RFID in Space: Exploring the Feasibility and Performance of Gen 2 Tags as a Means of Tracking Equipment, Supplies, and Consumable Products in Cargo Transport Bags onboard a Space Vehicle or Habitat

Dr. Erick C. Jones
Assistant Professor/Director
RFID Supply Chain Logistics Lab (www.unl.edu/rfscl)
NSF Industry/University Cooperative Research Center
Industrial and Management Systems Engineering
University of Nebraska – Lincoln
175 Nebraska Hall, Lincoln, NE 68588-0518
(402) 472-3695, ejones2@unl.edu

Casey Richards
Masters Student
Industrial and Management Systems Engineering
University of Nebraska – Lincoln
175 Nebraska Hall, Lincoln, NE 68588-0518

Kelli Herstein
Masters Student
Industrial and Management Systems Engineering
University of Nebraska – Lincoln
W163 Nebraska Hall, Lincoln, NE 68588
(402) 616-9491, kellikopocis@gmail.com

Rodrigo Franca
Masters Student
Industrial and Management Systems Engineering
University of Nebraska – Lincoln
W163 Nebraska Hall, Lincoln, NE 68588-0518

Evan L. Yagoda
NASA - Johnson Space Center / ESCG
ORION - CEV Habitation Accommodations
(281) 483-0921, evan.l.yagoda@nasa.gov

Reuben Vasquez
President, CEO
VerdaSee Solutions, Inc.
(847) 265-9441, reuben.vasquez@verdasee.com

October 31, 2008

Contents

EXECUTIVE SUMMARY

Background

The NASA Constellation Program has identified the need for an improved mechanism to track consumables and other critical hardware and supplies without impacting crew time. The current NASA Inventory Management System (IMS) tracks loose and stowed hardware via a barcode system, but only tracks items such as crew clothing, office supplies, and hygienic supplies at the bag level. Periodic, manually intensive crew audits must be conducted to identify the current state of the inventory. The NASA Constellation Program elected to evaluate RFID technologies for a new inventory management system. RFID technologies were selected in an effort to create the most effective and user-friendly IMS.

A research team of faculty and engineering students for the University of Nebraska-Lincoln's (UNL) Radio Frequency and Supply Chain Lab (RfSCL), engineers from VerdaSee Solutions, and personnel from NASA's Johnson Space Center investigated the current performance of commercial off-the-shelf (COTS) Generation 2 RFID passive tags and readers (Gen 2). The project also extended to Gen 2 technologies that may be available within the next year (2008-2009). This study was sponsored by NASA's Johnson Space Center for the Constellation Program.

Previous Study

A previous study in 2005 was conducted in which the available first generation passive RFID (Gen 1) technologies were tested for the NASA International Space Station (ISS) group at UNL's RfSCL. The results of the previous study suggested that Gen 1 passive tags had limited success on consumable items within cargo transport bags (CTB's) and would not be feasible in working with the aluminum Russian containers. Active tags had a higher degree of success but were not cost effective and their large size was not attractive for space applications. Alternative RFID tags such as surface acoustic wave (SAW) tags could not be validated due to lack of availability. Recommendations from that study were to use a portal type configuration for tracking product as it goes into designated areas, and tracing of consumed products. Other ideas suggested were development of smart bags with a UNL SAT (sensor active tag) technology, and investigation of smart shelves to accommodate real time location of products using ranging technologies.

Objective

Manufacturers of Gen 2 RFID tags have proven that there are significant improvements in some applications; however, it is good practice to test emerging technologies for use in specific industries. The objective of this project is to measure and evaluate the performance of the latest Gen 2 passive technologies. The specific goals included the following:

1. Evaluate the performance of off the roll COTS Gen 2 RFID tags (Research Study 1)
2. Evaluate the performance of Gen 2 tags on NASA consumables and supplies, (Research Study 2), and
3. Describe the possible uses of Gen 2 passive tags for NASA and suggest alternative RFID technologies that need to be investigated (Final Report)

Summary of Results

Research Study # 1 was performed to identify the best overall tags that would be suitable for item level tagging of consumables and supplies. The tags were selected based upon read range, orientation, and performance on three materials (cardboard, metal, and liquid). The two tags that produced the highest read rates on all materials and met NASA requirements were selected for further testing at the item level. These tags were the Omron Scorpion tag and the Avery Dennison 820/821 tag. Another tag, which was not available at the time of Research Study # 1, was selected for the second study as well. This tag, the Omni-ID liquid/metal tag, was designed to have improved performance on RF-unfriendly materials and was determined to be a suitable tag for liquids, gels, and metallic materials.

Research Study # 2 was performed to evaluate the performance of the selected tags directly at the item level. The tagged items were densely packed into both a CTB bag and a cardboard container. A sequential DOE approach was used to progressively improve the percentage of tags read within the container. Tags that were not read were adjusted by trying all three tags, repositioning the tag on the item, and adjusting the reader antenna configuration. It was determined that all consumables and supplies could be identified at the item level when used with the correct tag for that item. The fixed reader setup produced quicker and more accurate read rates than the mobile handheld reader. It was found that a fixed portal antenna configuration produced 100% read rates, depending on the orientation of the items within the CTB.

It was determined that all items within the CTB could meet the read specifications using a combination of the three tags that were selected. A fixed, four antenna, portal configuration provided excellent results when the antennas were within 1 – 2 feet of the CTB since it reduced the effect of tag orientation. Given an organized packing configuration within the CTB, the mobile handheld reader was able to read 100% of the tags when the reader was moved around all sides of the CTB. The limiting factor for mobile reader applications is antenna gain and output power, since the CTB must be scanned at close proximities in order to read all tags.

Summarizing the results, the main conclusions drawn from this study are:

Benefits

1) Gen 2 technologies have shown performance improvements over Gen 1.
2) Problems still persist with tagging metal and liquid materials; however, specialty tags have been developed that have shown significant improvements on these materials.
3) Stationary readers such as smart shelves or door portal configurations shown in Figure 4 in this study proved to be successful with a four antenna portal configuration.
4) Stationary passive readers are generally more accurate and provide longer read ranges than mobile readers.
5) Both the mobile and fixed RFID systems were capable of reading data from multiple densely packed tags at short distances (less than 1feet).

Challenges

6) Antenna gain is the limiting factor for mobile reader applications. The CTB must be scanned at close proximities in order to read all the tags inside it.
7) Stationary readers such as smart shelves or door portal configurations require power and room to be mounted.
8) Performance in stacking conditions or buried conditions (multiple CTB's) is very poor (low read rates or no reads) due to attenuation issues and increased distance between the desired tag and the reader antenna. This indicates that location based applications will not be successful with passive tags due to increased interference or blockage/attenuation issues.
9) Handheld demo software is not inventory application specific. Inventory management applications for use in RFID handheld scanners would need to be developed prior to implementation.
10) In order to ensure higher read accuracies on RF unfriendly inventory, liquid/metal specialty tags may need to be used. The specialty tags were not tested on all items at once inside the CTB and there is a possibility that performance will be degraded when multiple tags are present in close proximity of each other. This issue would need to be further investigated.

Summary of the Specific Gen 2 tags performance

1) The Omron Scorpion tag demonstrated higher read rates than other tags included in the study; however, they demonstrated low read rates or no reads for most RF-unfriendly materials (liquid and metal).
2) The Avery Dennison 820/821 tag demonstrated improved performance over the Omron Scorpion (higher average read rate) on metallic based items.
3) The Omni-ID liquid/metal tag demonstrated the best overall performance on most RF-unfriendly materials (included all liquids and metals).

Recommendations

UNL's RfSCL envisions that RFID technologies can be used for three functions: tracking, tracing, and locating. The tracking function in an RFID system is what was tested in this study. Tracking consists of an RFID tag that is identified by a reader and therefore its immediate location is known, regardless of past history. Tracing is similar to tracking, but involves the historical documentation throughout the supply chain, from point of manufacture to end use. Locating technologies identify the real-time location of the tag within a confined space. Locating may require more equipment (i.e. 3 reader set-ups for triangulation) or more advanced and costly RFID technologies such as active RFID tags that contain an onboard battery to power the tag. If actively locating of an item is a requirement (i.e. beeping tags), passive tags may not viable and other technologies will need to be evaluated.

Tracking recommendations:

1) Investigate the feasibility of increasing antenna gain and/or output power for mobile readers
    a. A modified COTS approach should be investigated for mobile readers
2) Investigation of NASA defined (using NASA operational materials such as metals and door opening) portal configurations should be investigated for fixed readers.
3) Investigate the feasibility of increasing antenna gain and/or output power for fixed reader configurations such as smart shelves.
4) Investigate the smart bag prototypes such as UNL's Sensor Active Tag (2005) idea for item level tracking
5) Investigate the use of semi-active Gen 2 (ISO 18000 part 1-6) standard tags and active RFID tags that adhere to the (ISO 18000 part 7 new standard)

Tracing recommendations:

6) Investigate the feasibility of RFID software to integrate with NASA inventory control systems to trace inventory information. For example: RFID software VerdaSee Navigator's ability to tie into NASA's IMS
7) Investigate the feasibility of creating user friendly mobile reader application
    a. A modified COTS approach should be investigated

Locating recommendations:

8) Investigate RFID based Real Time Location Systems ability to locate items in NASA type closed containers including, rooms, containers, CTB, boxes, and cases. This testing should include stacked or buried conditions for the tags and the containers. Similar to the final stacking testing that was performed in this study.

Hybrid tracking and locating

9) Investigate an RFID active (ISO 18000) and Gen 2 semi-active technology configurations that can be used with a container such as a CTB. This type of technology would increase accuracy and read ranges to the parent reader. This configuration will allow for:
    1) Tracking capabilities using the semi-active technology for scanning the contents within the container and the active technologies to provide battery assisted signals for

location of the container. An example for this design is the UNL's SAT design from 2005.

NASA GEN 2 RFID FINAL REPORT

1.0 Abstract

Current inventory management techniques for consumables and supplies aboard space vehicles are burdensome and time consuming. Inventory of food, clothing, and supplies are taken periodically by manually scanning the barcodes on each item. The inaccuracy of reading barcodes and the excessive amount of time it takes for the astronauts to perform this function would be better spent doing scientific experiments. Therefore, there is a need for an alternative method of inventory control by NASA astronauts. Radio Frequency Identification (RFID) is an automatic data capture technology that has potential to create a more effective and user-friendly inventory management system (IMS). In this paper we introduce a Design for Six Sigma Research (DFSS-R) methodology that allows for reliability testing of RFID systems. The research methodology uses a modified sequential design of experiments process to test and evaluate the quality of commercially available RFID technology. The results from the experimentation are compared to the requirements provided by NASA to evaluate the feasibility of using passive Generation 2 RFID technology to improve inventory control aboard crew exploration vehicles.

2.0 Introduction

The NASA Constellation Program has identified the need for an improved mechanism to track consumables and other critical hardware and supplies without impacting crew time. The current NASA Inventory Management System (IMS) tracks loose and stowed hardware via a barcode system, but only tracks items such as crew clothing, office supplies, and hygienic supplies at the bag level. Periodic, manually intensive crew audits must be conducted to identify the current state of the inventory. The NASA Constellation Program elected to evaluate RFID technologies for a new inventory management system. RFID technologies were selected in an effort to create the most effective and user-friendly IMS.

A research team of faculty and engineering students for the University of Nebraska-Lincoln's (UNL) Radio Frequency and Supply Chain Lab (RfSCL), engineers from VerdaSee Solutions, and personnel from the NASA Constellation Program investigated the current performance of commercial off-the-shelf (COTS) Generation 2 RFID passive tags and readers (Gen 2). The project also extended to Gen 2 technologies that may be available within the next year (2008-2009).

3.0 Background

Previously, a study of first generation RFID (Gen 1) technologies was tested for the NASA International Space Station (ISS) group at UNL's RfSCL. This study was composed of a team which included UNL, ISS, and Barrios inc., and was performed two years earlier in 2005. The previous study included Gen 1 passive tags and reader, active tags, and other alternatives such as surface acoustic wave (SAW) tags and readers were considered. SAW tags were investigated but not further tested at UNL due to production problems. Due to the further development and standardization of Gen 2 RFID technologies over the last two years because of mandates (Wal-Mart, Department of Defense, Sam's club, etc.), the available technology is being further investigated.

The results of the previous study suggested that Gen 1 passive tags had limited success on consumable items within cargo transport bags (CTB's) and did not perform well on metals and water packaged items. Further, these Gen 1 tags would not be feasible in working with the aluminum Russian containers. Active tags had a higher degree of success (higher read rates) but were not cost or weight effective ($25-$50 and up to 200 grams per tag). Alternate automated tags such as SAW tags could not be validated due to lack of availability and are furthermore not the industry standard. Recommendations from that study were to use a portal type configuration for tracking product as it goes into designated areas, and tracing of consumed products. Other ideas suggested were development of smart bags with a UNL SAT (sensor active tag) technology, and investigation of smart shelves to accommodate real time location of products using ranging technologies.

With the advent of Gen 2 technology, many deficiencies of Gen 1 have been rectified. Of the benefits associated with Gen 2 technology over Gen 1, the following traits have been considered for this study:

- Gen 2 tags have a lower cost per tag as compared to Gen1. The ability to keep costs down is an incentive to investing in RFID technologies rather than using traditional methods of inventory management.
- Gen 2 tags are more standardized due to recent mandates which have allowed versions of these tags to be created that are smaller and have less mass than Gen 1 tags.
- Gen 2 has an increased read range with lowered probability of interference which allows for item level tracking instead of merely tracking containers. The inability of Gen 1 tags to be used in item level tracking was a downfall that Gen 2 should rectify.
- Gen 2 offers increased security as compared to Gen 1 tags. The unique identifiers of these more secure tags make them more reliable and therefore a better solution for tracking items from the manufacturing phase to their use in space.
- New Gen 2 tags have been developed for improved performance on liquid and metal materials.

