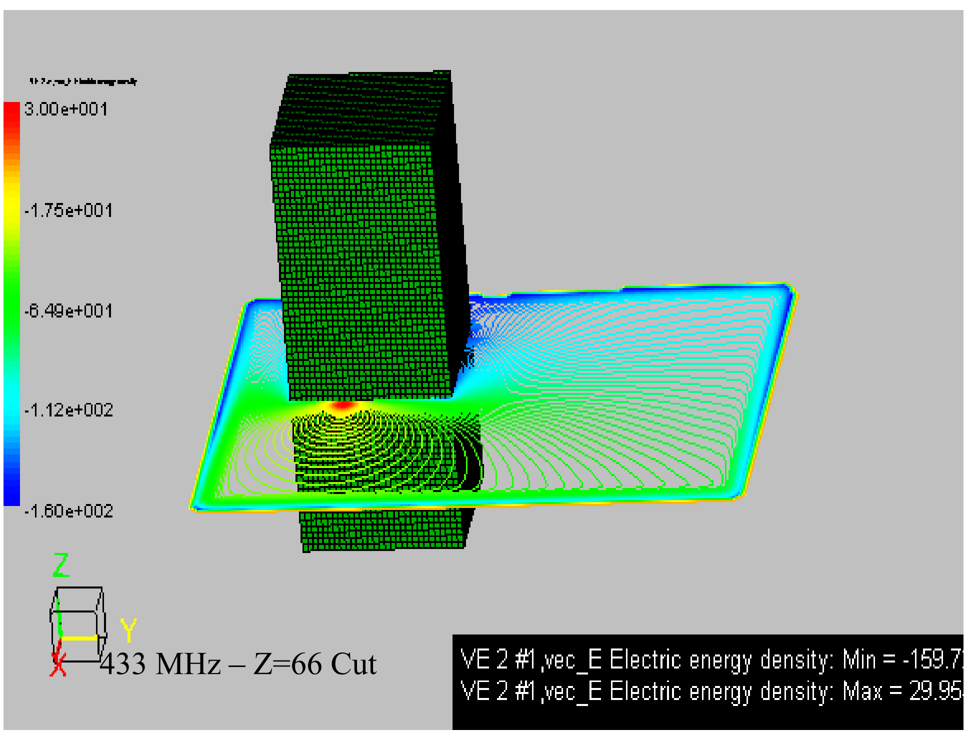


Figure E.3.2.1.c Simulation Region

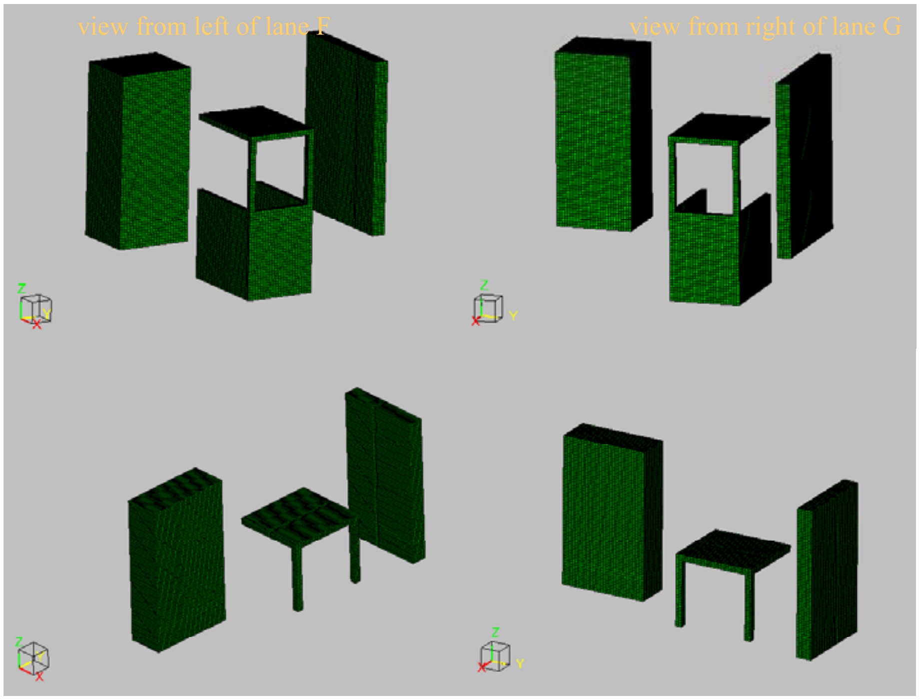


Figure E.3.2.1.d Simulated structures in the In-gate environment

E.3.2.2 In-Gate Simulation Results

This section presents results of our in-gate simulation effort. As mentioned before all the simulation results were obtained by running the CTLSS tool. This was a very computationally-intensive effort. A typical CTLSS run took roughly 8 to 12 CPU hours, and in the case of 2.44 GHz frequency runs with obstacles, it took over 30 CPU hours.

Note that figures shown in this section are only a subset of the data and figures generated during this simulation effort. This subset best conveys the insights obtained during the simulations. Further post-processing of all the obtained data can be done if needed.

<u>In-Gate Scenario: Region around Container Backdoor - Y, X cut Planes</u>

Figures 3.2.2. a-c and 3.2.3.a-c show radiation patterns and signal propagation in the space around the container door. Figures 3.2.2 and 3.2.3 show the radiation patterns in vertical cut planes that pass through the e-seal. In Figure 3.2.2, the cut is perpendicular to the door (normal to the Y axis), and in Figure 3.2.3 the cut is parallel to the door (an “X” cut normal to the X axis). The structure represents the full height of the right-side of the container door, with the structure extending about a foot back.

All figures have a red area representing the e-seal - the source of the radiation. Examining the radiation patterns that spread from the source, we can see that in the case of the 433MHz signal (Figures 3.2.2.a and 3.2.3.a), with the longest wavelength (69 cm), contours are uniform oval lines evolving around the e-seal.

On the other hand, for 2.44GHz (short wavelength -12cm), the contours evolving around e-seal are not uniform but have directional lobes. One reason is the reflection from the container door (backplane). The dipole has all three dimensions comparable to the wavelength and is offset from the container door by a few centimeters. This sets up a reflected “image” RF source that behaves as if it were “behind” the door. The combined radiation from the image source and the actual source can set up interference patterns, i.e., radial nodes of high and low signal strength.

In the areas on the top and bottom of the container, for all three frequencies signal drops off as it travels away from the back door. This drop seems to happen somewhat faster in the case of 2.44GHz frequency

In general, signals at higher frequencies are more directional, and as the frequency increases, there is higher likelihood that there will be regions with higher signal drop off. Looking at figures 3.2.2.a-c one can observe that signal strength in front of the e-seal, i.e., line-of-sight is good for 433MHz and 916MHz frequencies. For 2.44GHz there are gaps between signal lobes that may cause no-reads. A rule of thumb in communication systems is that operating effectiveness decreases by only 5%-10% as frequency increases from 433MHz – 2.44GHz.

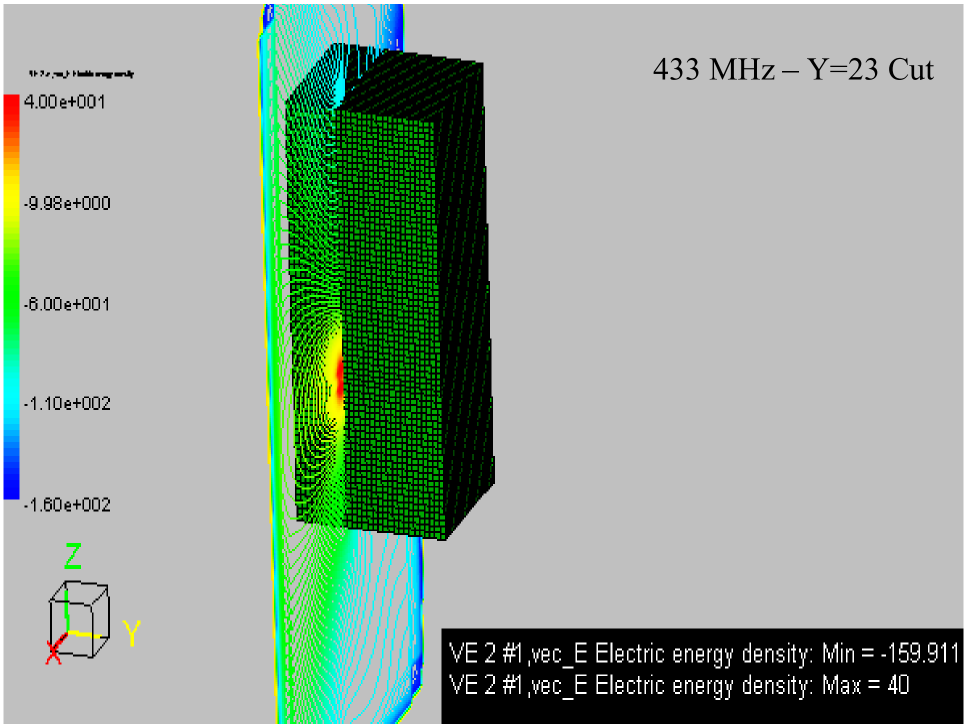


Figure E.3.2.2.a E-seal frequency = 433MHz, Y cut in e-seal plane

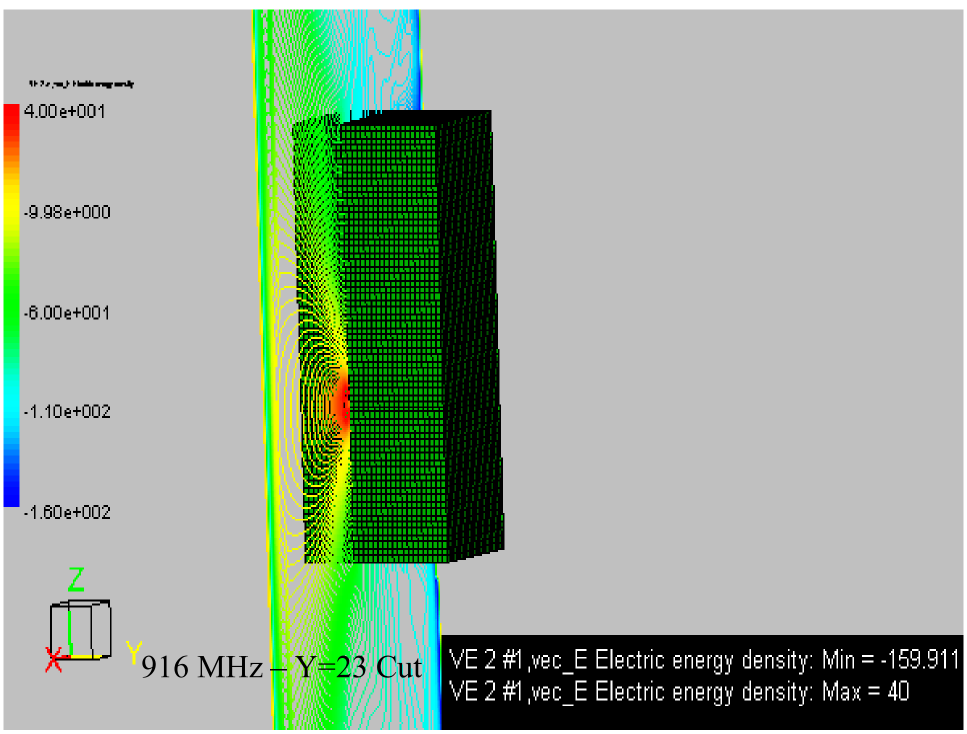


Figure E.3.2.2.b E-seal frequency = 916MHz, Y cut in e-seal plane

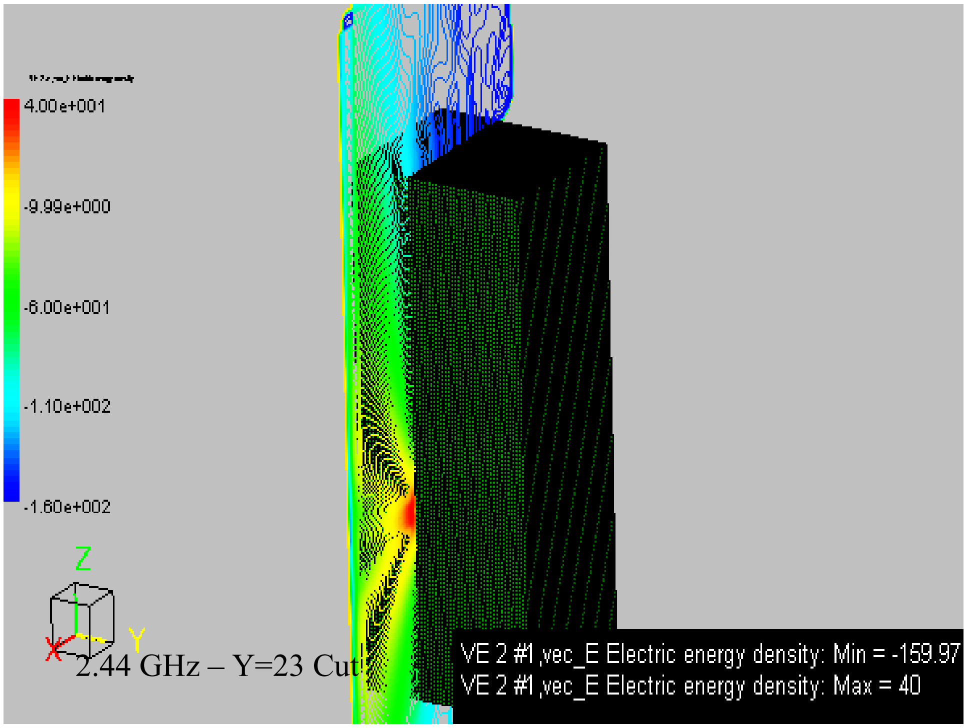


Figure E.3.2.2.c E-seal frequency = 2.44GHz, Y cut in e-seal plane

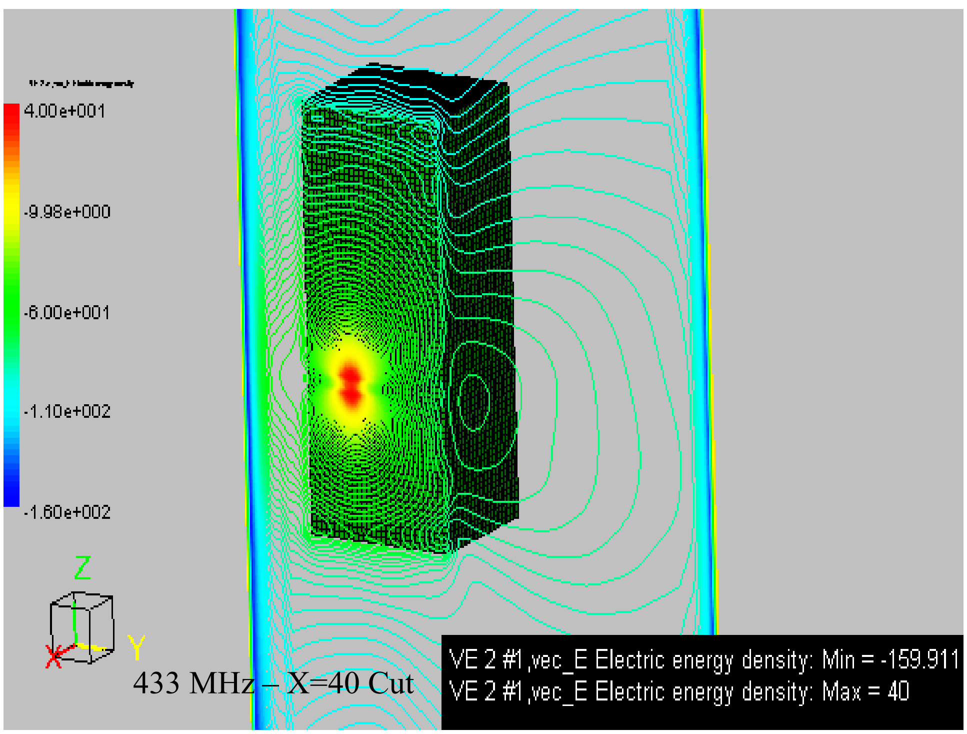


Figure E.3.2.3.a E-seal frequency = 433MHZ, X cut in e-seal plane

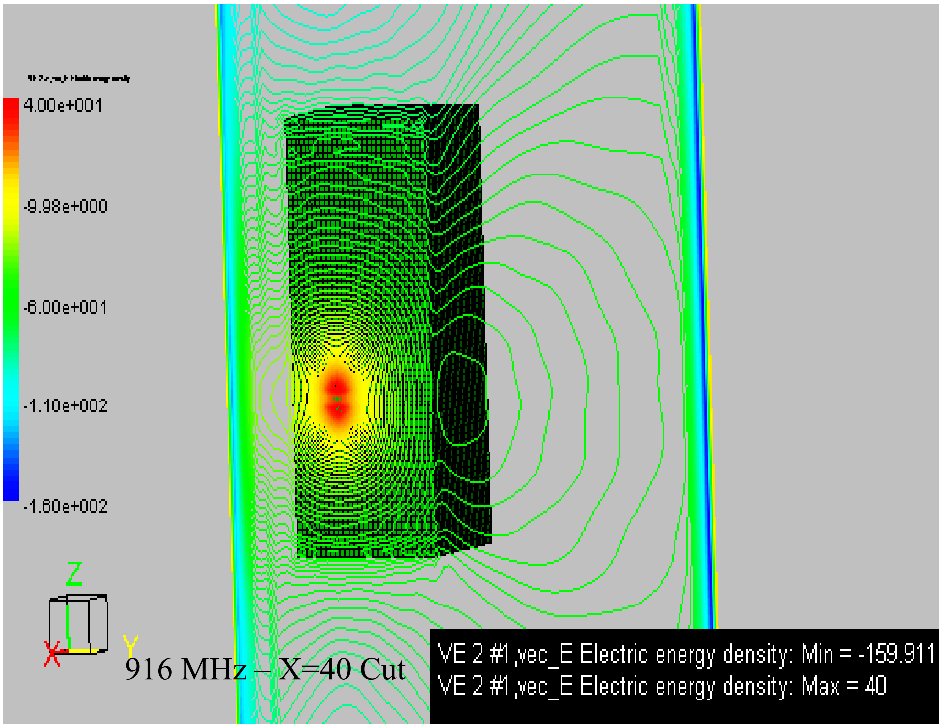


Figure E.3.2.3.b E-seal frequency = 916MHZ, X cut in e-seal plane

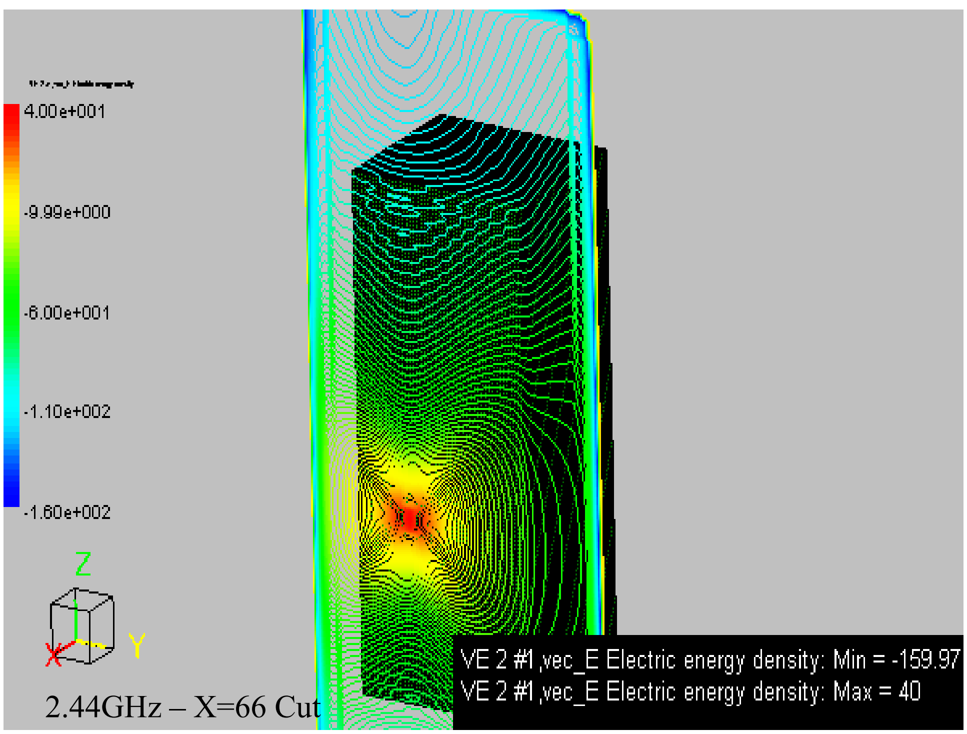


Figure E.3.2.3.c E-seal frequency = 2.44GHZ, X cut in e-seal plane

In-Gate Scenario: With Booth, Container Obstructions Z-cut Planes

In this scenario we examined signal propagation and radiation patterns when there are other structures in the area surrounding the container with e-seal. We examined the region in the back and to the right of the container. For the purpose of the simulation we placed a booth to the right of the container, and another container in the lane to the right of the booth. Figures E.3.2.4 – Figure E.3.2.7 show the results of our simulation runs in the Z cut planes. Note that the simulated region for 2.44GHz frequency was reduced to the top half of the region defined for 433MHz and 916MHz frequencies. Hence, figures E.3.2.4 and E.3.2.5 do not have 2.44GHz results since the simulation in the lower region was not performed for 2.44GHz frequency.

For all selected planes one can see that the contours for all three frequencies are not as uniform as the contours in the open space (Figures E.3.2.2, E.3.2.3 and E.3.4.1). This is largely due to superposition and cancellation with signals that are reflecting from structures in the region. However, the resultant radiation patterns are somewhat similar, suggesting that operational efficiency for all three frequencies is not much different.

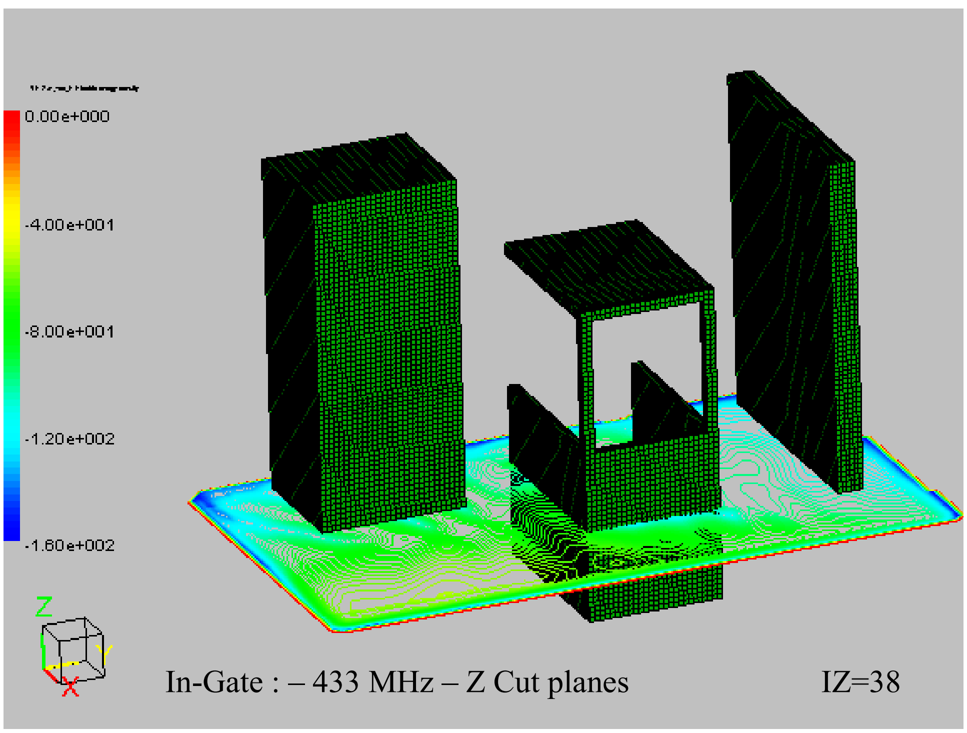


Figure E.3.2.4.a E-seal radiation patterns around obstacles
(frequency = 433MHZ, Z plane cut at 38)

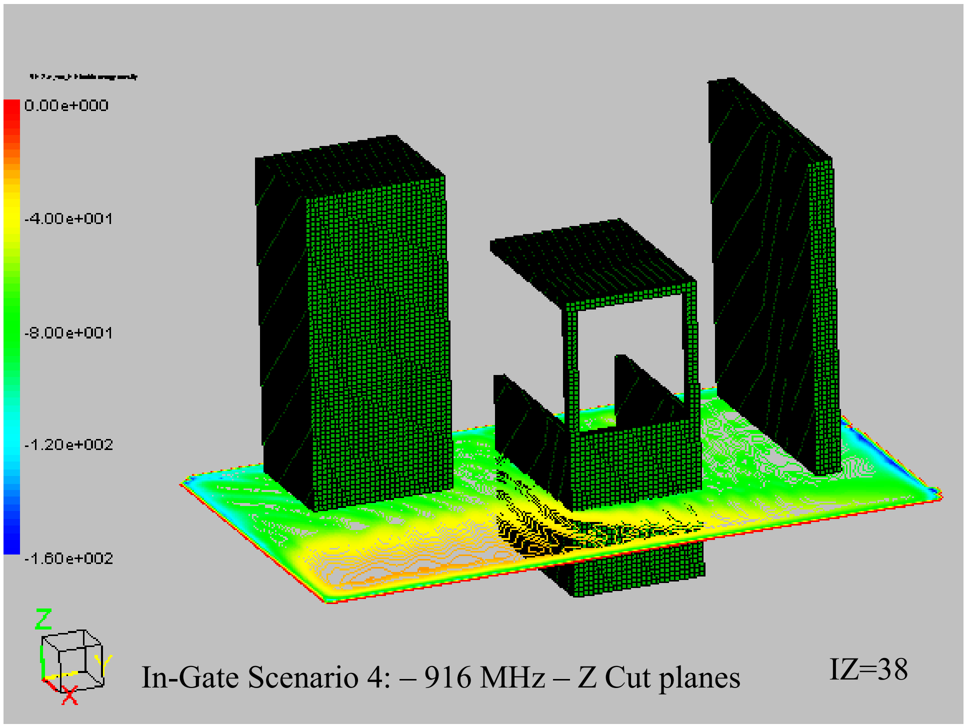


Figure E.3.2.4.b E-seal radiation patterns around obstacles
(frequency = 916MHZ, Z plane cut at 38)