4.0 Project Objective

Manufacturers of Gen 2 RFID tags have proven that there are significant improvements in some applications; however, it is good practice to test emerging technologies for use in specific industries. The objective of this project is to measure and evaluate the performance of the latest Gen 2 passive technologies. Furthermore, this study also will demonstrate the difference in tag performance based on tag placement at the item level as opposed to tagging a Ziploc® bag containing the item. Previously, ISS used Ziploc® bags to package some consumables.

The specific goals included the following:

1) Evaluate the performance of off the roll COTS RFID Gen 2 tags
2) Evaluate the performance of RFID Gen 2 labeled NASA consumables and supplies
3) Describe the possible uses of Gen 2 passive tags for NASA and suggest alternative RFID technologies that need to be investigated

In order for Gen 2 technologies to be deemed successful for implementation, NASA developed the following requirements:

1) The bag/container can be scanned within 15 seconds and identify the contents with an accuracy greater than or equal to 99%.
2) Tag sizes shall not exceed 3" x 2".
3) The items tagged in each bag/container must be comparable with the list of items provided by NASA.

The hypothesis of this experiment was that a given Gen 2 RFID tag at the item level can be reliably scanned at least 99% of the time when packed inside a cargo transport bag (CTB).

The hypothesis will be tested by completing two specific objectives:
1) Evaluate the performance of off the roll COTS RFID Gen 2 tags.
2) Evaluate the performance of RFID Gen 2 labeled NASA consumable items and supplies.

This study describes the testing of Gen 2 RFID technologies using Design of Experiments (DOE) methodologies.

5.0 Methodology

In this study, the research method derived by the RFSCL at UNL called Design for Six Sigma Research (DFSS-R) was utilized. It is based on a Plan-Do-Check-Act (PDCA) strategy and is a hybrid version of common Six Sigma and Design for Six Sigma (DFSS) methods (Yang & El Haik, 2003). This technique boasts the fusion of traditional research methods with industry's new gold standard, Six Sigma, into a methodology described as DFSS-R.

This methodology is based on a strategy to develop operational prototypes and is organized into a Plan, Predict, and Perform (3P) Model that utilizes 7 steps: Define, Measure, Analyze, Identify, Design, Optimize and Verify (DMAIDOV). In the study, development was not in scope so only the Define, Measure, Analyze, and Identify steps were used.

The DFSS-R methodology was utilized to test each of the specific objectives. The experiments were conducted in a lab environment where conditions are ideal and interference is minimal. A description of each testing procedure is followed by the results of the test. The results of each experiment were recorded and analyzed. The analysis of the two research studies is discussed below.

Specific Objective # 1: Evaluate the performance of off the roll COTS RFID Gen 2 tags.

Define: The goal is to measure the performance of COTS RFID Gen 2 tags on a representative list of NASA and known RFID Gen 1 problematic items. A controlled test was conducted to compare the performance of an assortment of 10 tags from two manufacturers. The tags consisted of nine unique tags from Avery Dennison and Omron. Tag 5 and Tag 10 are the same tag; however, Tag 5 is in the inlay from, while Tag 10 was attached to an adhesive label. A single tag of each type was used for all testing. These tags are listed in Table 1.

Table 1: Tag Inventory List for Research Study # 1.

Number	Item Model	Tag Description
1	NINJA-V750-D22M03-IM	OMRON GEN2 UHF TAG
2	AD-222	AVERY GEN2 UHF TAG
3	AD-820/AD-821	AVERY GEN2 UHF TAG
4	AD-431	AVERY GEN2 UHF TAG
5	WAVE-V750-D22M01-IM	OMRON GEN2 UHF TAG (INLAY ONLY)
6	SCORPION-V750-D22M04-IM	OMRON GEN2 UHF TAG
7	AD-622	AVERY GEN2 UHF TAG
8	LOOP-V750-D22M02-IM	OMRON GEN2 UHF TAG
9	AD-812/AD-811	AVERY GEN2 UHF TAG
10	WAVE-V750-D22M01-IM	OMRON GEN2 UHF TAG (WITH LABEL)

Testing of each of the 10 tags consists of a 3 x 6 x 2 experimental design with the following factors:

1) Material type (cardboard, metal, liquid)
2) Tag orientation
3) Read distance (5 feet, 10 feet)

For each of the materials, the object was placed in six orientations, and the tag was scanned for 30 seconds using a standard Gen 2 fixed reader and a single antenna. The equipment used for all experiments in this study is listed in Table 2.

Table 2: Equipment Inventory List.

Number	Item Model	Item Description	Supplier
1	WORKABOUTPRO	HANDHELD TERMINAL	PSION TECKLOGIX
2	WA4003-G2	DOCKING STATION DESKTOP KIT	PSION TECKLOGIX
3	RA2041	RADIO SUMMIT 802.11G CF WEP128	PSION TECKLOGIX
4	WA3010	BATTERY PACK ASSY HIGH CAP	PSION TECKLOGIX
5	V750-BA50C04-US	V750 NEW READER 915MHZ	OMRON
6	V740-HS01CA	MONO STATIC ANTENNA	OMRON
7	V740-A01 10M	ANTENNA CABLES	OMRON

Measure: The performance metric will be the read rate (reads per second) of the 10 COTS RFID tags using a fixed reader. This gives an adequate comparison of the read strength when the independent variables are introduced. The number of successful reads was also recorded and used as another means for comparison.

Analyze: The tag which has the highest average read rate on a representative group of materials will be ranked highest. An analysis was performed using Minitab 14.1 statistical software to determine if there was a significant difference between the tags.

Identify: Identify the three (3) best performing COTS RFID Gen 2 tags to be used to complete Specific Objective # 2.

Summary of Research Study # 1

The first experiment compared the performance of the tags on three materials: cardboard, metal, and liquid. The cardboard trials were used as the control, since eight of the ten tags were readable 100% of the time. The metal and liquid trials were then compared with the control and these materials were found to have a significant effect on the read rate of the tags.

The results from this experiment indicate that all four main factors (distance, tag type, material, and orientation) had a significant effect on the resulting read rate (using an alpha value of $p < 0.05$). Two of the three 2-way interactions were also found to be statistically significant. Tag Number by Material Type and Material Type by Tag Orientation were found to be significant, while Tag Number by Tag Orientation was found to be not significant. The results of the analysis are displayed in Table 3 and the interaction and main effects plot are shown in Figure 1 and Figure 2, respectively.

Table 3: Analysis of selected factors on the read rate of Gen 2 RFID tags.

Factor	Type	Levels	Values
Distance	fixed	2	5, 10
Tag	fixed	10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10
Material	fixed	3	1, 2, 3
Orientation	fixed	6	1, 2, 3, 4, 5, 6

Analysis of Variance for Reads per Second, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Distance	1	2855.5	2855.5	2855.5	29.52	0.000
Tag	9	5260.0	5260.0	584.4	6.04	0.000
Material	2	18603.6	18603.6	9301.8	96.18	0.000
Orientation	5	1872.8	1872.8	374.6	3.87	0.002
Error	342	33077.1	33077.1	96.7		
Total	359	61669.1				

S = 9.83447   R-Sq = 46.36%   R-Sq(adj) = 43.70%

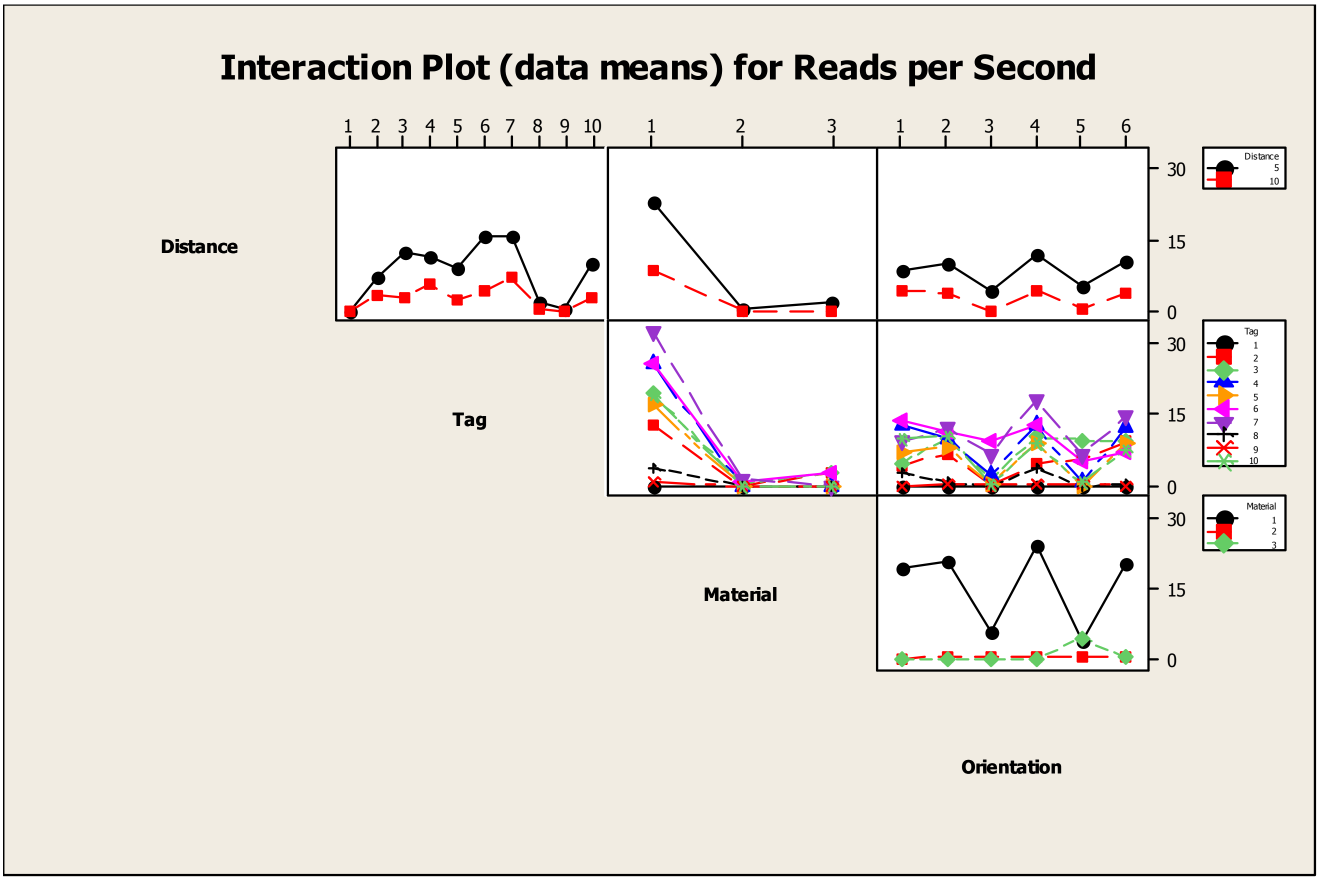


Figure 1: Interaction plot for factor analysis on the read rate of Gen 2 RFID tags.

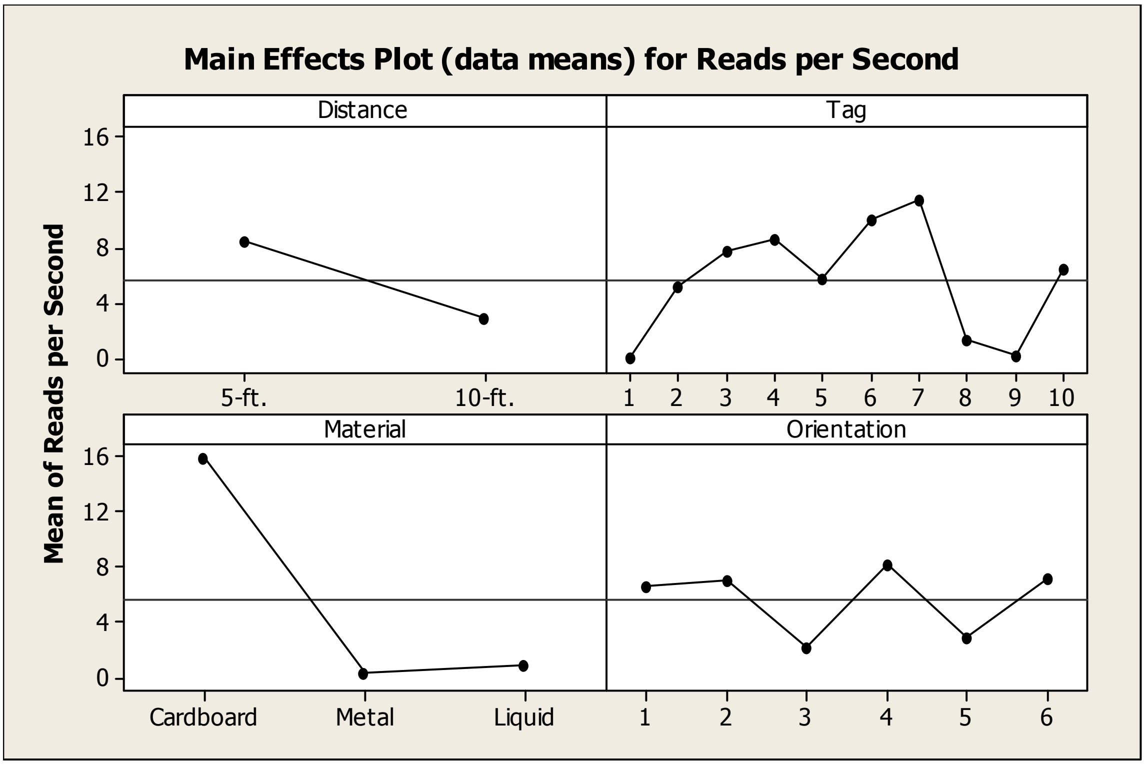


Figure 2: Main effects plot for factor analysis on the read rate of Gen 2 RFID tags.

As expected, the material type was found to be an important factor in the performance of the tag. Only three of the tags performed exceptionally well when placed on either a metal or liquid substance. The tag type was also a significant factor since some tags did perform better than others. Finally, tag orientation was found to be statistically significant; however, it has very little effect compared to the material type.