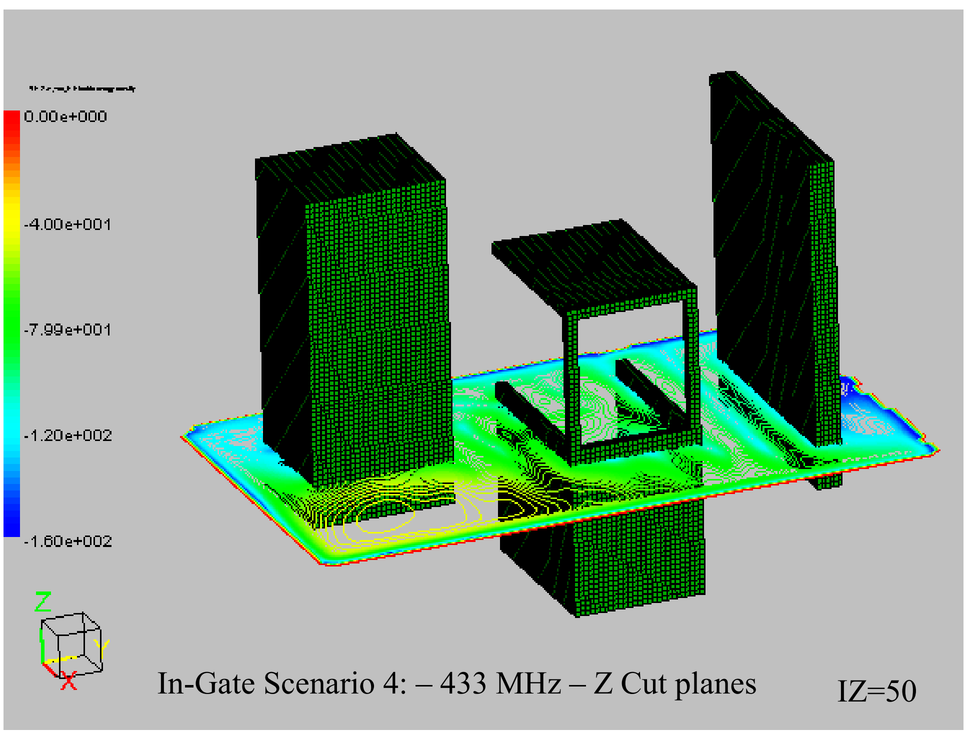


Figure E.3.2.5.a E-seal radiation patterns around obstacles
(frequency = 433MHZ, Z plane cut at 50)

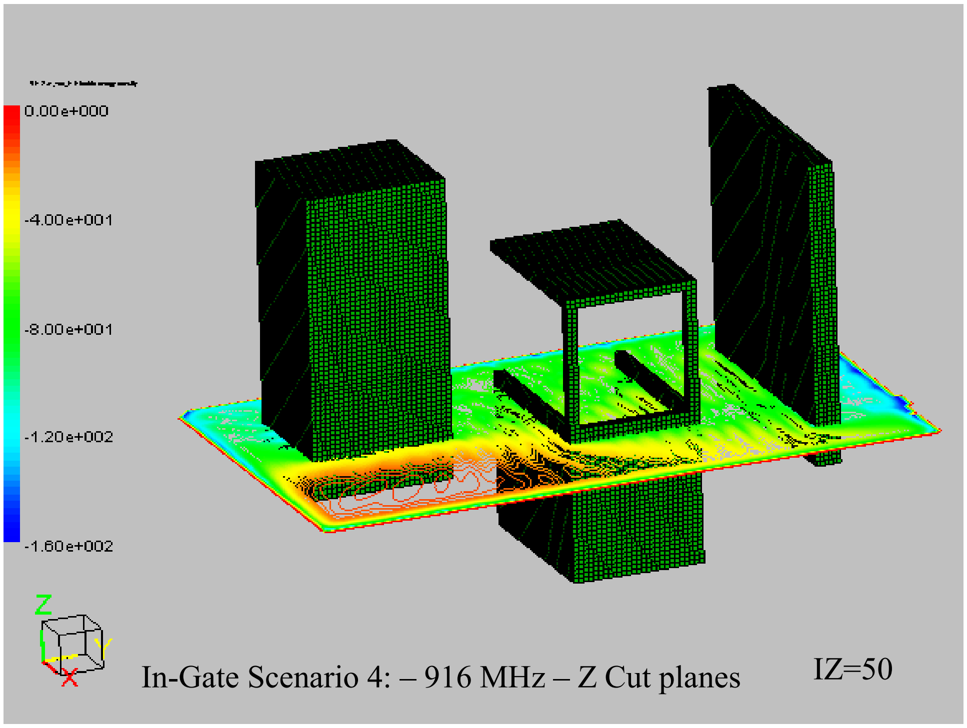


Figure E.3.2.5.b E-seal radiation patterns around obstacles
(frequency = 916MHZ, Z plane cut at 50)

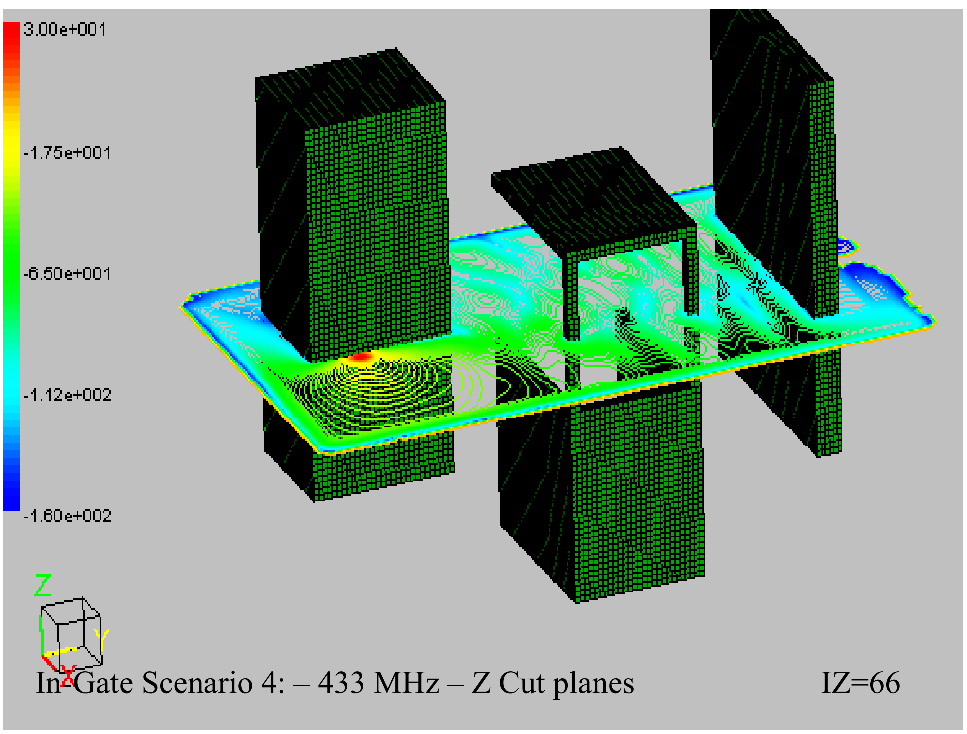


Figure E.3.2.6.a E-seal radiation patterns around obstacles
(frequency = 433MHZ, Z plane cut at 66)

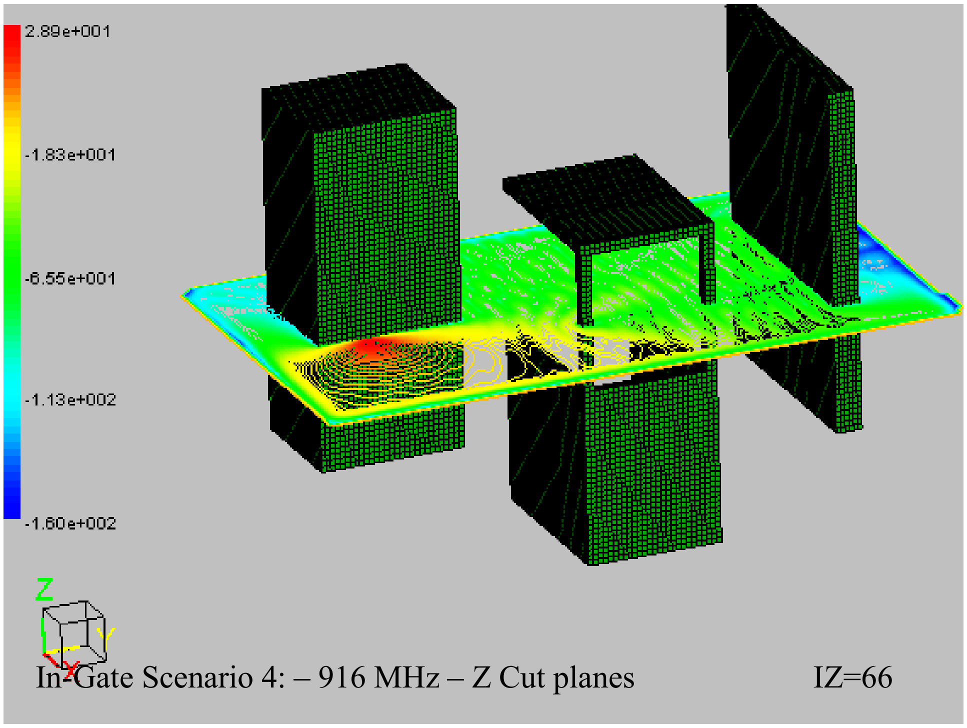


Figure E.3.2.6.b E-seal radiation patterns around obstacles
(frequency = 916MHZ, Z plane cut at 66)

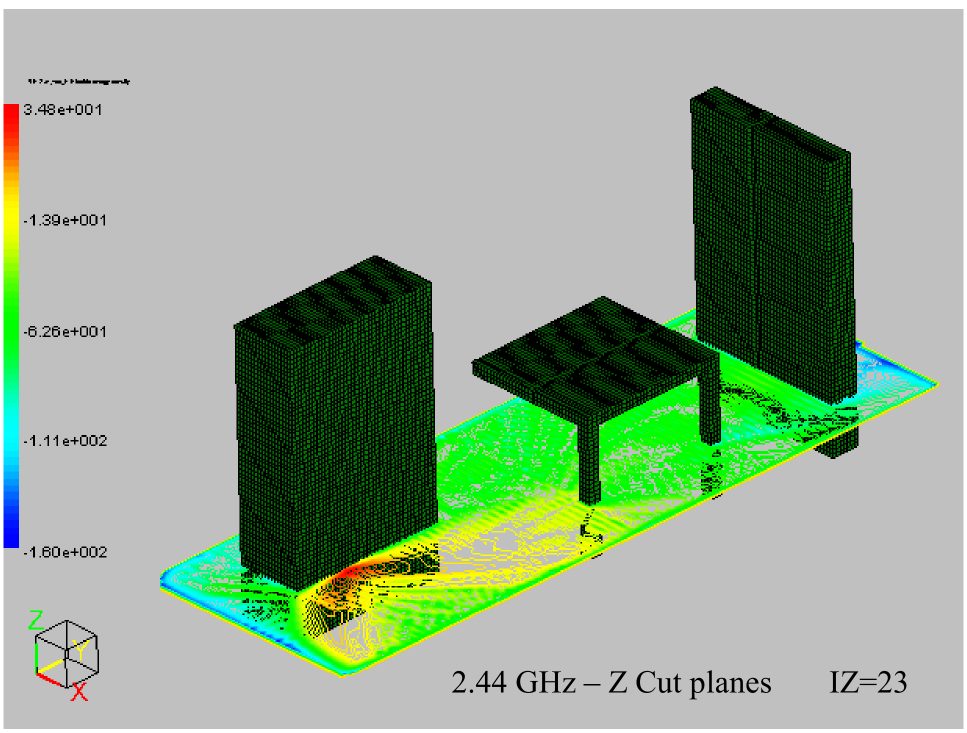


Figure E.3.2.6.c E-seal radiation patterns around obstacles
(frequency = 2.44GHZ, Z plane cut at 23 or 66 level from ground)

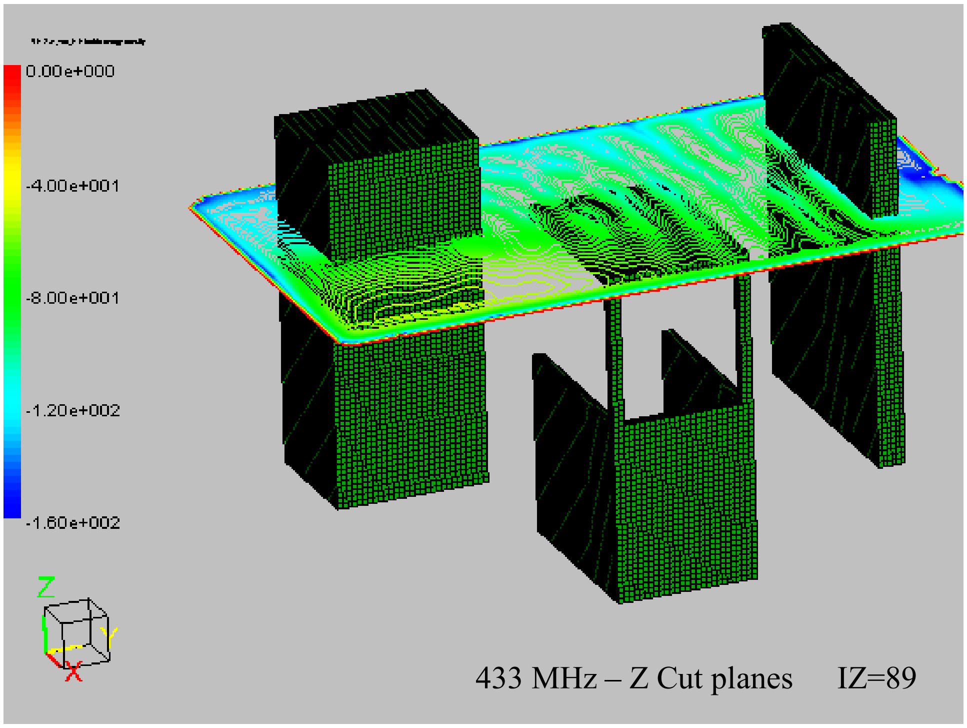


Figure E.3.2.7.a E-seal radiation patterns around obstacles
(frequency = 433MHz, Z plane cut at 89)