The tags selected for item level experimentation were chosen based upon their performance on all three material types. Some tags produced higher read rates on cardboard than the selected tags, but they exhibited poor read rates on metal and liquid. The tags selected for Research Study # 2 are:

1) Omron Scorpion
2) Avery Dennison 622
3) Avery Dennison 820/821

<u>**Specific Objective # 2**</u>: Evaluate the performance of RFID Gen 2 labeled NASA consumable items.

Define: The goal is to measure the performance of the tags selected from Research Study # 1 on NASA consumable items and supplies inside a NASA CTB and cardboard containers. The Omron Scorpion tag and the Avery Dennison 820/821 tag, which were two of the top performing tags, were selected along with the Omni-ID Prox tag, which is a liquid/metal specialty tag that was not tested in the previous experiment. This liquid/metal tag consists of a trivial spacer between the antenna and the adhesive that allows better performance on traditionally non-RF friendly materials including some metal and liquid or gel materials. All of the tags met the size requirements set forth by NASA and produced read rates greater than 99% on all material types within a distance of 5 feet. The Avery Dennison 622 tag was excluded from Research Study # 2 due to its large size, which did not meet the initial requirements. The three tags selected for this study are listed in Table 4.

Table 4: Tag Inventory List for Research Study # 2.

Number	Item Model	Tag Description
1	AD-820/AD-821	AVERY GEN2 UHF TAG
2	OMRON SCORPION-V750-D22M04-IM	OMRON GEN2 UHF TAG
3	OMNI-ID PROX	OMNI-ID GEN2 UHF TAG

This experiment followed a sequential Design of Experiments (DOE), in which successive trials were adjusted based upon the results of previous trials to achieve improved performance. Trials were performed to evaluate the following effects:

1) Tag placement upon on item and orientation within the CTB.
2) Performance within a CTB versus a cardboard container.
3) Number of reader antennas used and the distance from the tags.

Measure: The performance metric will be percent of tags within the CTB or cardboard containers that are read within 15 seconds using a fixed or mobile reader.

Analyze: The tagged items which were able to be read within the CTB's will be documented and ranked. Items that are not read will be modified using RFID tag repositioning, repacking and RFID reader antenna adjustments. An analysis of the performance was conducted to evaluate the combination of tags, positioning, and antennas that provided the best results.

Identify: Identification of COTS RFID Gen 2 tag, antenna, and reader limitations. Suggestions on RFID Gen 2 modifications or alternative RFID technologies are based on the limitations.

Summary of Research Study # 2

The goal of Research Study # 2 was to identify problems with item level tagging and determine the factors that have the most significant effect on the read rate. The testing procedure followed a sequential DOE methodology in which results from the previous trial were used to alter the current trial to produce higher read rates. The items were each placed into a Ziploc® bag initially and the RFID tag was attached to the bag. After collecting some initial data, the tag was placed directly on the items. The results in this study present the data at the item level only. To eliminate a source of error, all items were packed into the CTB or cardboard container the same way for every trial. This packing configuration is shown in Figure 3.

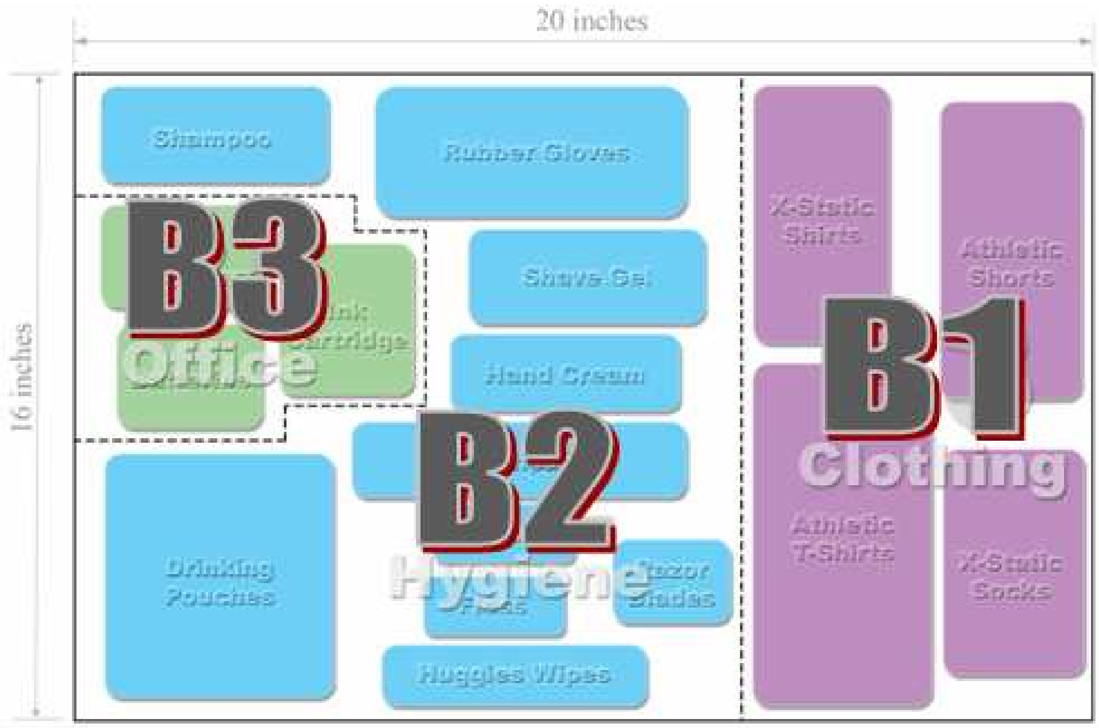


Figure 3: Packing configuration for CTB and cardboard container.

The experiment was performed using both the CTB and cardboard container. The factors evaluated were distance from tag to antenna, number of antennas, placement of antennas, and orientation. The orientation of the tag was evaluated by scanning the CTB or cardboard container in a static position and then rotating the entire container during the scan. From this it could be determined if the item's properties were causing poor read rates or if the orientation of the tag was causing blocking issues. Results of the testing are shown in Table 5 for the CTB trials and Table 6 for the cardboard container trials. The far right column lists the percentage of tags within the container that were read.

Table 5: Results of item level testing in CTB.

Test Type	Trial Number	Distance (feet)	Number of Antennas	Antenna Placement	Movement of Items	B1 Clothing	B2 Hygiene	B3 Office	Number of Reads	Percentage
CTB	1	1	4	2 per side	Static	100%	85%	75%	20/23	87%
CTB	2	1	4	2 per side	Static	75%	92%	75%	19/22	86%
CTB	3	1	4	2 per side	Static	100%	92%	75%	20/22	91%
CTB	4	1	4	2 per side	Rotating	100%	100%	100%	22/22	100%
CTB	5	1	4	2 per side	Static	100%	100%	100%	22/22	100%
CTB	6	3	4	2 per side	Static	75%	92%	75%	19/22	86%
CTB	7	3	4	2 per side	Rotating	75%	100%	75%	20/22	91%
CTB	8	3	2	same side	Static	75%	69%	25%	14/22	64%
CTB	9	3	2	same side	Static	75%	100%	75%	20/22	91%
CTB	10	3	2	same side	Static	100%	69%	0%	14/22	64%
CTB	11	3	2	same side	Static	100%	100%	50%	20/22	91%
CTB	12	3	2	1 per side	Rotating	100%	100%	75%	21/22	95%
CTB	13	1	2	1 per side	Static	100%	92%	75%	20/22	91%
CTB	14	1	2	1 per side	Rotating	100%	100%	75%	21/22	95%
CTB	15	1	1	one side	Static	100%	54%	75%	15/22	68%
CTB	16	1	1	one side	Rotating	100%	100%	75%	21/22	95%
CTB	17	3	1	one side	Rotating	100%	100%	50%	20/22	91%

Table 6: Results of item level testing in cardboard container.

Test Type	Trial Number	Distance (feet)	Number of Antennas	Antenna Placement	Movement of Items	B1 Clothing	B2 Hygiene	B3 Office	Number of Reads	Percentage
Cardboard	1	3	1	one side	Static	50%	69%	75%	14/21	67%
Cardboard	2	3	1	one side	Rotating	75%	92%	100%	19/21	90%
Cardboard	3	3	1	one side	Rotating	75%	100%	75%	19/21	90%
Cardboard	4	1	1	one side	Static	50%	92%	75%	17/21	81%
Cardboard	5	1	1	one side	Rotating	100%	100%	75%	20/21	95%
Cardboard	6	1	2	same side	Static	75%	85%	100%	18/21	86%
Cardboard	7	1	2	same side	Rotating	100%	100%	100%	21/21	100%
Cardboard	8	3	2	same side	Rotating	100%	100%	100%	21/21	100%
Cardboard	9	3	2	same side	Static	75%	77%	75%	16/21	76%
Cardboard	10	3	4	2 per side	Static	75%	85%	75%	17/21	81%
Cardboard	11	3	4	2 per side	Rotating	100%	100%	100%	21/21	100%
Cardboard	12	1	4	2 per side	Static	75%	92%	100%	19/21	90%
Cardboard	13	1	4	2 per side	Rotating	100%	100%	100%	21/21	100%
Cardboard	14	1	4	2 per side	Static	100%	100%	100%	21/21	100%

Figure 4 demonstrates that factors such as antenna placement and orientation (movement of items) have a much larger effect than others. The following results can be derived from the graphs in Figure 4:

Test Type (CTB or Cardboard): There is only a slight difference in the read rate between the items packed into a CTB and the items packed into a cardboard box. This would lead us to believe that the CTB bag is not significantly degrading the performance of the RFID tags.

Distance: As the distance from the tags to the reader antenna increases, a slight decrease in the read rate is expected. It was also noted that as the number of antennas increase, the probability that all tags are read increases significantly as well.

Number of Antennas: As the number of antennas increase, the read rate is expected to increase as well. More antennas create a stronger radio frequency field and reduce the chances of a tag being missed due to orientation issues.

Placement of Antennas: The results show that the antennas perform better when placed on opposite sides of each other rather than on the same side. This is due partially because some tags become blocked by other tags or materials and a symmetrical antenna setup reduces the chance of blocking.

Movement of Items (orientation): The most significant factor was determined to be the orientation of the tag within the CTB. When the CTB was held in a static position, an average of 84% of the tags were read, however, when movement was introduced and the CTB was rotated, the read rate increased to 95%. Read rates were accomplished with 100% accuracy at both static and rotating bag movements when using the four antenna configuration with two antennas in parallel at opposite sides of the CTB spaced four feet apart (refer to Table 5, Trials 4 & 5).

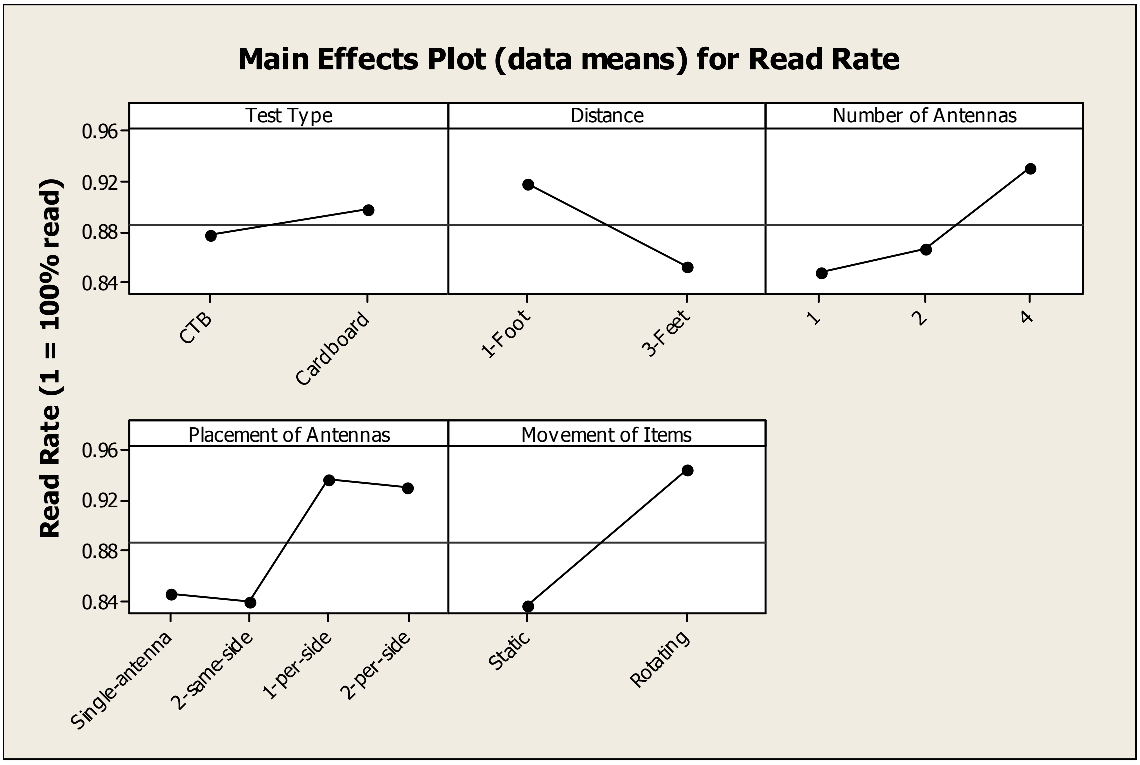


Figure 4: Main effects plot for factor analysis on the read rate of Gen 2 RFID tags.

The mobile handheld reader showed results similar to that of a single antenna fixed setup. This was expected since the signal propagates in a single direction in both of these scenarios and there is a greater chance for blocking due to orientation issues. The initial results of the mobile reader tests at both the Ziploc® level and item level are shown in Table 7. The trials from this test followed a sequential DOE progression and it was later discovered that with the correct combination of the three types of tags, all items within the CTB could be read by the mobile reader. In order to achieve this 100% read rate, however, the reader must be held in close proximity of the CTB (less than one foot away) and the CTB must be rotated or the reader must be moved around all sides of the CTB. This 100% read rate was from successive trials and is not shown with the initial results. The mobile reader was not as consistent as the close range, four antenna fixed reader setup, which is believed to be caused by the difference in antenna gain between the fixed and mobile readers.