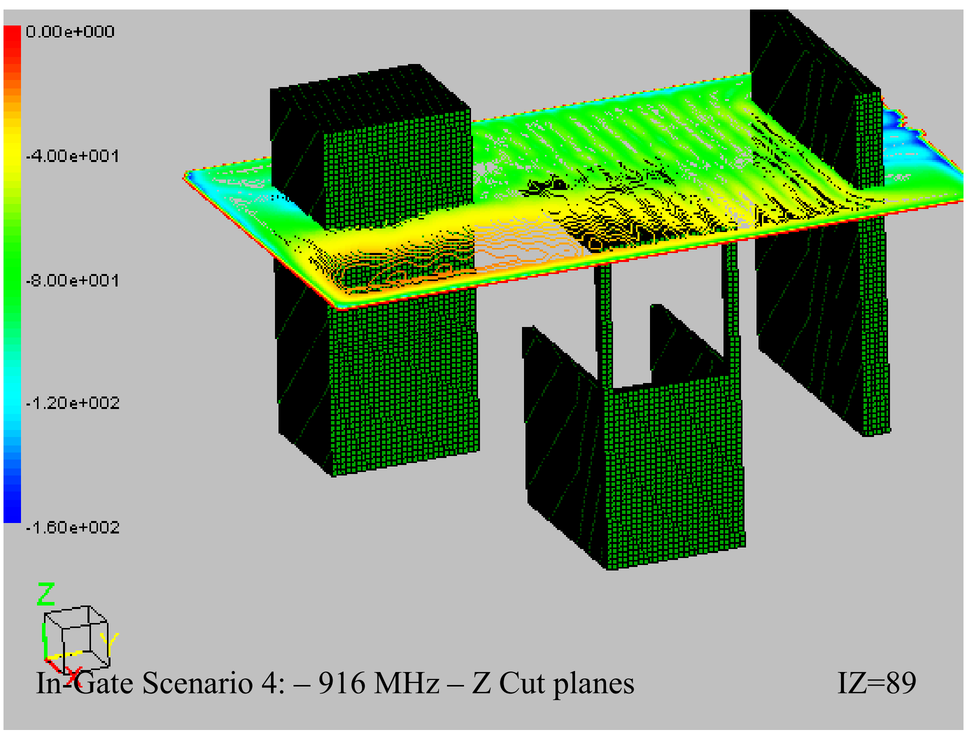


Figure E.3.2.7.b E-seal radiation patterns around obstacles
(frequency = 916MHZ, Z plane cut at 89)

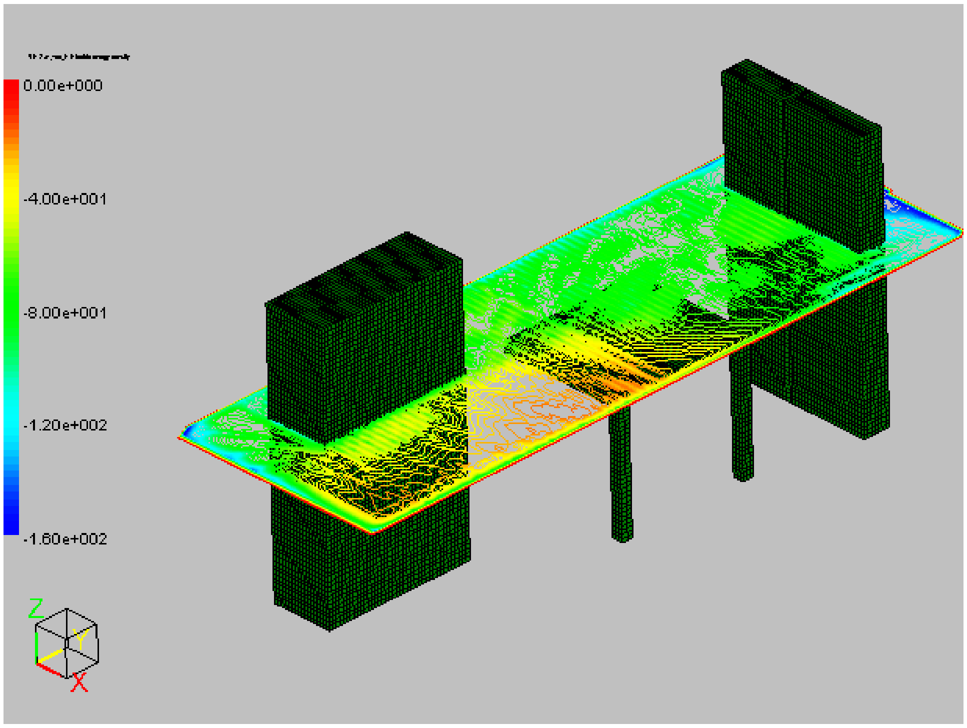


Figure E.3.2.7.c E-seal radiation patterns around obstacles
(frequency = 2.44GHZ, Z plane cut at 54)

<u>In-Gate Scenario: With Booth, Container Obstructions Y-cut Planes</u>

The Y cut in the e-seal plane can be compared with the same Y cuts in open space (Figure E.3.2.2). Again we can see that contours are not as uniform, and this is the result of signals reflected from surrounding structures.

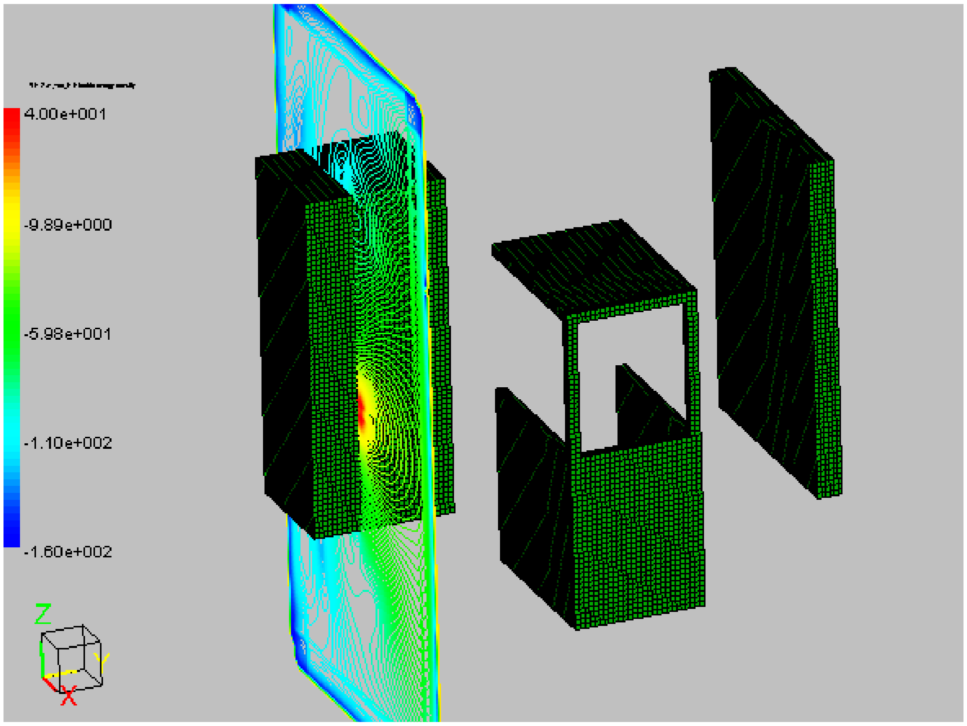


Figure E.3.2.8.a E-seal radiation patterns around obstacles
(frequency = 433MHZ, Y plane cut at 23)

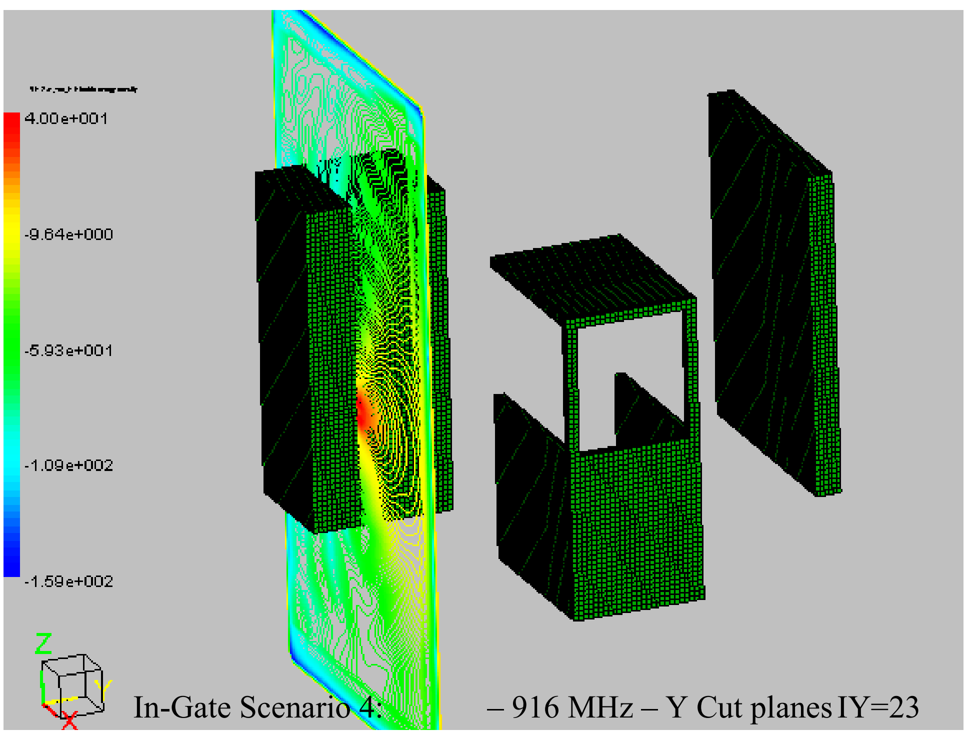


Figure E.3.2.8.b E-seal radiation patterns around obstacles
(frequency = 916MHZ, Y plane cut at 23)

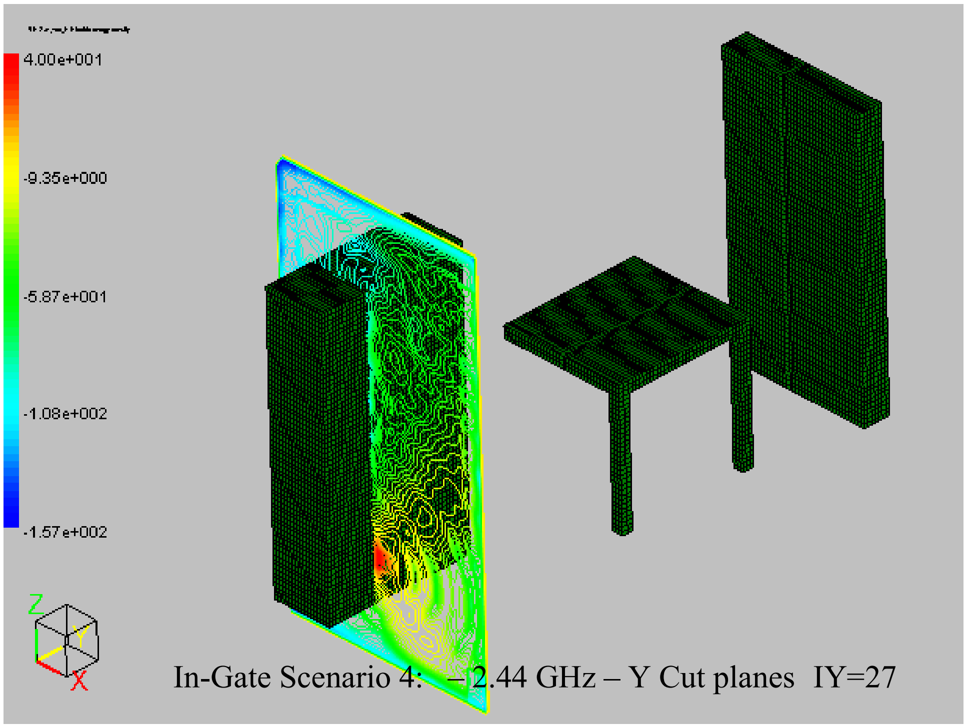


Figure E.3.2.8.c E-seal radiation patterns around obstacles
(frequency = 2.44GHZ, Y plane cut at 27)

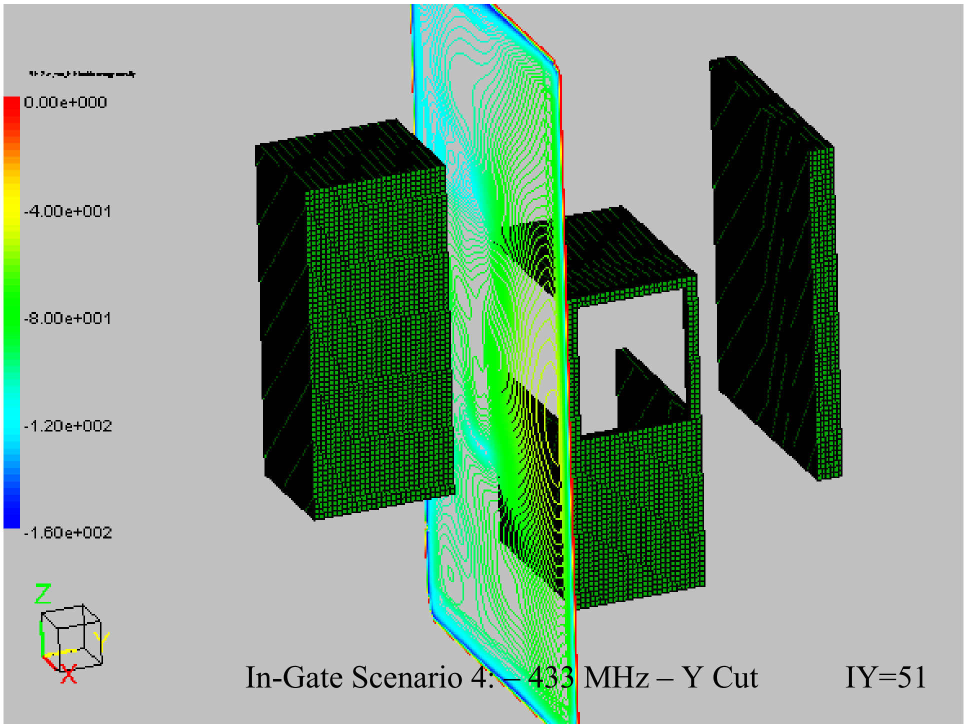


Figure E.3.2.9.a E-seal radiation patterns around obstacles
(frequency = 433MHZ, Y plane cut at 51)