Table 7: Initial results of mobile handheld reader tests.

Reader Type	Trial	B1(Clothing)	B2(Hygiene)	B3(Office)	Total
Mobile (Tag on Ziploc® only)	1	88%	92%	67%	87%
Mobile (Tag on Ziploc® only)	2	63%	50%	67%	57%
Mobile (Tag on Ziploc® only)	3	75%	75%	33%	70%
Mobile (Tag on Ziploc® only)	4	100%	67%	67%	78%
Mobile (Item level only)	5	63%	50%	33%	52%
Mobile (Item level only)	6	100%	83%	33%	83%
Mobile (Item level only)	7	88%	75%	67%	78%
Mobile (Item level only)	8	100%	92%	100%	96%

The results from the two experiments were then used to create an optimal experimental setup that would produce the highest percentage of reads. This is exemplified in Trials 4 and 5 of Table 5, where two antennas were setup per side at a distance of one foot from the CTB (antennas were 4 feet apart). The items used in this study had different properties and therefore a single tag may not be effective on all items. Three tag types from three separate manufacturers were used in combination on items within the CTB to achieve consistent reads. The number of antennas, placement of the antennas, and distance from the tags were evaluated to determine the most effective setup.

6.0 Summary of Results

Research Study # 1 was performed to identify the best overall tags that would be suitable for item level tagging of consumables and supplies. The tags were selected based upon read range, orientation, and performance on three materials (cardboard, metal, and liquid). The two tags that produced the highest read rates on all materials and met NASA requirements were selected for further testing at the item level. These tags were the Omron Scorpion tag and the Avery Dennison 820/821 tag. Another tag, which was not available at the time of Research Study # 1, was selected for the second study as well. This tag, the Omni-ID Prox, was designed to have improved performance on RF-unfriendly materials and was determined to be a suitable tag for liquids, gels, and metallic materials.

Research Study # 2 was performed to evaluate the performance of the selected tags directly at the item level. The tagged items were densely packed into both a CTB bag and a cardboard container. A sequential DOE approach was used to progressively improve the percentage of tags read within the container. Tags that were not read were adjusted by trying all three tags, repositioning the tag on the item, and adjusting the reader antenna configuration. It was determined that all consumables and supplies could be identified at the item level when used with the correct tag for that item. The fixed reader setup produced quicker and more accurate read rates than the mobile handheld reader. It was found that a fixed portal antenna configuration produced 100% read rates, depending on the orientation of the items within the CTB.

7.0 Limitations

This study is limited to one type of basic RFID software and Gen 2 passive tags that were available from VerdaSee Technologies, Inc.

7.1 Other Observations

The previous Gen 1 study was more inclusive of technologies and RFID standardization was not as coordinated as at the time of this new study. For implementation anywhere into the supply chain, it is advantageous that Gen 2 is more standardized than Gen 1. A direct comparison of the data from the Gen 1 and Gen 2 studies was not performed; however, the problems encountered with liquid and metal in the Gen 1 study were overcome in the Gen 2 study by the addition of specialized tags.

Also, it was noted by the research team that the mobile reader software provided for this study is not an inventory application demo. It is a manufacturer’s application used solely for demonstrating the ability to scan an RFID Gen 2 chip embedded in a tag form factor. Any future testing will include inventory management applications for use in RFID handheld scanners. The fixed reader software by VerdaSee can be used as a development platform and can easily be modified to fit the user's needs. Software was not one of the focuses of this study, however, and further research could be performed to compare other available software packages.

8.0 Conclusions

RFID technologies present the opportunity for reduced manual inventory efforts. Current barcode techniques provide traceability but at the expense of tedious manual labor. The previous generation of RFID technologies showed potential benefits, however previous studies by Jones (2005) have demonstrated that complete automated inventory audits were not possible.

Progressive developments in Gen 2 RFID tags are reducing the problems associated with liquid and metal materials, as well as orientation issues. The objective of this study was to investigate and evaluate the technology to determine if it is a viable option for an inventory control system that would significantly reduce labor time. Utilizing the DFSS-R methodology derived in the RfSCL at the University of Nebraska, Gen 2 automated inventory auditing capabilities were tested.

Throughout this testing, the items that were not read successfully were adjusted until a consistent read was produced. This was accomplished by testing all three of the selected tags and adjusting the placement of the tag on the item and/or the positioning of the item within the CTB. It was discovered in Research Study # 1 that the material that the tag was attached to had the greatest effect on the probability of producing a consistent read. It was then determined that tags designed for RF-unfriendly materials, were readable on metallic-based and liquid-based items while the standard tags produced low read rates or no reads. These items were read nearly 100% of the time at the item level using this liquid/water designated tag. A 100% read rate was not consistently achieved due to orientation and blocking issues.

It was determined that all items within the CTB could meet the read specifications using a combination of the three tags that were selected. The biggest challenge presented is the orientation of those items within the CTB bag. If the tags come in contact with one another, blocking can occur and the tag will not be read. A fixed, four antenna, portal configuration provided excellent results when the antennas were within 1 – 2 feet of the CTB since it reduced the effect of tag orientation.

The mobile handheld reader was able to read 100% of the tags when the reader was moved around all sides of the CTB, depending on the orientation of the tags. The limiting factor for mobile reader applications is the antenna gain. Increasing the power output of the reader may reduce the need to either spin the CTB or move the reader around the CTB in order to read every tag within the CTB. An increase in power may also reduce the chance of missing tags due to orientation issues and could increase read distance as well.

As expected, the Gen 2 RFID tags still had some problems with liquid and metal based materials. Liquid and gel type materials proved to be much more detrimental than metal based materials, however, the tags designated for liquid and water materials easily overcame the readability issues. It was concluded that Gen 2 tags have improved over Gen 1 tags; however, in a multiple tag environment other issues deter the consistency of the tags, the most significant of which is packing orientation and blocking issues.

Summarizing the results, the main conclusions drawn from this study are:

Benefits

1) Gen 2 technologies have shown performance improvements over Gen 1.
2) Problems still persist with tagging metal and liquid materials; however, specialty tags have been developed that have shown significant improvements on these materials.
3) Stationary readers such as smart shelves or door portal configurations shown in Figure 5 in this study proved to be successful with a four antenna portal configuration.
4) Stationary passive readers are generally more accurate and provide longer read ranges than mobile readers.
5) Both the mobile and fixed RFID systems were capable of reading data from multiple densely packed tags at short distances (less than 1feet).

Challenges

1) Antenna gain is the limiting factor for mobile reader applications. The CTB must be scanned at close proximities in order to read all the tags inside it.
2) Stationary readers such as smart shelves or door portal configurations shown in Figure 5 require power and room to be mounted.
3) Performance in stacking conditions or buried conditions (multiple CTB's) is very poor (low read rates or no reads) due to attenuation issues and increased distance between the desired tag and the reader antenna. This indicates that location based applications will not be successful with passive tags due to increased interference or blockage/attenuation issues.
4) Handheld demo software is not inventory application specific. Inventory management applications for use in RFID handheld scanners would need to be developed prior to implementation.
5) In order to ensure higher read accuracies on RF unfriendly inventory, liquid/metal specialty tags may need to be used. The specialty tags were not tested on all items at once inside the CTB and there is a possibility that performance will be degraded when multiple tags are present in close proximity of each other. This issue would need to be further investigated.

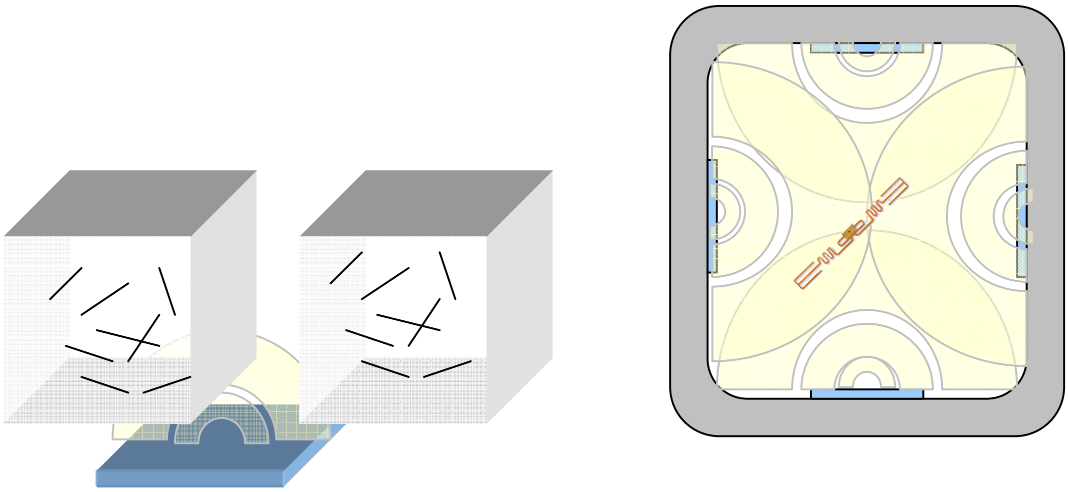


Figure 5: Smart shelf concept and door portal configuration diagram.

Summary of the Gen 2 tags:

1) The Omron Scorpion tag demonstrated higher read rates than other tags included in the study; however, they demonstrated low read rates or no reads for most RF-unfriendly materials (liquid and metal).
2) The Avery Dennison 820/821 tag demonstrated improved performance over the Omron Scorpion (higher average read rate) on metallic based items.
3) The Omni-ID Prox tag demonstrated the best overall performance on most RF-unfriendly materials (included all liquids and metals).

9.0 Recommendations

RFID from Manufacture to Space use:
The cost effectiveness of using a standard RFID technology such as Gen 2 RFID technologies is driven by exploitation and use of the technology earlier in the supply chain. NASA as an end user of consumables and supplies can receive a large benefit by the use of RFID tagged items. By having the manufacturer or distributor apply reliable Gen 2 tag to items early in the supply chain (manufacturing or warehousing), other supply chain partners (distributors, retailers, and end users) can utilize the tracking and tracing benefits to reduce costs and increase efficiencies. Opportunities such as integration into warehouse management, ERP, and inventory control systems can be realized due to the fact the RFID data capture is standardized. NASA and other end users can leverage the fact that RFID technologies can be read and written to, which can further leverage the technology. After the technologies have been procured, NASA can perform end user functions such as identify which mission, which astronaut, and or which crew vehicle inventory is assigned to. Other benefits such as implantable subzero temperature usage, and biometrics have promise in the future. The benefit of automatically capturing information at the asset and item level from manufacturer to its end use in space is the potential opportunity for using RFID technologies at NASA.

UNL's RfSCL envisions that RFID technologies can be used for three functions: tracking, tracing, and locating. The tracking function in an RFID system is what was tested in this study. Tracking consists of an RFID tag that is identified by a reader and therefore its immediate location is known, regardless of past history. Tracing is similar to tracking, but involves the historical documentation throughout the supply chain, from point of manufacture to end use. Locating technologies identify the real-time location of the tag within a confined space. Locating may require more equipment (i.e. 3 reader set-ups for triangulation) or more advanced and costly RFID technologies such as active RFID tags that contain an onboard battery to power the tag. If actively locating of an item is a requirement (i.e beeping tags), passive tags may not viable and other technologies will need to be evaluated.

For tracking purposes the recommendations are as follows:

1) Investigate the feasibility of increasing antenna gain and/or output power for mobile readers
    a. A modified COTS approach should be investigated for mobile readers
2) Investigation of NASA defined (using NASA operational materials such as metals and door opening) portal configurations should be investigated for fixed readers.
3) Investigate the feasibility of increasing antenna gain and/or output power for fixed reader configurations such as smart shelves.

4) Investigate the smart bag prototypes such as UNL's Sensor Active Tag (2005) idea for item level tracking
5) Investigate the use of semi-active Gen 2 (ISO 18000 part 1-6) standard tags and active RFID tags that adhere to the (ISO 18000 part 7 new standard)

For tracing purposes the recommendations are as follows:

1) Investigate the feasibility of RFID software to integrate with NASA inventory control systems to trace inventory information. For example: RFID software VerdaSee Navigator's ability to tie into NASA's IMS
2) Investigate the feasibility of creating user friendly mobile reader application
   a. A modified COTS approach should be investigated

For locating purposes the recommendations are as follows:

1) Investigate RFID based Real Time Location Systems ability to locate items in NASA type closed containers including, rooms, containers, CTB, boxes, and cases. This testing should include stacked or buried conditions for the tags and the containers. Similar to the final stacking testing that was performed in this study.

Hybrid tracking and locating

1) Investigate an RFID active (ISO 18000) and Gen 2 semi-active technology configuration that can be used with a container such as a CTB. This type of technology would increase accuracy and read ranges to the parent reader. This configuration will allow for:
   a. Tracking capabilities using the semi-active technology for scanning the contents within the container and the active technologies to provide battery assisted signals for location of the container. An example for this design is the UNL's SAT design from 2005. A schematic of this configuration is shown below in Figure 6.