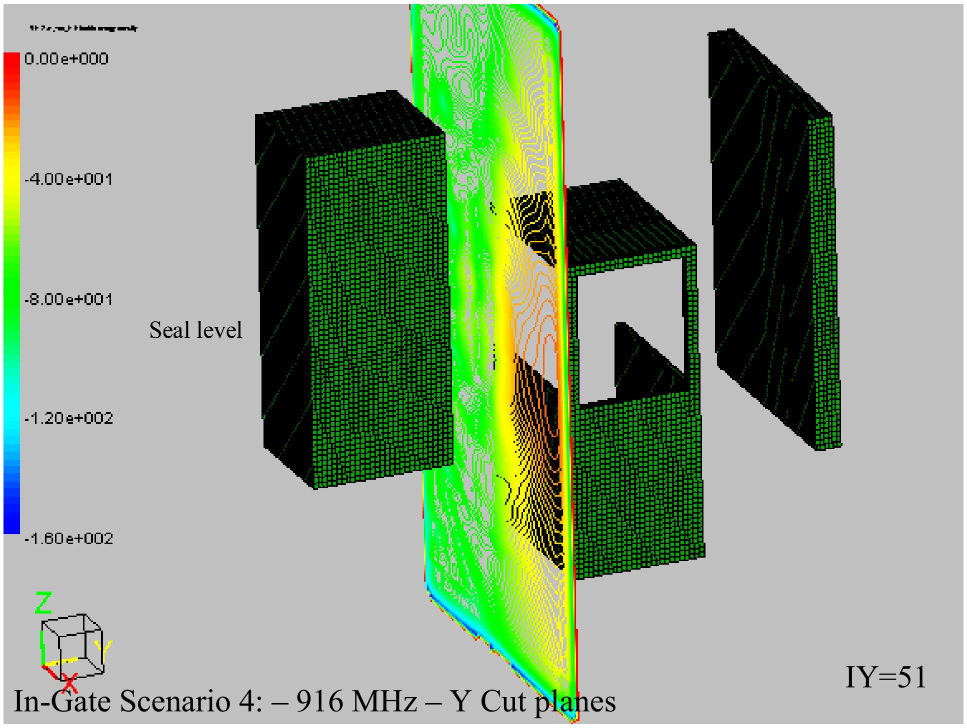


Figure E.3.2.9.b E-seal radiation patterns around obstacles
(frequency = 916MHZ, Y plane cut at 51)

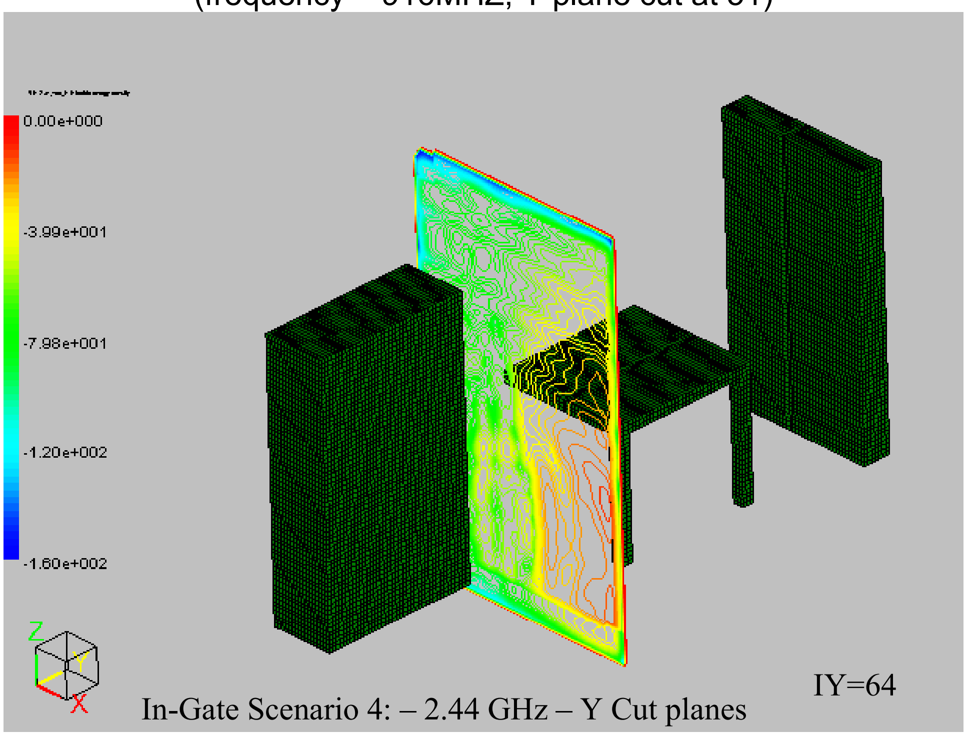


Figure E.3.2.9.c E-seal radiation patterns around obstacles
(frequency = 2.44GHZ, Y plane cut at 64)

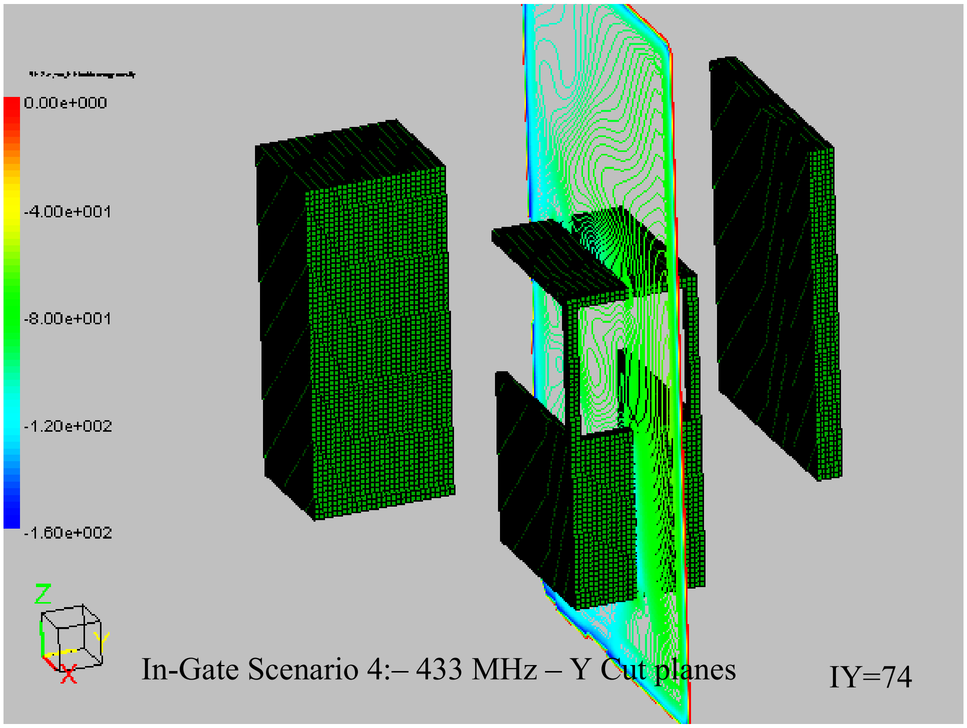


Figure E.3.2.10.a E-seal radiation patterns around obstacles
(frequency = 433MHZ, Y plane cut at 74)

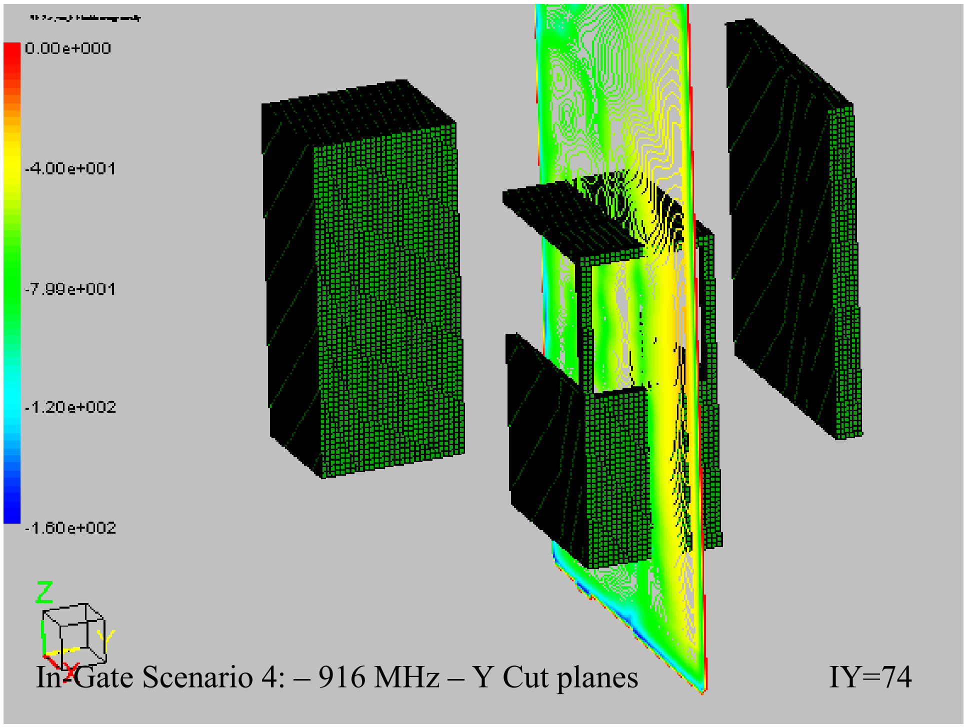


Figure E.3.2.10.b E-seal radiation patterns around obstacles
(frequency = 916MHZ, Y plane cut at 74)

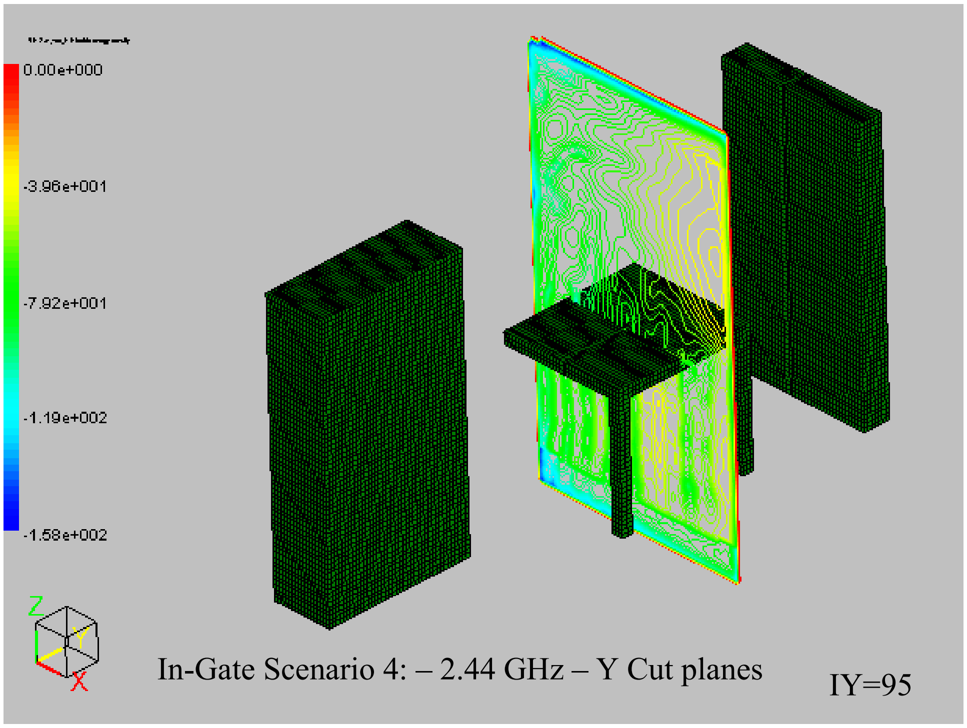


Figure E.3.2.10.c E-seal radiation patterns around obstacles
(frequency = 2.44GHZ, Y plane cut at 95)

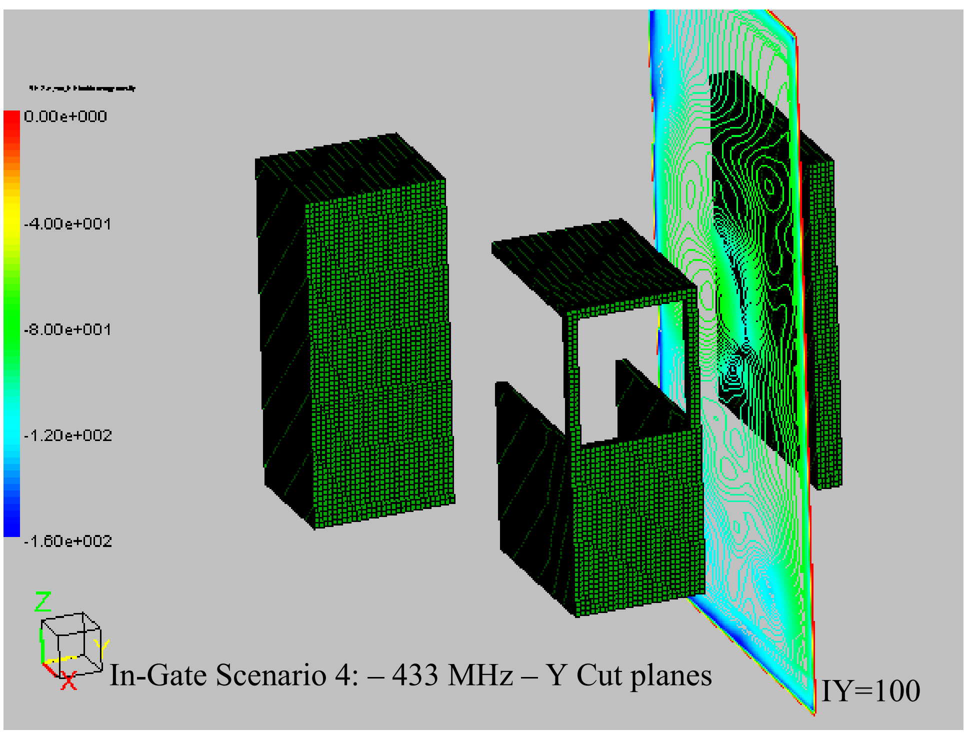


Figure E.3.2.11.a E-seal radiation patterns around obstacles
(frequency = 433MHZ, Y plane cut at 100)

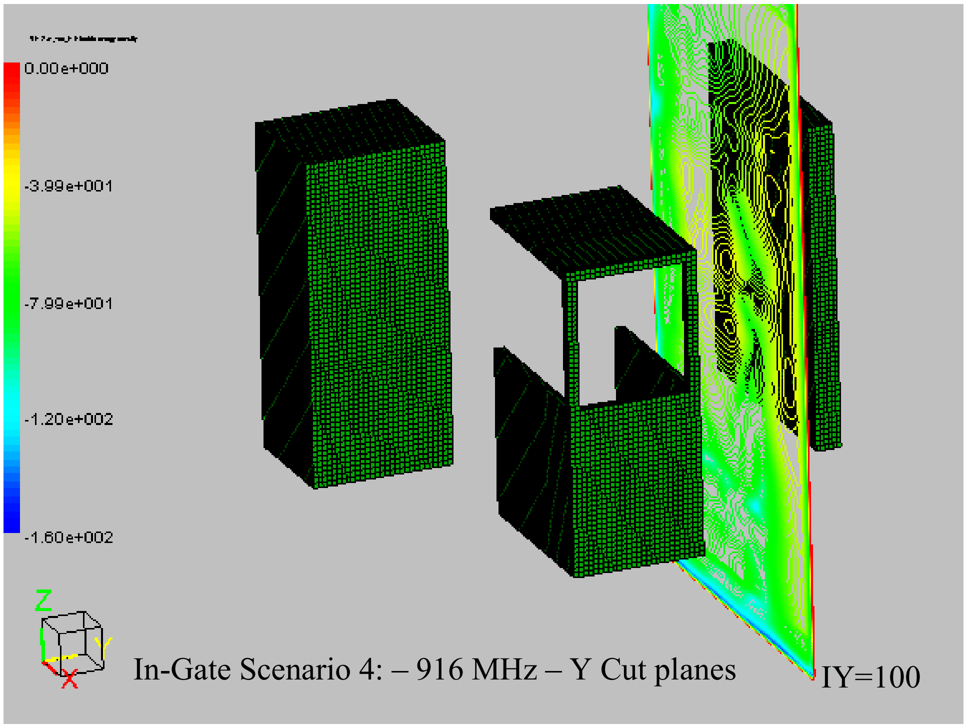


Figure E.3.2.11.b E-seal radiation patterns around obstacles
(frequency = 916MHZ, Y plane cut at 100)

E.3.2.3 In-Gate Simulation Conclusions

The objective of the in-gate simulation was to investigate signal propagation in the in-gate environment, and in particular signal propagation and radiation patterns when signals reach obstacles commonly found in the in-gate area, such as booths and other containers. To accomplish this, we constructed two sets of scenarios. The first set simulated an e-seal on the back of the container in the region with no obstructions. The second set investigated signal propagation in the environment with obstacles. The objective was to determine how well signals of different frequencies traveled around objects and the potential impact from signal diffractions.

In the case when there are no obstructions in the region, the simulation results show that signal strength contours for 433MHz frequencies, with 69-cm wavelength, are fairly uniform, and signals wrap somewhat better around the edges then do 916MHz and 2.44GHz signals. For 916MHz signals, radiation contours are less uniform. Finally, for 2.44GHz, with 12cm wavelength), the contours evolving around e-seal are not uniform but have directional lobes. One reason is the reflection from the container door (backplane). The dipole has all three dimensions comparable to the wavelength and is offset from the container door by a few centimeters. This sets up a reflected “image” RF source that behaves as if it were “behind” the door. The combined radiation from the image source and the actual source can set up interference patterns, i.e., radial nodes of high and low signal strength . This directivity may create gaps where signal drops off sharply, and may result in regions with no-reads.

The patterns produced in the environment with structures are not as uniform as the patterns in the case where there are no obstructions. Pattern of RF intensity exhibits wave-like variations, which is typical of interference due to superposition with reflected signals from all the structures. However, examining the patterns one can conclude that their propagation characteristics are somewhat similar.

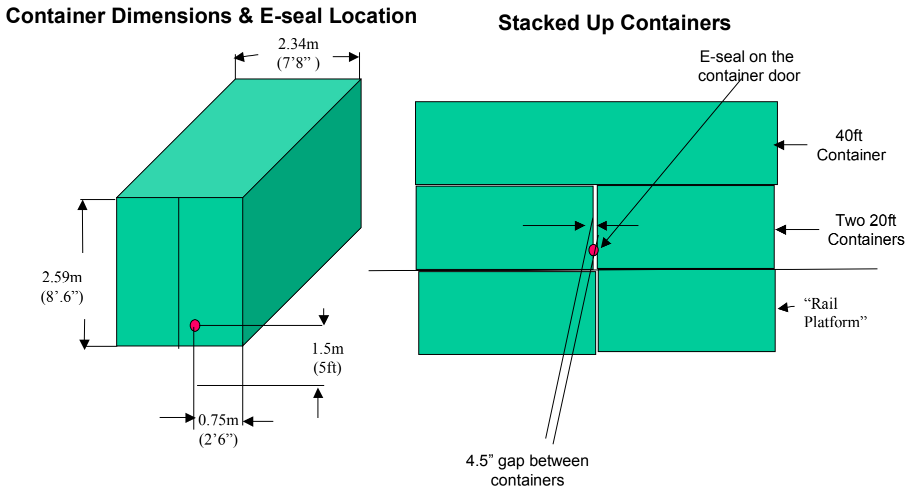
E.3.3 On-Rail Simulation

E.3.3.1 Scenario and Configuration

Figure E.3.3.1.a shows the challenging e-seal environment of containers stacked in a well car. The objective of the on-rail simulations was to examine the effectiveness of e-seals in transmitting RF signals to the reader when the e-seal is in the gap between stacked-up containers. The model geometry was intended to simulate the situation where a 40' container was placed atop two 20' containers on a flat railcar, rather than in a well car.

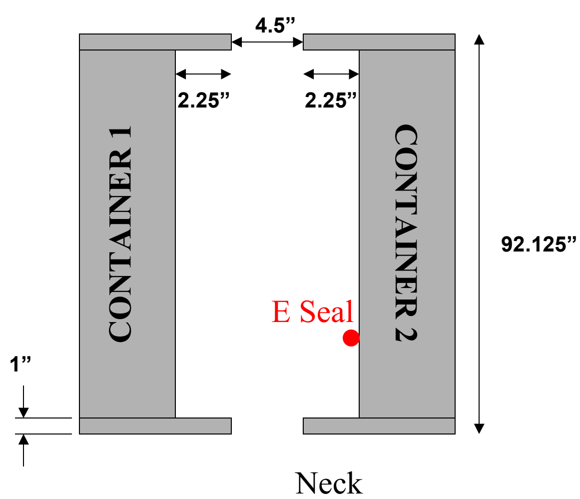
The model was also based on the experimental configuration used in the terminal testing. This configuration is shown in Figure E.3.3.1.b. In this configuration, a 40' container was placed atop two 20' containers, which in turn were elevated to represent their placement on a railcar and rail bed. There is a 4.5" gap between the end surfaces of the two 20' containers. E-seals of various frequencies were modeled on the back door of the container as shown in Figures E.3.3.1.b-c.

Figure E.3.3.1.a On-Rail Scenario



2

Figure E.3.3.1.b On-rail geometry and dimensions



View from Top of the Containers
E Seal Between two Containers

3

Figure E.3.3.1.c On Rail Container geometry and dimensions

CTLSS Simulation Setup

CTLSS simulation was conducted by placing an RF dipole antenna at the location of the e-seal in the gap between two containers. A top view of the gap structure is illustrated in Figure E.3.3.1.c. The gap is enclosed by end surfaces of two containers, with two necks of 2.25” sticking out from either side separated by a 4.5” space in the middle. The container on the top and the railcar on the bottom also enclose it vertically. Therefore, the gap space can act as an RF cavity with slots on both sides. The cavity structures in the simulation are illustrated in Figure E.3.3.2. The X direction is along the rail, the Y direction is horizontal along the container door, and the Z direction is vertically upward.

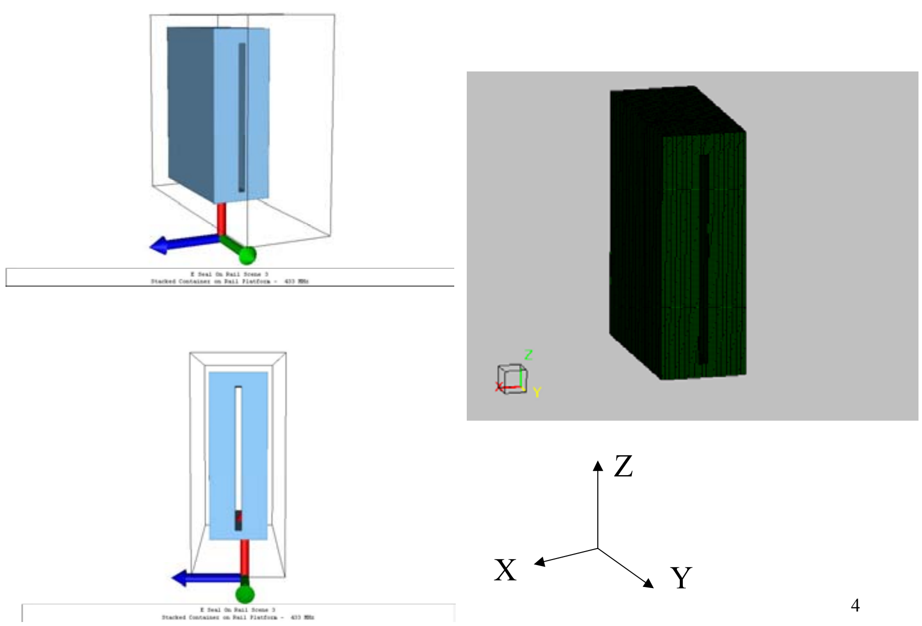
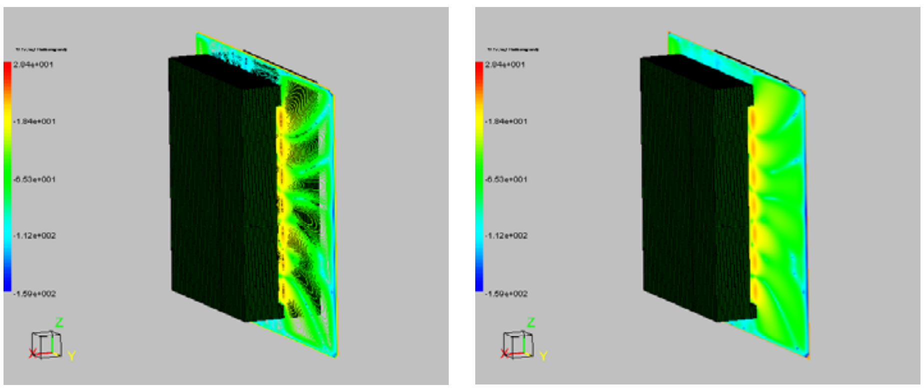


Figure E.3.3.2 On Rail Simulation Structure (e-seal in the slot)

E.3.3.2 Simulation Results

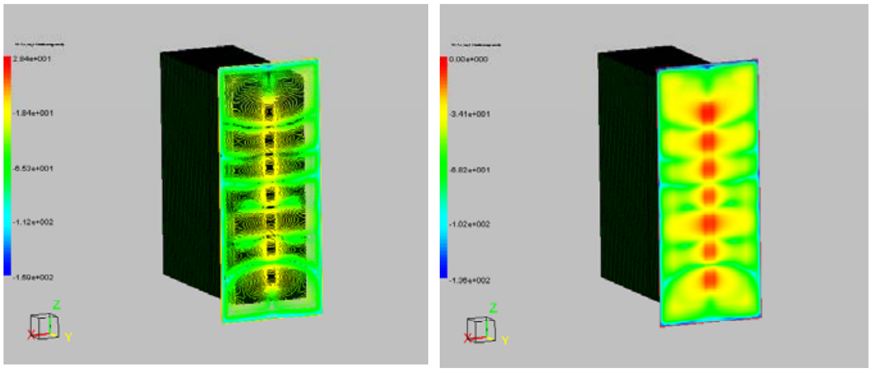
<u>E-seal at 433 MHz Frequency</u>

The first case shown is the simulation of an e-seal at 433 MHz with a dipole antenna oriented in the X direction. In Figure E.3.3.3, contour plots of signal intensity at the X=0 cut plane are shown passing through in the middle of the gap. One can see that there are “lumps” vertically along the slot. This is the result of the e-seal effectively being in a microwave resonant cavity. I.e., the empty space between two containers is a microwave cavity with side slots that allow microwave/RF signals to leak to the outside. With the e-seal acting like a microwave antenna within the cavity, certain cavity modes are excited that have distinct mode patterns (the “lumps”) within the cavity. Figure E.3.3.4 shows the RF pattern in a cut plane along the side of the container (normal to the Y axis); this view shows the same lumpy structures. Such a lumpy intensity spectrum may also be viewed as the “diffraction” pattern of the RF waves as they emerge from the cavity slot on the sidewall. Since signal propagation is lumpy in nature outside the gap space, the overall radiation pattern around the container will not be uniformly distributed. This may create no-read regions.