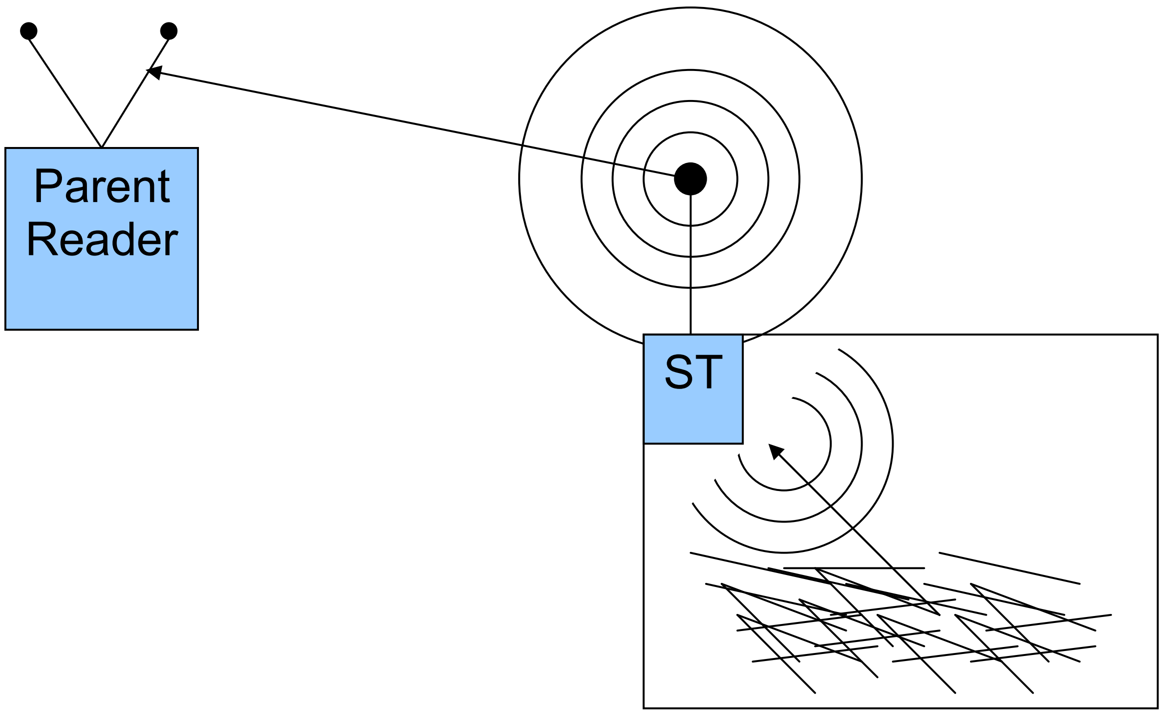


Figure 6: Sensor Active Tag (SAT) Diagram

RESEARCH STUDY # 1

1.0 Introduction

This is an initial progress report of the results of tag testing at the Radio Frequency and Supply Chain Logistics Lab. These lab tests represent "ideal" circumstances by which the tag and readers are tested for readability in a controlled environment. These results are considered the benchmark for this study, meaning that all other tests of these tags will be compared against the performance of these tags under lab conditions.

It has been determined that the Design for Six Sigma Research (DFSS-R) Method developed at the University of Nebraska – Lincoln as a derivative of traditional Six Sigma Methodology will be the cornerstone for these experiments. Using this method to keep the design of experiments consistent throughout all stages of testing, a more accurate definition of the tag capabilities can be assessed.

2.0 Background

In this study, the research method derived by the RFSCL at UNL called Design for Six Sigma Research (DFSS-R) is being utilized. It is based on a Plan-Do-Check-Act (PDCA) strategy and is a hybrid version of common Six Sigma and Design for Six Sigma methods. With the fusion of traditional research methods with industry's new gold standard, Six Sigma, into a methodology we describe as DFSS-R. The methodology is based on a strategy to develop operational prototypes and is organized into a Plan, Predict, and Perform (3P) model shown in Figure 1 (Report 1).

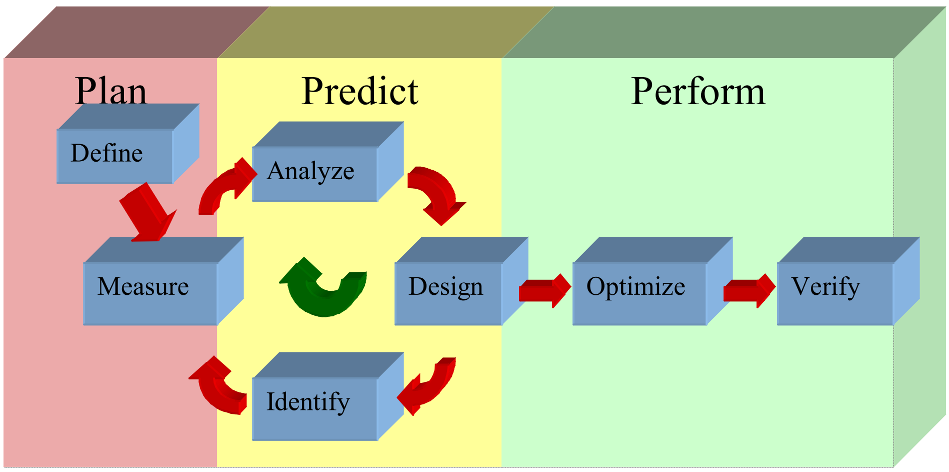


Figure 1 (Report 1): DFSSR 3P's Methodology.

The Define, Measure, and Analyze portions detail the Plan and Predict phases of this methodology. In these phases, experiments are conducted, measured and evaluated. The later perform phase has not been utilized because the scope of this project is to determine the capabilities of these tags rather than improve upon previous design.

This research was motivated by NASA's need for an RFID Inventory Management System (IMS). All equipment used for this experiment is off-the-shelf technology that is commercially available. VerdaSee Technologies has provided the tags, readers, and laptop computer used for this study to the lab. Table 1 (Report 1) is a detailed list of the equipment used including the supplier, model, and quantity, while Table 2 (Report 1) lists the 10 different tags that were tested in this experiment.

Table 1 (Report 1): Equipment Inventory List.

Number	Item Model	Item Description	Supplier
1	WORKABOUTPRO	HANDHELD TERMINAL	PSION TECKLOGIX
2	WA4003-G2	DOCKING STATION DESKTOP KIT	PSION TECKLOGIX
3	RA2041	RADIO SUMMIT 802.11G CF WEP128	PSION TECKLOGIX
4	WA3010	BATTERY PACK ASSY HIGH CAP	PSION TECKLOGIX
5	V750-BA50C04-US	V750 NEW READER 915MHZ	OMRON
6	V740-HS01CA	MONO STATIC ANTENNA	OMRON
7	V740-A01 10M	ANTENNA CABLES	OMRON

Table 2 (Report 1): Tag Inventory List.

Number	Item Model	Tag Description
1	NINJA-V750-D22M03-IM	OMRON GEN2 UHF TAG
2	AD-222	AVERY GEN2 UHF TAG
3	AD-820/AD-821	AVERY GEN2 UHF TAG
4	AD-431	AVERY GEN2 UHF TAG
5	WAVE-V750-D22M01-IM	OMRON GEN2 UHF TAG (INLAY ONLY)
6	SCORPION-V750-D22M04-IM	OMRON GEN2 UHF TAG
7	AD-622	AVERY GEN2 UHF TAG
8	LOOP-V750-D22M02-IM	OMRON GEN2 UHF TAG
9	AD-812/AD-811	AVERY GEN2 UHF TAG
10	WAVE-V750-D22M01-IM	OMRON GEN2 UHF TAG (WITH LABEL)

The tags consisted of nine unique tags from Avery Dennison and Omron. Tag 5 and Tag 10 are the same tag; however, Tag 5 is in the inlay from, while Tag 10 was attached to an adhesive label. A single tag of each type was used for all testing.

3.0 Methodology

A controlled test was performed in the RFID Lab at the University of Nebraska-Lincoln to compare the performance of the 10 different tags that were received. The dependent variable was chosen to be the number of reads per second, which gives a good comparison of the read strength when the independent variables are introduced. The number of successful reads was also recorded and used as another means for comparison.

Testing of each of the 10 tags incorporates a 3 x 6 x 2 experimental design with the three independent variables being: material type (3 levels), tag orientation (6 levels), and distance from the reader antenna (2 levels). This gives a total of 36 trials per tag. Each tag was tested on three material types: cardboard, metal (aluminum), and liquid (bottled water). For each of those materials, the object was placed in six orientations, which are listed in Table 3 (Report 1) and can also be seen in Figure 2 (Report 1) through Figure 4 (Report 1).

Table 3 (Report 1): Tag Orientations.

Orientation	Description
1	Tag Facing Reader - Orientated 0° from Horizontal
2	Tag Facing Upward - Orientated 0° from Horizontal
3	Tag Facing 90° from Reader - Orientated 0° from Horizontal
4	Tag Facing Reader - Orientated 90° counter-clockwise from Horizontal
5	Tag Facing Upward - Orientated 90° counter-clockwise from Horizontal
6	Tag Facing 90° from Reader - Orientated 90° counter-clockwise from Horizontal

Orientation 1 Orientation 2 Orientation 3

Orientation 4 Orientation 5 Orientation 6

Figure 2 (Report 1): Tag Orientations – Material 1 (Cardboard).

Orientation 1 Orientation 2 Orientation 3

Orientation 4 Orientation 5 Orientation 6

Figure 3 (Report 1): Tag Orientations – Material 2 (Metal).

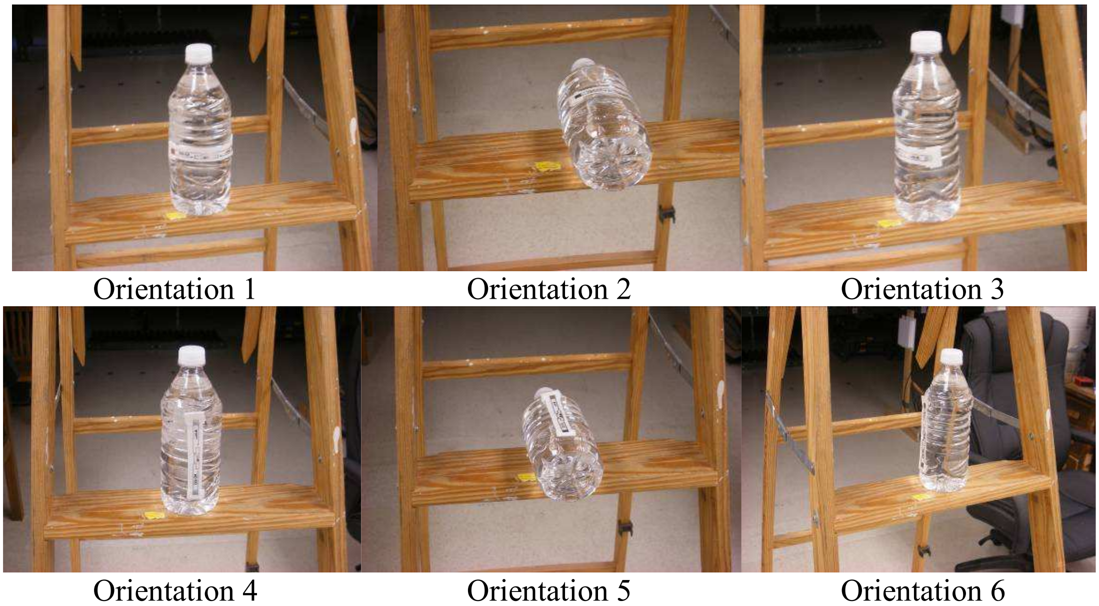


Figure 4 (Report 1): Tag Orientations – Material 3 (Liquid).

The setup consisted of an Omron V750 Reader/Writer and a single Omron V740 antenna. Tags were placed at the same height as the reader antenna for all testing. Data was collected using Navigator 2008 software by VerdaSee Solutions, Inc.

The tags will be tested at two distances: close range (5 feet) and mid range (10 feet). Tags have not been tested at the maximum distance of the reader.

4.0 Results

After completion of the testing at a distance of 5 feet, it was determined that Tag 1 (Omron Ninja) was only capable of being read within 4 feet and thus was excluded from the analysis. The data was analyzed using MINITAB ver. 14.1 statistical software. When we compare the scanning results at 5 feet using an alpha value of 0.05 (5 % chance we are making an erroneous conclusion (Type I error), we discovered that the material type is the most significant factor. All nine tags were readable on the cardboard material; however, only three of those tags were readable on the metal and liquid materials. The tag type was found to be statistically significant; meaning the average performance of all tags was not equal. Finally, the tag orientation was also statistically significant. The orientation is the least significant independent variable and has the least effect on the outcome of the test. The average reads per second are plotted by each variable in Figure 5 (Report 1).

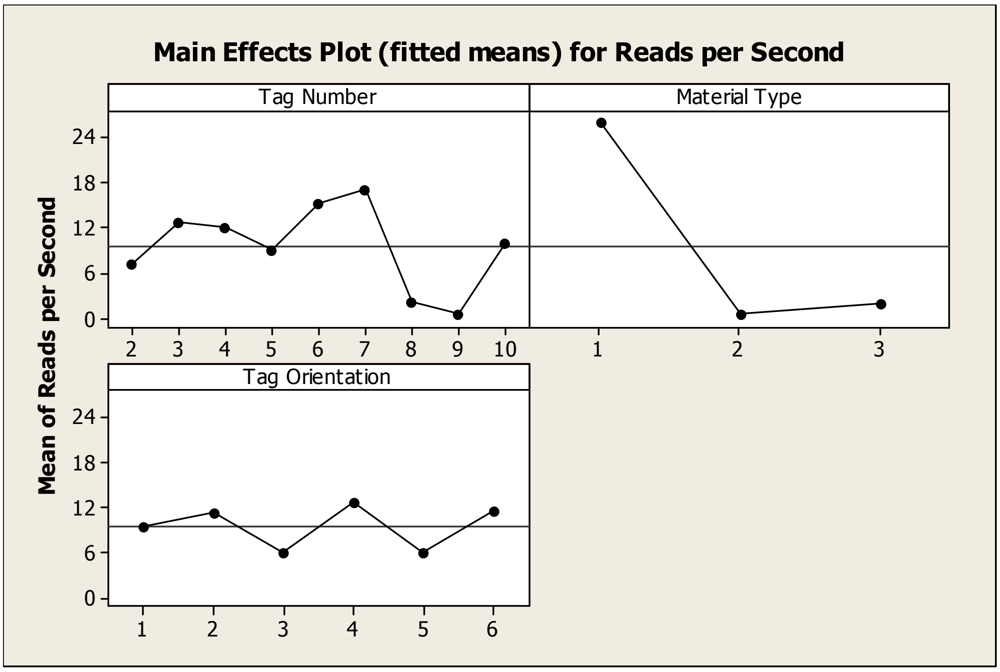


Figure 5 (Report 1): Main Effects Plot for Number of Reads per Second.

Two of the three 2-way interactions were also found to be statistically significant. Tag Number by Material Type and Material Type by Tag Orientation were found to be significant, while Tag Number by Tag Orientation was found to be not significant. The interactions are shown in Figure 6 (Report 1) and Figure 7 (Report 1) below.

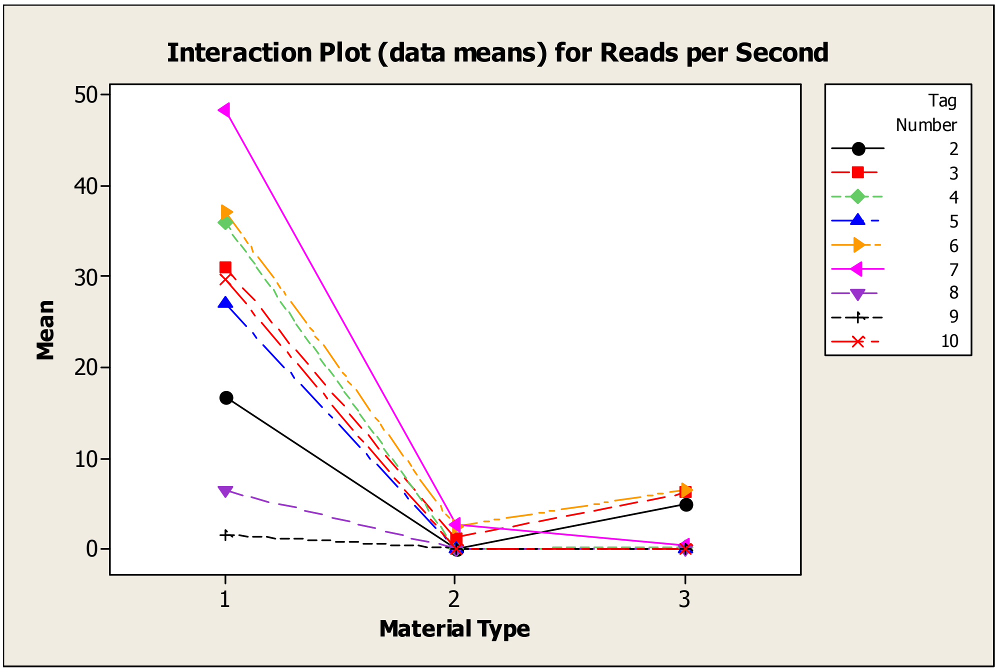


Figure 6 (Report 1): Tag Number by Material Type Interactions.

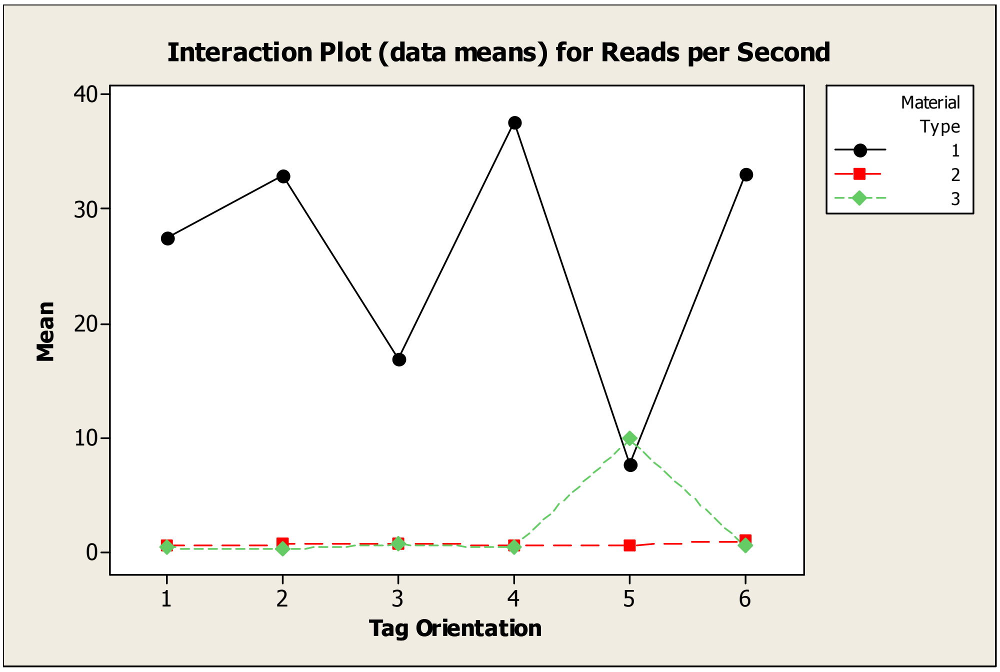


Figure 7 (Report 1): Material Type by Tag Orientation Interactions.

Summary of Tag Readability

At a distance of 5 feet from the reader antenna, only Tag 3 (AD 820/821) and Tag 6 (Omron Scorpion) were read 100% of the time on all three materials. Tag 7 (AD 622) also performed nearly perfect on all three materials, but was only read approximately 83% of the time on the liquid material. As previously mentioned, Tag 1 was not readable on any of the materials and it was determined that this particular tag is only suitable for close range applications.

When the tags were moved back to a distance of 10 feet from the reader antenna, similar results were produced. However, at 10 feet from the reader antenna, none of the tags were read 100% of the time. This is due to both a weaker RF signal further from the reader and the varying antenna designs. Tag 1 (Omron Ninja) and Tag 9 (AD 812/811) were not readable under any conditions. It was also found that none of the tags were readable when placed directly on the metal or water at this distance. This shows that the read strength decreases rapidly as the tag moves away from the antenna.

Of the nine tags that were readable at a distance of at least 5 ft., eight of them were readable 100% of the time on cardboard, while one was readable only 50% of the time. The reflective properties of the metal material proved to be a detrimental factor, as only three tags were read 100% of the time and the remaining six tags were not read at all. Finally, the liquid-filled water bottle had varying effects on readability, as only half of the tags were able to be read at all. Two tags were read 100% of the time, one tag was read approximately 83% of the time, two tags were readable 15% – 35% of the time, and five tags were not readable at all.

5.0 Conclusion/Discussion

As expected, the material type was found to be an important factor in the performance of the tag. Only three of the tags performed exceptionally well when placed on either a metal or liquid substance. The tag type was also a significant factor since some tags did perform better than others. Finally, tag orientation was found to be statistically significant; however, it has very little effect compared to the material type.

There were also significant 2-way interactions present in the test. The Tag Number by Material Type interaction was significant, which was evident since some tags performed better than others on different material types. The Material Type by Tag Orientation was significant because certain orientations cause the radio waves emitted from the reader to be more susceptible to deflection or absorption on the different materials.

The three best performing tags that were selected for the second phase of testing are:

1. Omron Scorpion
2. Avery Denison 622
3. Avery Denison 820/821

The second phase of testing will consist of individual testing of each of the three tags on all items that will be placed inside the CTB bags for use onboard a space vehicle or habitat.

RESEARCH STUDY # 2

1.0 Introduction

The scope of this project has been to make the determination as to the performance of Gen 2 RFID tags when used in the confines of a Cargo Transport Bag (CTB) and the feasibility of tagging the contents of these CTBs by item level versus only tagging the Ziploc® bags containing specified items. This report details the results of CTB testing with Gen 2 RFID tags at the Radio Frequency and Supply Chain Logistics Lab (RfSCL) at the University of Nebraska - Lincoln. These lab tests represent "ideal" circumstances by which the tag and readers are tested for readability. These results are considered the benchmark for this study, meaning that all other tests of these tags will be compared against the performance of these tags under lab conditions.

The methodology for this project is outlined by the Design for Six Sigma Research (DFSS-R) Method developed by the RfSCL lab. This technique was developed as a derivative of traditional Six Sigma Methodology for use in research areas, which has been determined to be the foundation for these experiments. By using this method to keep the design of experiments consistent throughout all stages of testing; a more accurate definition of the tag capabilities has been assessed.

2.0 Background

The NASA Constellation Program has elected to evaluate RFID technologies for a new Inventory Management System (IMS). Currently, NASA's astronauts spend hours tracking inventory using a barcode reader system. The use of RFID would eliminate the need for astronauts to manually track consumables. These consumables include food, tools, and other supplies; however, the consumables used in this study were limited to hygienic products, office supplies, and clothing. This study is also designed to identify passive RFID's current abilities to locate products within cargo transport bags (CTB) in an environment with multiple CTB's. In 2005, the RfSCL was given a similar research grant by the International Space Station Program to study the use of Gen 1 tags to complete the aforementioned task. The results of the previous research concluded that Gen 1 RFID tags did not meet the required specifications of greater than 99% accuracy and therefore surface acoustic wave (SAW) tags were selected for future studies. SAW tags, however, are not the standard and there is a desire to re-evaluate the current state of Gen 2 technologies. With the advent of Gen 2 technology, many deficiencies of Gen 1 have been rectified. Of the benefits associated with Gen 2 technology over Gen 1, the following traits have been considered for this study:

- Gen 2 tags have a lower cost per tag as compared to Gen1. The ability to keep costs down is an incentive to investing in RFID technologies rather than using traditional methods of inventory management.
- Gen 2 tags are more standardized due to recent mandates which have allowed versions of these tags to be created that are smaller and have less mass than Gen 1 tags.
- Gen 2 has an increased read range with lowered probability of interference which allows for item level tracking instead of merely tracking containers. The inability of Gen 1 tags to be used in item level tracking was a downfall that Gen 2 should rectify.

- Gen 2 offers increased security as compared to Gen 1 tags. The unique identifiers of these more secure tags make them more reliable and therefore a better solution for tracking items from the manufacturing phase to their use in space.
- New Gen 2 tags have been developed for improved performance on liquid and metal materials.

All equipment used for this experiment is commercial off-the-shelf technology (COTS). The tags, readers, and laptop computer used for this study have been provided to the RfSCL lab by VerdaSee Technologies. Table 1 (Report 2) is a detailed list of the equipment used including the supplier, model, and quantity, while Table 2 (Report 2) lists the 4 different tags that were tested with this experiment.

Table 1 (Report 2): Equipment Inventory List.

Number	Item Model	Item Description	Supplier
1	WORKABOUTPRO	HANDHELD TERMINAL	PSION TECKLOGIX
2	WA4003-G2	DOCKING STATION DESKTOP KIT	PSION TECKLOGIX
3	RA2041	RADIO SUMMIT 802.11G CF WEP128	PSION TECKLOGIX
4	WA3010	BATTERY PACK ASSY HIGH CAP	PSION TECKLOGIX
5	V750-BA50C04-US	V750 NEW READER 915MHZ	OMRON
6	V740-HS01CA	MONO STATIC ANTENNA	OMRON
7	V740-A01 10M	ANTENNA CABLES	OMRON

Table 2 (Report 2): Tag Inventory List.

Number	Item Model	Tag Description
1	AD-820/AD-821	AVERY GEN2 UHF TAG
2	AD-622	AVERY GEN2 UHF TAG
3	SCORPION-V750-D22M04-IM	OMRON GEN2 UHF TAG
4	OMNI-ID PROX	OMNI-ID GEN2 UHF TAG

3.0 Problem Statement

In an effort to create the most effective, expeditious, and user-friendly IMS for NASA's astronauts, the Constellation Program has decided to test RFID technologies. Previously, the International Space Station (ISS) Program investigated using Gen 1 RFID tags for inventory management; however, the tags did not meet the required specifications. The more recent Gen 2 tags are now under consideration for tracking and location purposes by the Constellation Program. Furthermore, this study also will demonstrate the difference in tag performance based on tag placement at the item level as opposed to tagging a Ziploc® bag containing the item. Previously, ISS used Ziploc® bags to package some consumables. This study expands the package requirement to investigate tags on the Ziploc® bags as well as tags directly at the item level.

4.0 Methodology

In this study, the research method derived by the RFSCL at UNL called Design for Six Sigma Research (DFSS-R) was utilized. It is based on a Plan-Do-Check-Act (PDCA) strategy and is a hybrid version of common Six Sigma and Design for Six Sigma (DFSS) methods. This technique boasts the fusion of traditional research methods with industry's new gold standard, Six Sigma, into a methodology described as DFSS-R.

This methodology is based on a strategy to develop operational prototypes and is organized into a Plan, Predict, and Perform (3P) Model that utilizes 7 steps: Define, Measure, Analyze, Identify, Design, Optimize and Verify (DMAIDOV). In this report, the results are described within the scope of the Plan and Predict phases of this methodology by detailing the Define, Measure, and Analyze steps.

The Plan phase has two steps. In the first step (Define), the RFID technologies described by Tables 1 and 2 are reviewed to determine the best performers based solely on lab results tested with representative materials. In the second step (Measure), the best performers were separated from the group to create a control group of four tags (Table 2, Report 2). The performance of Gen 2 RFID tags inside the CTB containing the individually tagged items was tested and recorded.

In the Predict phase only the Analyze step was used in this study. In the Predict phase, a CTB packed with tagged items was scanned with a mobile reader on five sides (excluding the bottom) and a fixed reader using up to four antennas in multiple configurations. When using a mobile reader, the CTB is scanned from only five directions, since the bottom of the CTB cannot be scanned when placed in a static condition. In this study, the fixed antennas were mounted in a vertical position with up to two antennas per side. In a four-antenna configuration, the setup replicates a door portal in which the CTB would pass through (refer to Figure 2, Report 2). The performance of each reader was recorded and the results were tested for statistical significance using Minitab 14.1.