433 MHz – Dipole in X – X=40 plane Cut 5

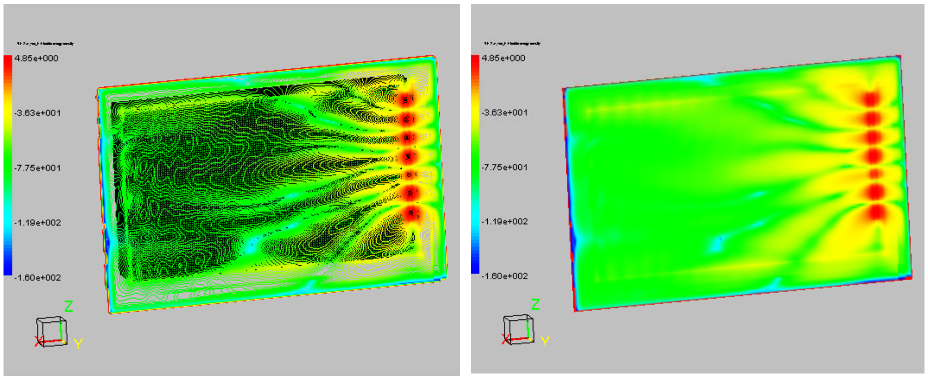
Figure E.3.3.3 E-seal frequency=433MHz X cut at 40



433 MHz – Dipole in X – Y=54 plane Cut 6

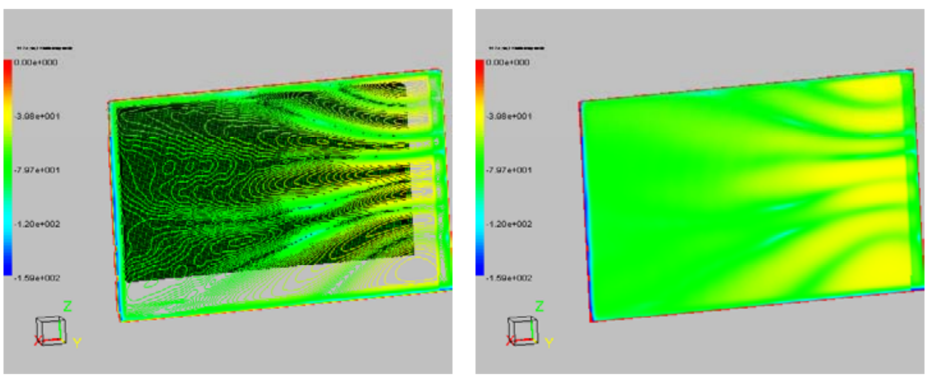
Figure E.3.3.4 E-seal frequency=433MHz Y cut at 54

To further illustrate the effect of non-uniform spatial distribution of RF signals, CTLSS simulations of larger space (up to 3 meters) along the container wall are conducted. In the larger simulation, the gap is modeled as a simple rectangular slot without the presence of detailed neck structures. The Y cut plane up to 3 m in X length along the container surface is illustrated in Figure E.3.3.5. Again, the color contours of signal strength contain striation patterns that are similar to the plots in the previous figures. It is worthwhile to note that the striation pattern diminishes as the distance from the slot along container surface increases. Beyond 2 m from the slot along the surface (along X), the intensity map shows uniform intensity distribution, albeit at a much lower signal strength level. Figure E.3.3.6 shows the same cut plane as in Figure E.3.3.5 (parallel to container surface), but at 1 m distance away from the container surface. Again, signal intensity striations persist up to 2 m along the surface from the slot position. These findings need to be compared and validated with read results obtained during terminal testing.



433 MHz – Dipole in X – Larger X region -Y=39 plane Cut 7

Figure E.3.3.5 E-seal frequency=433MHz Y cut at 39



433 MHz – Dipole in X – Larger X region -Y=66 plane Cut 8

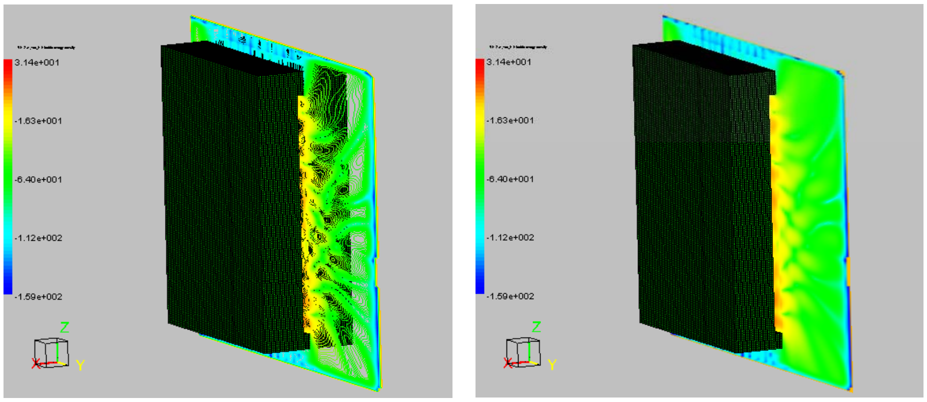
Figure E.3.3.6 E-seal frequency=433MHz Y cut at 66

CTLSS simulations have also been conducted by placing a dipole antenna along both Y and Z directions (i.e. along the surface of container backdoor, in two orientations). In both cases, the RF signals are strongly attenuated within the gap. In fact, the attenuation is so severe that there is no presence of RF signals outside the gap. Apparently, for these two dipole orientations, the 433 MHz frequency is below the cut-off frequency of the specific cavity/waveguide modes that the antenna is intended to excite. Therefore, RF signals do not propagate out of the microwave cavity/waveguide. Radiating elements in the e-seal may contain all three dipole components. Non-propagation of two dipole components in the gap implies added power loss, and therefore a less efficient link between the e-seal in the gap and the reader outside the gap.

<u>E-seal at 916MHz Frequency</u>

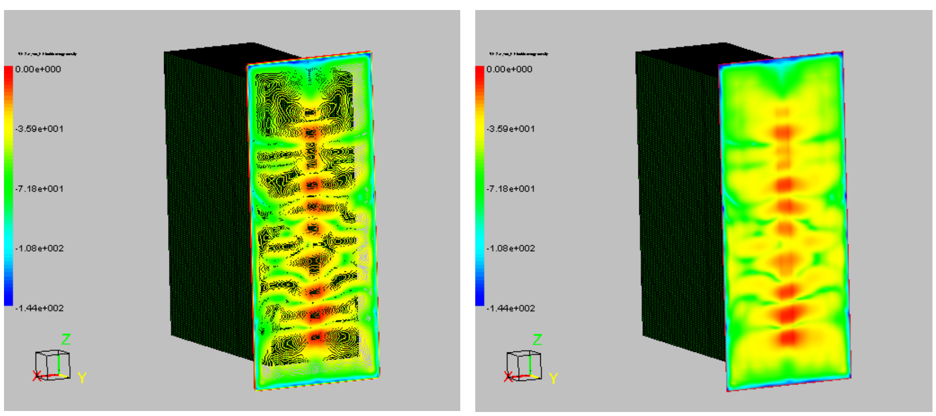
For this frequency, the CTLSS simulation was performed by placing an X-oriented dipole antenna in the gap. Figure E.3.3.8, shows signal intensity contours on the plane passing through the gap (X cut). The RF pattern is similar to that of the 433 MHz. However, there are more “lumps” of intensity peaks than the 433 MHz case, indicating that higher order waveguide modes are excited by the e-seal at higher frequency. Figure E.3.3.9 shows contour plots of signal intensity, i.e., lumpy RF structures, in Y cut plane outside the cavity slot. Figures E.3.3.10 and E.3.3.11 are contour plots of RF intensity at Y cut planes that are parallel to the container wall. These plots contain an enlarged simulation region in X. Comparing these plots with those of the 433 MHz in Figures E.3.3.5 and 3.3.6, one can observe that there are more striations with smaller spatial structures at higher frequency. A potential impact of the high frequency e-seals is to have more uneven and smaller spatial regions of signal variations.

Another important observation from the 916 MHz study is that when a dipole antenna oriented in the Z direction (i.e. along the vertical surface of the container backdoor) is used in the simulation, RF can be excited in the gap and propagate effectively to outside. This is contrary to the 433 MHz results (Figure E.3.3.7), which show that no excitation is feasible with such dipole orientation. The understanding is that 916 MHz is above the cut-off frequency of the waveguide modes in the cavity/waveguide formed by the gap, thus making the excitation of RF possible. Therefore, higher frequency e-seals have better coupling efficiency in the gap and may be more effective radiation devices for the on-rail scenario



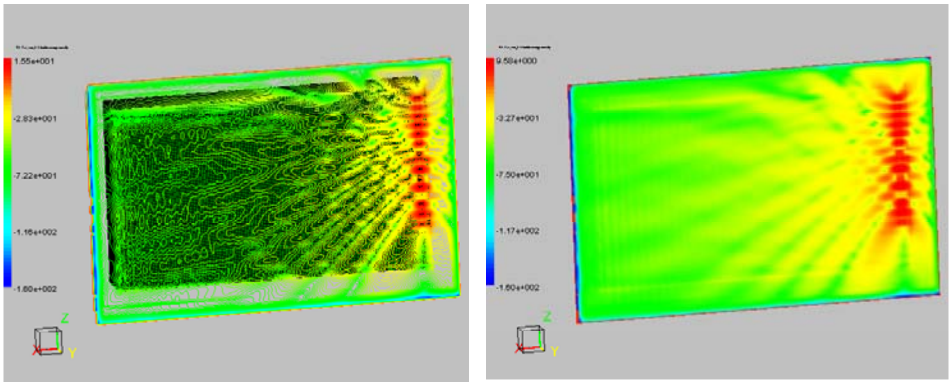
916 MHz – Dipole in X – X=40 plane Cut 10

Figure E.3.3.8 E-seal frequency=916MHz X cut at 40



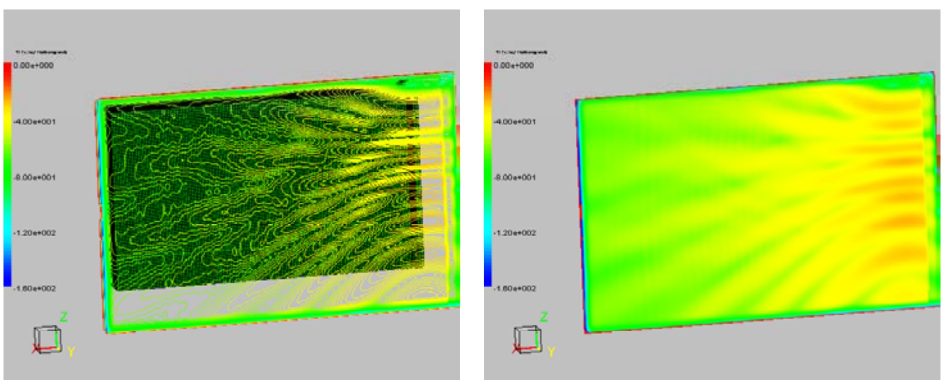
916 MHz – Dipole in X – Y=54 plane Cut 11

Figure E.3.3.9 E-seal frequency=916MHz Y cut at 54



916 MHz – Dipole in X – Y=39 plane Cut 12

Figure E.3.3.10 E-seal frequency=916MHz Y cut at 39

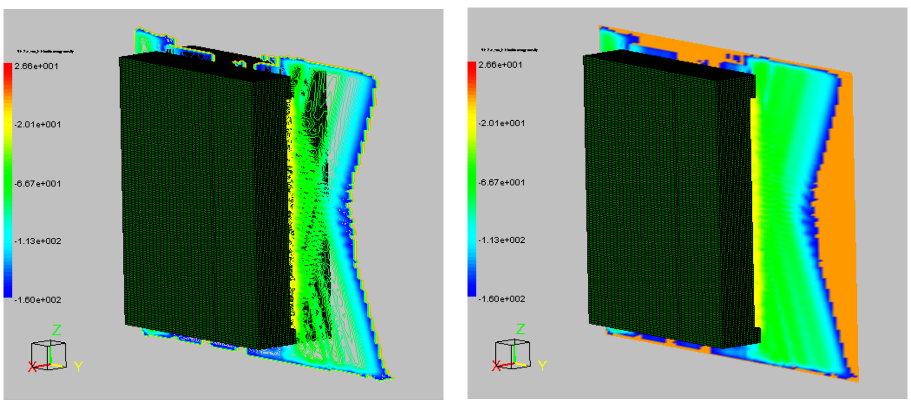


916 MHz – Dipole in X – Y=66 plane Cut 13

Figure E.3.3.11 E-seal frequency=916MHz Y cut at 66

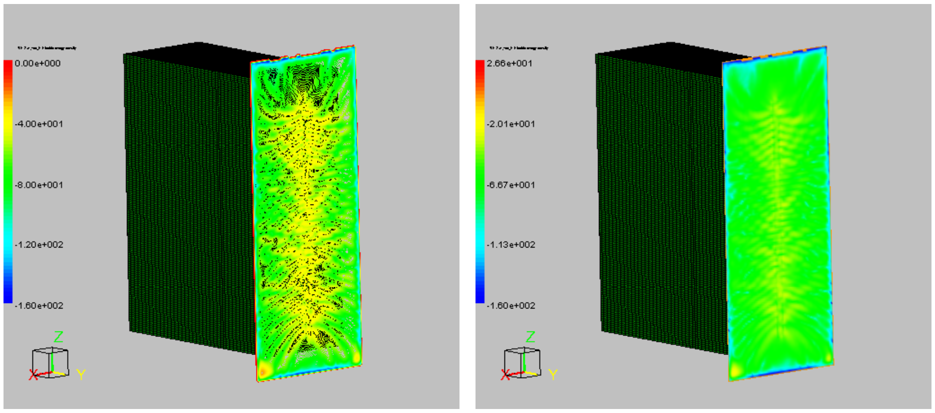
<u>E-seal at 2.44GHz Frequency</u>

For this frequency, the CTLSS simulation was performed by placing an X-oriented dipole antenna in the gap. Figure E.3.3.12 shows signal intensity contours on the plane passing through the gap (X cut). The RF pattern shows fairly uniform signal intensity distribution coming out of the slot. Figure E.3.3.13 shows contour plots of signal intensity at Y cut plane (parallel to side surface of the container) outside the cavity slot. The RF pattern shows many very fine striations in front of the slot, which is consistent with the trend that intensity striations become finer in space as frequency increases. At 2.44 GHz, the striations are fine enough so that the overall RF distribution in space is somewhat uniform. Hence, higher frequency e-seal may be more desirable for the on-rail environment because of its signal uniformity outside the gap.