Plan – Define

Due to the failure of the Gen 1 tag to meet the required specifications of greater than 99% accuracy, the researchers believe that Gen 2 testing be performed under similar conditions to determine if a change in outcome exists. This study will test products provided by VerdaSee that are being considered by the NASA Constellation Program. A tag comparison study (Research Study # 1) was completed in the RFID Lab at the University of Nebraska-Lincoln to determine the best performing tags on materials such as cardboard, metal, and liquid. From an initial group of ten tags tested, three were picked as top performers to continue testing. The number of successful reads was used as a basis for comparison and the percentage of tags read was calculated. The three best performing tags that were selected for this phase of testing are:

1. Omron Scorpion
2. Avery Denison 622
3. Avery Denison 820/821

A controlled test was then performed using these tags to compare them at the individual item level. The tags were tested at the item level, given a list of items that are packed into a standard CTB bag. The items are divided into three main categories: Clothing, Hygiene, and Office Supplies. The items tested in this study are listed in Table 3 (Report 2). According to the product sheets provided by NASA, the three types of items are bagged separately. For this study, the item types will be referred to as B1 for Clothing, B2 for Hygiene, and B3 for Office Supplies. Cardinal Directions were used as nomenclature for the sides of the bag. North describes the side of the bag to which the flap opens away with South being side where the "hinge" of the bag is located. East and west are the sides of the bag respective to the north and south. The top of the bag describes the flap of the bag when closed with the bottom of the bag being the side parallel to the top. The products within the CTB were organized according to the three main categories, using inventory lists provided by NASA. For clarification, Figure 4 (Report 2) illustrates the actual CTB with a map of products within the bag based on type.

Table 3 (Report 2): Item Inventory List.

Clothing (B1)	Hygiene (B2)	Office Supply (B3)
Athletic Shorts	Rubber Gloves	Batteries
Athletic T-Shirt	Shave Cream	Microcassette
X-Static Socks	Hand Cream	Ink Cartridge
X-Static Shirt	Toothpaste	
	Toothbrush	
	Razor	
	Razor Blades	
	Floss	
	Huggies Wipes	
	Drinking Pouches	
	Shampoo	

Plan – Measure

After an initial evaluation of the items, it was determined that even though the AD 622 tag performed well, the tag's large size (4" x 4") made it difficult for use at the item level tagging and was excluded from this phase of testing. The Omron Scorpion and AD 820/821 tags are similar in size (3" x 1.5") and were easily attached to most items. The final tag utilized in this study was the Omni-ID Prox tag which consists of a trivial spacer between the antenna and the adhesive that allows better performance on traditionally non-RF friendly materials including some metal and liquid or gel materials. This tag was not part of the initial group that was previously tested for selection of top performers. However, this newly available tag is reputed to be a good tag for metal and liquid items, and is included in this item level test. This tag is shown attached to the ink cartridge and toothpaste in Figure 1 (Report 2).

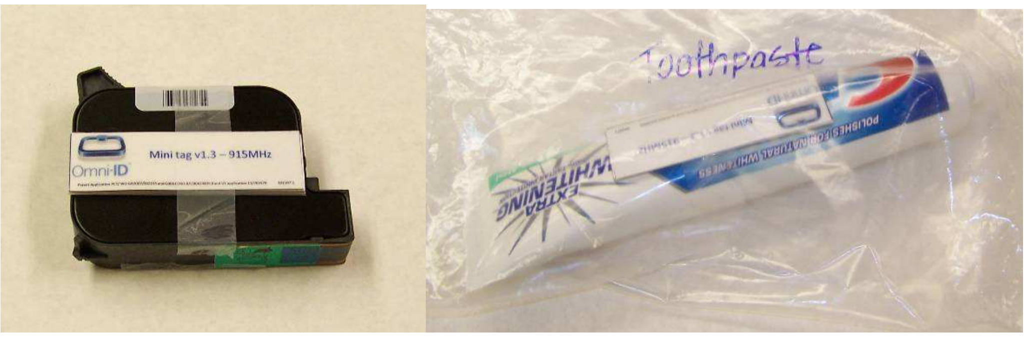


Figure 1 (Report 2): Omni-ID tag attached to ink cartridge and toothpaste.

Testing consisted of several progressive steps:

Test 1: Full CTB with all items randomly packed; Tags placed on Ziploc® bags
Test 2: Full CTB with all items randomly packed; Tags placed directly on items
Test 3: Partial CTB with arranged packing configuration; Evaluation of RF-unfriendly materials
Test 4: Partial CTB with arranged packing configuration; Container comparison using cardboard box
Test 5: Pallet configuration with arranged packing configuration; CTB buried in a pallet of partially packed cardboard boxes

The fixed reader setup consisted of an Omron V750 Reader/Writer and up to four Omron V740 antennas. Antenna configuration for the fixed reader can be seen in Figure 2 (Report 2). Data was collected using Navigator 2008 software by VerdaSee Solutions, Inc. The handheld Psion mobile reader was also utilized for some of the tests.

Figure 2 (Report 2): Fixed Antenna Configuration.

5.0 Results

Predict – Analyze

The data was analyzed using MINITAB ver. 14.1 statistical software. The results were compared using an alpha value of 0.05 (5 % chance we are making an erroneous conclusion (Type I error).

Test 1: Full CTB with all items randomly packed; Tags placed on Ziploc® bags
Test 2: Full CTB with all items randomly packed; Tags placed directly on items

The first initial test was performed with a mobile reader placed less than one foot away and a fixed reader with a single antenna placed 5 feet away from a full CTB. Clothing, hygiene items, and office supplies were all packed randomly into the CTB. All items were packed into Ziploc® bags and the Omron Scorpion tags were placed on the bags. Table 4 (Report 2) illustrates the results of Tests 1 and 2. Trials 1 and 2 of the fixed reader setup correspond to the Ziploc® level tagging, while trials 3 and 4 correspond to the item level tagging. For the mobile tests, trials 1 through 4 correspond to the Ziploc® level tagging and trials 5 through 8 correspond to the item level tagging. Tests 1 and 2 were performed in unison to allow for tag density to play a role in tag performance. Using the fixed reader for four trials, an average of 83% of the tags were read with a high of 96% during Trial 4. The mobile reader accomplished an average of 72% of the tags read with a high of 96% during Trial 8. The exception items, or RF-unfriendly materials which were missed, included x-static socks, shampoo, deodorant, batteries, and toothpaste. Test 3 further evaluates these items by applying alternate tags to achieve consistent reads. The successive trials in Table 4 (Report 2) indicate adjustments in the packing orientation and tag placement (i.e. adding spacers between the tag and item) to achieve better performance.

Table 4 (Report 2): Results of Tests 1 and 2.

Reader Type	Trial	B1(Clothing)	B2(Hygiene)	B3(Office)	Total
Fixed (Tag on Ziploc® only)	1	88%	58%	100%	74%
Fixed (Tag on Ziploc® only)	2	88%	83%	33%	78%
Fixed (Item level only)	3	88%	83%	33%	78%
Fixed (Item level only)	4	100%	100%	67%	96%
Mobile (Tag on Ziploc® only)	1	88%	92%	67%	87%
Mobile (Tag on Ziploc® only)	2	63%	50%	67%	57%
Mobile (Tag on Ziploc® only)	3	75%	75%	33%	70%
Mobile (Tag on Ziploc® only)	4	100%	67%	67%	78%
Mobile (Item level only)	5	63%	50%	33%	52%
Mobile (Item level only)	6	100%	83%	33%	83%
Mobile (Item level only)	7	88%	75%	67%	78%
Mobile (Item level only)	8	100%	92%	100%	96%

With the addition of a cardboard spacer to the tag on the water pouches, all tags except the toothpaste were read using the mobile reader (96% read rate – Trial 8). The cardboard spacer is shown in Figure 3 (Report 2). Cardboard was used as the spacer substrate because the cardboard offers very little interference to the RFID tag.

Figure 3 (Report 2): Cardboard spacer applied between tag and drinking pouch.

The direction of the CTB was also tested to further evaluate the tag orientation issues within the CTB. This was done by packing the CTB and scanning it with a single antenna from each side separately and recording the results. Table 5 (Report 2) illustrates tag performance for each item type based on the orientation of the fixed reader's antenna. The best tag performance was demonstrated by clothing when the reader antenna is facing the East and West sides of the CTB, each at 100% accuracy. Moreover, office supply products demonstrated the worst tag performance with read successes at 50% accuracy each when the reader antenna is facing the North and South positions of the CTB. This result supports the theory that tag liquid/gel materials detract from tag performance. On average, the most successful read rates were exhibited when the reader antenna is facing the East and West side of the CTB, obtaining 81% accuracy.

Table 5 (Report 2): Results Based on Antenna Orientation.

Reader Type	Direction	B1(Clothing)	B2(Hygiene)	B3(Office)	Total
(Single Antenna)					
Fixed	North	75%	69%	50%	67%
Fixed	East	100%	77%	75%	81%
Fixed	South	75%	77%	50%	71%
Fixed	West	100%	77%	75%	81%

The mobile reader also saw a slight decrease to 83% and missed similar items.

Test 3: Partial CTB with arranged packing configuration; Evaluation of RF-unfriendly materials

The third test was to evaluate the effect of multiple antennas, distance from the antennas, and tag orientation (movement of the CTB). The items were packed according to group (clothing, hygiene, office supplies) and the packing configuration can be seen in Figure 4 (Report 2). The antenna configurations were as follows: one antenna on one side of the CTB, two antennas in parallel at one side of the CTB, two antennas placed on opposite sides of the CTB, and four antennas with two antennas in parallel at opposite sides of the CTB.

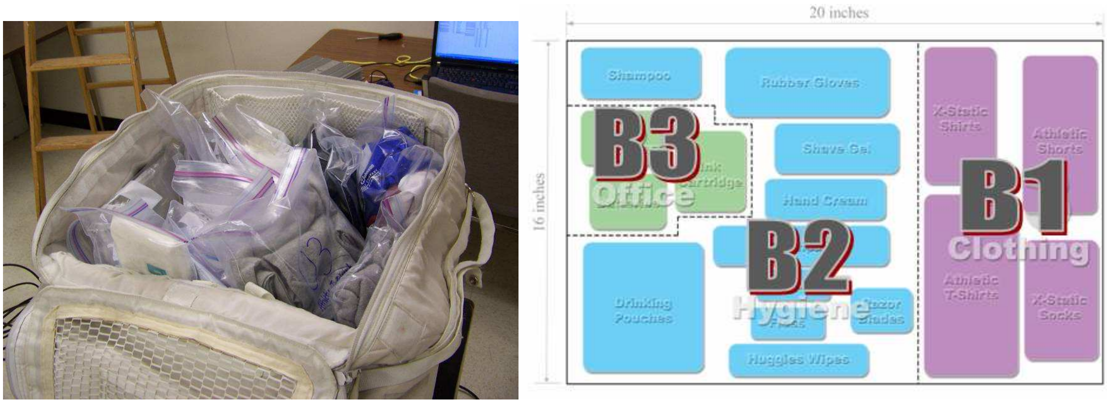


Figure 4 (Report 2): CTB Packing Configuration.

The results of this test can be seen in Figure 5 (Report 2). This figure represents data collected only with the fixed reader setup.

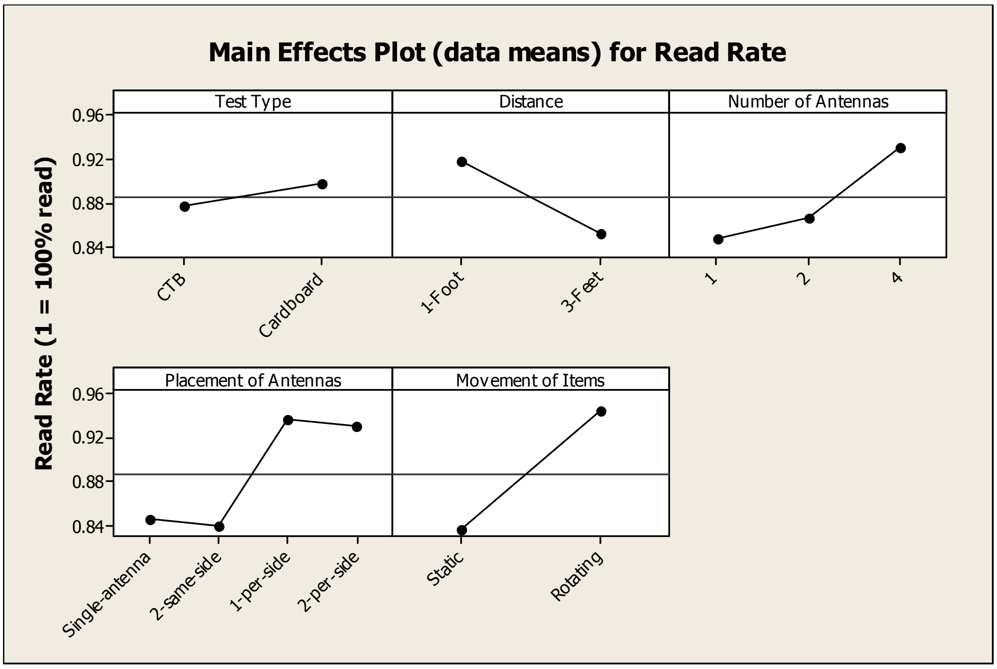


Figure 5 (Report 2): Significance of Main Effects for Test 3 & 4.

Figure 5 (Report 2) demonstrates that some factors have a much larger effect than others. As the distance of the tags from the antenna increases, a slight decrease in the read rate is expected. The probability that all tags are read increases significantly as the number of antennas increase. The data collected from the CTB test is shown in Table 6 (Report 2).

Table 6 (Report 2): Results of Testing in CTB.