2.44 GHz – Dipole in X – Y=54 plane Cut 15

Figure E.3.3.12 E-seal frequency=2.44GHz Y cut at 54



2.44 GHz – Dipole in X – Y=71 plane Cut 16

Figure E.3.3.13 E-seal frequency=2.44GHz Y cut at 71

E.3.3.3 On-Rail Conclusions

The on-rail simulation results show non-uniformity of signals observed alongside the container. This is due to resonance of RF signals in the gap between the containers and diffraction as the signals propagate out of this slot and to the outside. Because of these physical effects, higher-frequency e-seals may offer two advantages:

- Better coupling to the gap which acts as a microwave cavity; or better excitation efficiency in the gap cavity (or waveguide).
- More uniformity of signal distribution outside the gap, which may reduce sharp spatial variation of signal strength that can cause strong location dependency in reader responses.

E.3.4 On-Road Simulation

E.3.4.1 Scenarios and Configuration

The on-road simulation scenario is the same as the in-gate scenarios without obstructions. Hence, the configuration used for in-gate scenarios should be also applicable in the on-road environment.

E.3.4.2 Simulation Results

In this section we present results from the in-gate simulation run with no obstructions, in Z cut plane (Figures E.3.4.1.a-c). The results presented in Figures E.3.2.2 and E.3.2.3 are also applicable to the on-road environment. The Y cut plane is interesting, to examine the effects of reader antenna placement over the road. The patterns in Z cut planes are more interesting when looking at reader placement on the roadside.

The results again indicate that for lower frequencies (longer wavelength), contours are more uniform. At higher frequencies (shorter wavelength), signals are more directional, producing contours that are not as uniform. In the regions between the signal lobes the signal drops off, and that may result in no-reads in those regions. This needs to be validated against the read data collected at the terminal.

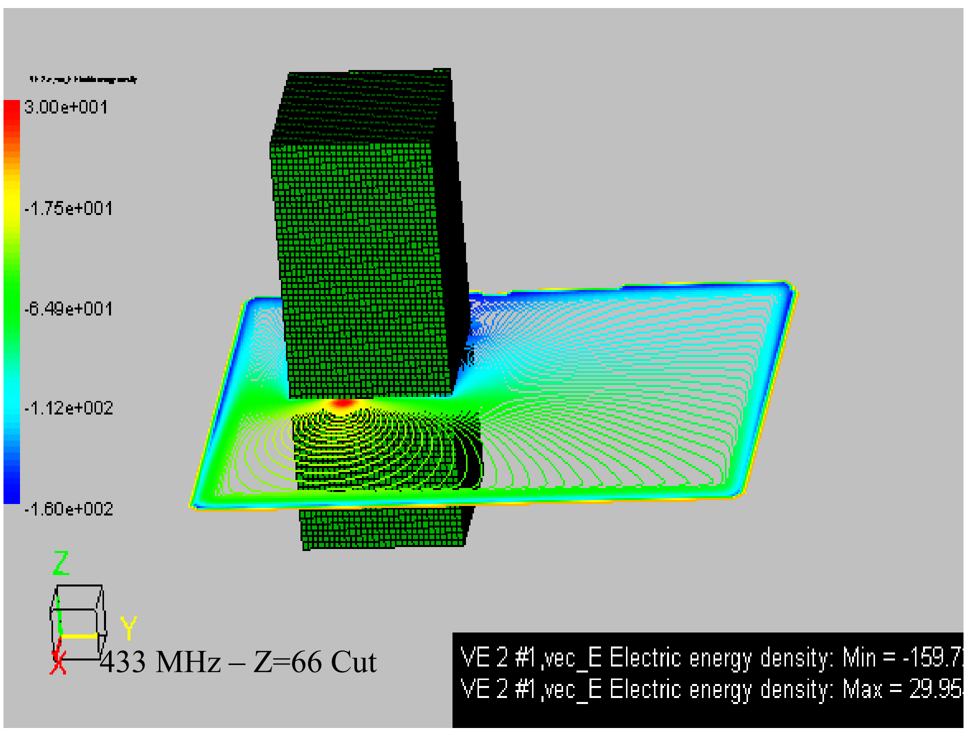


Figure E.3.4.1.a E-seal Signal Propagation with no Obstructions, 433MHz, Z cut at e-seal level

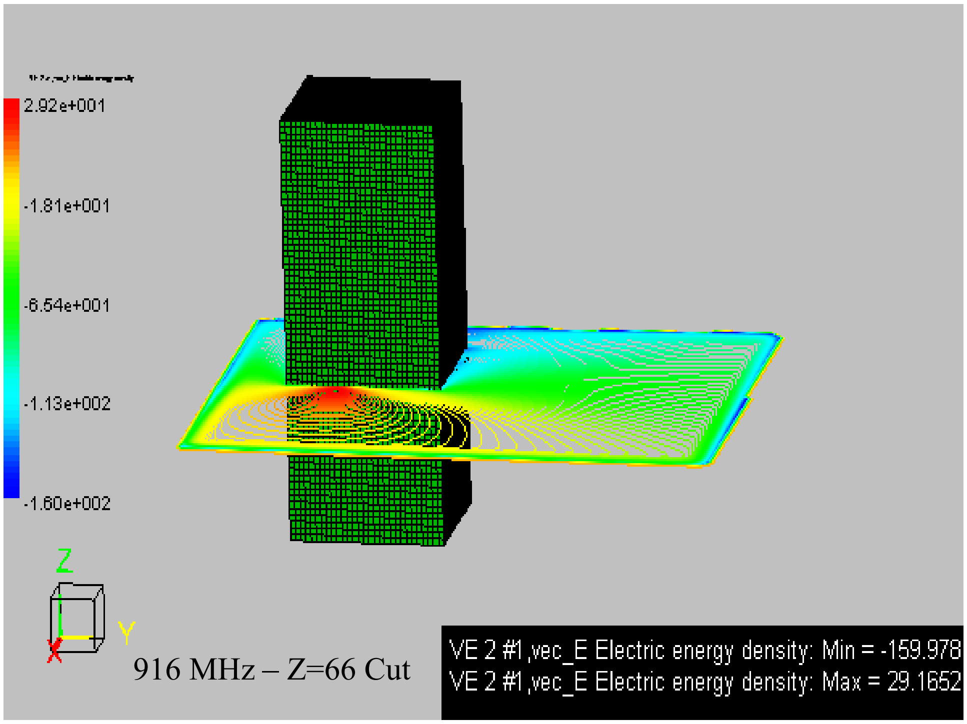


Figure E.3.4.1.b E-seal Signal Propagation with no Obstructions
(916MHz, Zcut at e-seal level)

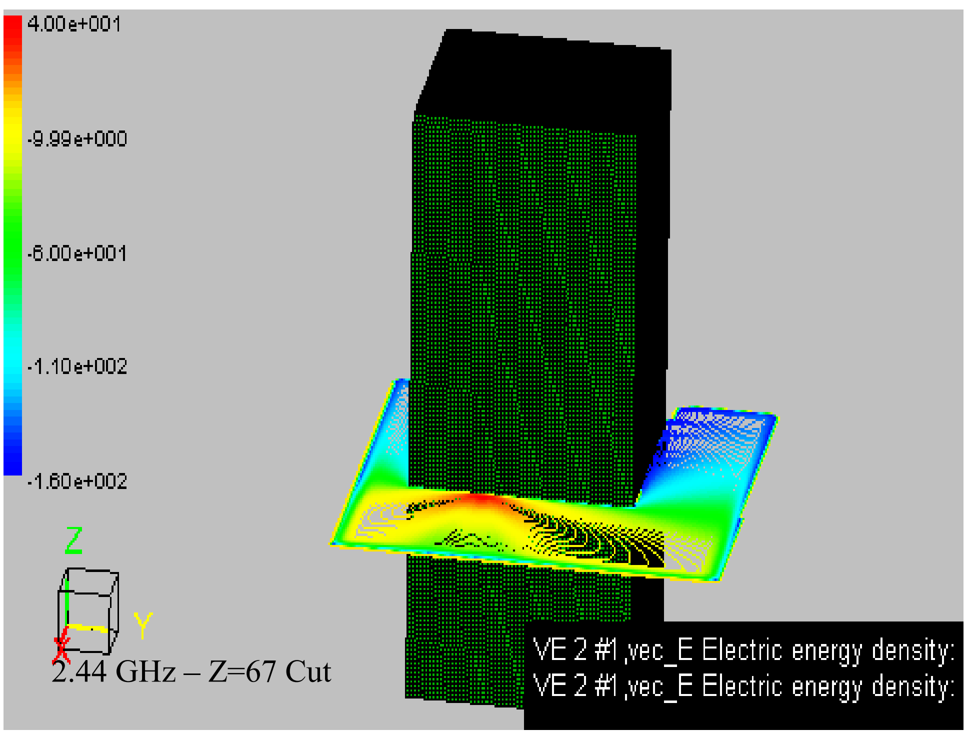


Figure E.3.4.1.c E-seal Signal Propagation with no Obstructions
(2.44GHz, Zcut at e-seal level)

E.3.4.3 On-road Simulation Conclusions

The results indicate that for lower frequencies (longer wavelength), contours are more uniform and spread out. At higher frequencies/ shorter wavelength, signals become more direct. For 2.44GHz frequency, gaps between direct signals may create regions with no-reads. The impact of the non-uniform patterns, resulting in no-reads, needs to be investigated against terminal read results.

E.4 CONCLUSIONS

The simulation effort investigated signal propagation and radiation patterns of three frequencies (433MHz, 916MHz and 2.44GHz) in the in-gate, on-rail, and on-road environments. The objective of the in-gate simulation was to investigate signal propagation in the terminal environment and, in particular, signal propagation and radiation patterns when signals reach obstacles commonly found in the in-gate area, such as booths and other containers. The objective of the on-rail simulations was to examine the effectiveness of e-seals in transmitting RF signals to the reader when the e-seal is in the gap between stacked-up containers. The on-road simulation scenario was similar to the in-gate scenarios with no obstructions.

For 433MHz signals, the in-gate simulation results show that signal strength contours, when there are no obstructions, are fairly uniform, and with a 69-cm wavelength, signals wrap around the edges of the container somewhat better then do signals for the other two frequencies. For 916MHz signals, radiation contours are less uniform. Finally, for 2.44GHz with a 12-cm wavelength), the contours evolving around e-seal are not uniform but have directional lobes. One reason is the reflection from the container door (backplane). The dipole has all three dimensions comparable to the wavelength and is offset from the container door by a few centimeters. This sets up a reflected “image” RF source that behaves as if it were “behind” the door. The combined radiation from the image source and the actual source can set up interference patterns, i.e., radial nodes of high and low signal strength. This directivity may create gaps where signal drops off sharply, and may result in regions with no-reads.

The patterns produced in the environment with structures are not as uniform as the patterns in the case where there are no obstructions. Pattern of RF intensity exhibits wave-like variations, which is typical of interference due to superposition with reflected signals from all the structures. Examining the patterns one can conclude that their propagation characteristics are somewhat similar. This is consistent with a rule-of-thumb in radio communications that operating effectiveness decreases by only 5%-10% as frequency increases from 433MHz –

2.44GHz. Hence, within the simulation region, we saw no great advantages of one frequency over the others.

The on-rail simulation results show non-uniformity of signals observed alongside the container. This is due to resonance of RF signals in the gap between the containers and diffraction as the signals propagate out of this slot and to the outside. Because of these physical effects, higher-frequency e-seals may offer two advantages:

- Better coupling to the gap which acts as a microwave cavity; or better excitation efficiency in the gap cavity (or waveguide).
- More uniformity of signal distribution outside the gap, which may reduce sharp spatial variation of signal strength that can cause strong location dependency in reader responses.

The on-road results also indicate that for lower frequencies (longer wavelength), contours are more uniform. At higher frequencies (shorter wavelength), signals are more directional, producing contours that are not as uniform. In the regions between the signal lobes the signal drops off, and that may result in no-reads in those regions. This needs to be validated against the read data collected at the terminal.

Since radiation patterns may vary significantly among various e-seals even at the same frequency, signal uniformity becomes an important factor. Uniformity helps ensure that if signal strength is maintained above a certain level for a particular distance along the road or rail, there should be no “no-read” regions within this distance as a result of poor signal strength.