Test Type	Trial Number	Distance (feet)	Number of Antennas	Antenna Placement	Movement of Items	B1 Clothing	B2 Hygiene	B3 Office	Number of Reads	Percentage
CTB	1	1	4	2 per side	Static	100%	85%	75%	20/23	87%
CTB	2	1	4	2 per side	Static	75%	92%	75%	19/22	86%
CTB	3	1	4	2 per side	Static	100%	92%	75%	20/22	91%
CTB	4	1	4	2 per side	Rotating	100%	100%	100%	22/22	100%
CTB	5	1	4	2 per side	Static	100%	100%	100%	22/22	100%
CTB	6	3	4	2 per side	Static	75%	92%	75%	19/22	86%
CTB	7	3	4	2 per side	Rotating	75%	100%	75%	20/22	91%
CTB	8	3	2	same side	Static	75%	69%	25%	14/22	64%
CTB	9	3	2	same side	Static	75%	100%	75%	20/22	91%
CTB	10	3	2	same side	Static	100%	69%	0%	14/22	64%
CTB	11	3	2	same side	Static	100%	100%	50%	20/22	91%
CTB	12	3	2	1 per side	Rotating	100%	100%	75%	21/22	95%
CTB	13	1	2	1 per side	Static	100%	92%	75%	20/22	91%
CTB	14	1	2	1 per side	Rotating	100%	100%	75%	21/22	95%
CTB	15	1	1	one side	Static	100%	54%	75%	15/22	68%
CTB	16	1	1	one side	Rotating	100%	100%	75%	21/22	95%
CTB	17	3	1	one side	Rotating	100%	100%	50%	20/22	91%

It was also noted that the antennas perform better when placed on opposite sides of each other rather than on the same side. This is due partially because some tags become blocked by other tags or materials and a symmetrical antenna setup reduces the chance of blocking. The most significant factor was determined to be the orientation of the tag within the CTB. When the CTB was held still in a static position, 84% of the tags were read (average of all static trials, Table 6, Report 2), however, when the CTB was rotated, the read rate increased to 95% (average of all rotating trials, Table 6, Report 2). Read rates were accomplished with 100% accuracy at both static and rotating bag movements when using the four antenna configuration with two antennas in parallel at opposite sides of the CTB spaced four feet apart.

Test 4: Partial CTB with arranged packing configuration; Container comparison using cardboard box

The next test was performed to determine if the CTB itself was degrading the performance of the tags. The tagged items were placed into a similar sized corrugated box and packed using the same configuration as in Test 3. This test was subjected to fourteen trials. These trials included trials at both one and three feet with 1, 2, and 4 antenna configurations with the box remaining static on a table or rotating. The antenna configurations were the same as Test 3 with the exclusion of two antennas placed on opposite sides of the cardboard box. As seen in Figure 5, there is only a slight difference in the read rate between the items packed into a CTB and the items packed into a cardboard box. This would lead us to believe that the CTB bag is not significantly degrading the performance of the RFID tags. Table 7 (Report 2) illustrates the results of tag performance from within the cardboard box of equal dimensions. The best results were when the cardboard box was rotating with two antennas on one side of the box and when four antennas are used with 2 on each side of the box at both the static and rotating positions. The worst tag performance occurred at 67% reads with one antenna and no movement. Read rates were accomplished with 100% accuracy at both static and rotating box movements when using the four antenna configuration with two antennas in parallel at opposite sides of the box spaced four feet apart.

Table 7 (Report 2): Results of Testing in Cardboard Box.

Test Type	Trial Number	Distance (feet)	Number of Antennas	Antenna Placement	Movement of Items	B1 Clothing	B2 Hygiene	B3 Office	Number of Reads	Percentage
Cardboard	1	3	1	one side	Static	50%	69%	75%	14/21	67%
Cardboard	2	3	1	one side	Rotating	75%	92%	100%	19/21	90%
Cardboard	3	3	1	one side	Rotating	75%	100%	75%	19/21	90%
Cardboard	4	1	1	one side	Static	50%	92%	75%	17/21	81%
Cardboard	5	1	1	one side	Rotating	100%	100%	75%	20/21	95%
Cardboard	6	1	2	same side	Static	75%	85%	100%	18/21	86%
Cardboard	7	1	2	same side	Rotating	100%	100%	100%	21/21	100%
Cardboard	8	3	2	same side	Rotating	100%	100%	100%	21/21	100%
Cardboard	9	3	2	same side	Static	75%	77%	75%	16/21	76%
Cardboard	10	3	4	2 per side	Static	75%	85%	75%	17/21	81%
Cardboard	11	3	4	2 per side	Rotating	100%	100%	100%	21/21	100%
Cardboard	12	1	4	2 per side	Static	75%	92%	100%	19/21	90%
Cardboard	13	1	4	2 per side	Rotating	100%	100%	100%	21/21	100%
Cardboard	14	1	4	2 per side	Static	100%	100%	100%	21/21	100%

Table 6 (Report 2) and Table 7 (Report 2) show the results of the fixed reader when reading items in the CTB and cardboard box tests. The CTB data was further analyzed to show the various effects of factors such as the number of antennas used, antenna configuration, and movement of the CTB. Table 8 (Report 2) shows the data separated by static or rotational movement and then sorted by the number of antennas. It can be seen that rotating the CTB produced more accurate reads than the static scenario. It is also clear that increasing the number of antennas will greatly improve the probability of producing 100% reads.

Table 8 (Report 2): Breakdown of CTB testing by Number of Antennas.

Test Type	Trial Number	Distance (feet)	Number of Antennas	Antenna Placement	Movement of Items	B1	B2	B3	Number of Reads	Percentage
CTB	4	1	4	2 per side	Rotating	100%	100%	100%	22/22	100%
CTB	7	3	4	2 per side	Rotating	75%	100%	75%	20/22	91%
CTB	12	3	2	1 per side	Rotating	100%	100%	75%	21/22	95%
CTB	14	1	2	1 per side	Rotating	100%	100%	75%	21/22	95%
CTB	16	1	1	1 per side	Rotating	100%	100%	75%	21/22	95%
CTB	17	3	1	1 per side	Rotating	100%	100%	50%	20/22	91%
Mean						96%	100%	75%		95%
Std Dev						10%	0%	16%		3%
CTB	5	1	4	2 per side	Static	100%	100%	100%	22/22	100%
CTB	2	1	4	2 per side	Static	75%	92%	75%	19/22	86%
CTB	3	1	4	2 per side	Static	100%	92%	75%	20/22	91%
CTB	1	1	4	2 per side	Static	100%	85%	75%	20/23	87%
CTB	6	3	4	2 per side	Static	75%	92%	75%	19/22	86%
CTB	9	3	2	same side	Static	75%	100%	75%	20/22	91%
CTB	11	3	2	same side	Static	100%	100%	50%	20/22	91%
CTB	13	1	2	1 per side	Static	100%	92%	75%	20/22	91%
CTB	8	3	2	same side	Static	75%	69%	25%	14/22	64%
CTB	10	3	2	same side	Static	100%	69%	0%	14/22	64%
CTB	15	1	1	1 per side	Static	100%	54%	75%	15/22	68%
Mean						92%	81%	50%		78%
Std Dev						13%	19%	32%		14%

Table 9 (Report 2) shows the CTB trials arranged by highest read percentage. It is clear from this table that rotating the CTB produces higher read rates than a static scenario. Also, the two trials that produced 100% reads utilized four antennas at a distance of four feet apart (one foot from the CTB).

Table 9 (Report 2): Breakdown of CTB testing by Read Percentage.

Test Type	Trial Number	Distance (feet)	Number of Antennas	Antenna Placement	Movement of Items	B1	B2	B3	Number of Reads	Percentage
CTB	4	1	4	2 per side	Rotating	100%	100%	100%	22/22	100%
CTB	5	1	4	2 per side	Static	100%	100%	100%	22/22	100%
CTB	12	3	2	1 per side	Rotating	100%	100%	75%	21/22	95%
CTB	14	1	2	1 per side	Rotating	100%	100%	75%	21/22	95%
CTB	16	1	1		Rotating	100%	100%	75%	21/22	95%
CTB	7	3	4	2 per side	Rotating	75%	100%	75%	20/22	91%
CTB	3	1	4	2 per side	Static	100%	92%	75%	20/22	91%
CTB	9	3	2	same side	Static	75%	100%	75%	20/22	91%
CTB	11	3	2	same side	Static	100%	100%	50%	20/22	91%
CTB	13	1	2	1 per side	Static	100%	92%	75%	20/22	91%
CTB	17	3	1		Rotating	100%	100%	50%	20/22	91%
CTB	1	1	4	2 per side	Static	100%	85%	75%	20/23	87%
CTB	6	3	4	2 per side	Static	75%	92%	75%	19/22	86%
CTB	2	1	4	2 per side	Static	75%	92%	75%	19/22	86%
CTB	15	1	1		Static	100%	54%	75%	15/22	68%
CTB	8	3	2	same side	Static	75%	69%	25%	14/22	64%
CTB	10	3	2	same side	Static	100%	69%	0%	14/22	64%

The data could be analyzed further by distance or antenna placement; however, these tables are not shown. A significant drop in performance is experienced as the tags move farther from the reader antennas. A small (4 ft. by 4 ft.) portal configuration would eliminate unsuccessful reads due to read ranges. This would also be the recommended antenna placement since an antenna on the top, bottom, and both sides would greatly reduce the chance of an unsuccessful read due to tag orientation within the CTB.

Test 5: Pallet configuration with arranged packing configuration; CTB buried in a pallet of partially packed cardboard boxes

The last test completed was a simple pallet configuration in which the cardboard boxed containing the CTB items was buried in a pallet of partially packed cases. Four antennas (2 per side) were placed at a distance of eight feet apart for three trials. The box containing the CTB items was placed in the center of the pallet and covered by multiple boxes containing very few tagged items. This was done to simulate a CTB stacked under multiple other CTB's. The data collected is shown in Table 10 (Report 2).

Table 10 (Report 2): Results of Pallet Testing.

Test Type	Trial Number	Number of Antennas	Antenna Placement	Movement of Items	B1 Clothing	B2 Hygiene	B3 Office	Number of Reads	Percentage
Pallet	1	4	2 per side	Pass through	50%	69%	75%	14/21	67%
Pallet	2	4	2 per side	Pass through plus rotation	75%	85%	75%	17/21	81%
Pallet	3	4	2 per side	Rotation only	75%	77%	50%	15/21	71%

With a single pass through the portal, only 67% of the tags were read, but when the pallet was rotated as it passed through, the read rate increased to 81% (Table 10, Report 2). This shows that blocking can easily occur and thus a portal design with antennas on the sides, top, and bottom would perform much better. When the CTB was passed through this type of portal configuration with the antennas placed around 2 to 3 feet apart, 100% of the items were read.

6.0 Mobile Reader Results

NASA is also interested in the performance of a mobile reader device to read the Gen2 RFID tags within the CTB. The results of a comparison between two Psion Teklogix handheld RFID readers are presented in this section. Both readers are similar with the exception that one has a linearly polarized antenna and the other has a much larger, circular polarized antenna.

The same items were used from the fixed reader testing, with the CTB packed approximately half full of items from all three groups: clothing (B1), hygiene (B2), and office supply (B3). Results from the previous tests were utilized in determining the best performing tag for each item. The item listing and corresponding tag used are listed in Table 11 (Report 2). Note that the X-Static shirt was tagged with both the AD 820/821 tag and an Omni-ID Prox tag.

Table 11 (Report 2): Item list with corresponding tag type.

Group	Item	Tag
B1	X-Static Shirt	AD 820/821
B1	X-Static Shirt	Omni-ID Prox
B1	Athletic T-Shirt	Omron Scorpion
B1	Black Socks	Omron Scorpion
B1	Underwear	Omron Scorpion
B2	Razor Blades	AD 820/821

B2	Toothpaste	Omni-ID Prox
B2	Water Pouch	Omni-ID Prox
B2	Mouthwash	Omni-ID Prox
B2	Shampoo	Omron Scorpion
B2	Huggies Wipes	Omron Scorpion
B2	Shave Cream	Omron Scorpion
B2	Comb	Omron Scorpion
B2	Deodorant	Omron Scorpion
B3	Batteries	AD 820/821
B3	Microcassette	AD 820/821

All tests were performed on a single packing configuration with these items. Both readers were held within one foot of the CTB and scanned from all four sides and the top. This was repeated for both readers. The results of the testing are shown in Table 12 (Report 2).

Table 12 (Report 2): Mobile reader comparison results.

Trial	Reader Type	
	Psion (Linear)	Psion (Circular)
1	87%	80%
2	73%	87%
3	87%	93%
4	88%	94%
5	88%	88%
6	94%	88%

Table 12 (Report 2) shows that there is only a slight increase in accuracy with the circular polarized reader. However, this was not always the case, because in two trials the linear polarized reader outperformed the circular polarized one. The circular polarized reader is also much bulkier and heavier than the linear reader and their size should be considered when comparing the two.

All items that were not read throughout the trials were non-RF friendly materials including the shave cream, batteries, shampoo, and the x-static shirt. The RFID tags were readable on all items outside of the CTB, but when placed inside the CTB with numerous items, orientation plays a major role and there is a greater chance the tag becomes blocked. The testing shows that direct item level tagging may exhibit readability problems for non-RF friendly materials, especially highly metallic or liquid items.

Recommendations to some of the problems encountered include:

1) Tagging the battery packaging rather than the batteries themselves.
2) Applying a spacer to the tag for X-Static clothing.
3) Using the Omni-ID tags for liquid/paste materials including toothpaste, shave cream, shampoo, and ink cartridges.
4) Using the Avery Dennison 820/821 tags for metallic items including razors, razor blades, and micro cassettes.

7.0 Conclusion

Throughout the five tests, the items that did not meet read requirements were adjusted until successful read rates were achieved. These items included the toothpaste, ink cartridge, microcassette, shampoo, x-static socks, and x-static shirt. It was determined that the AD-820/821 tag, which is designed for RF-unfriendly materials, did meet the required specification of at least 99% read rates on items such as the microcassette, where the Omron Scorpion did not. It did still create problems with the toothpaste, ink cartridge, and x-static clothing, however. These items were then tested using the Omni-ID Prox tag and read rates improved to 95% for these items. This tag was readable on all of the aforementioned exception items. These items were read 100% of the time during some of the trials using this liquid/water designated tag; however, orientation and blocking issues during other trials caused the overall average to be 95%.

It was then determined that all tags would meet read requirements using a combination of the Omron Scorpion, AD-820/821, and the Omni-ID tags. The biggest challenge presented is the orientation of those items within the CTB bag. If the tags come in contact with one another, blocking can occur and read rates will drop below 100%. A fixed, four antenna, portal configuration provided 100% read rates when the antennas were within 1 – 2 feet of the CTB.

The mobile reader was able to read 100% of the tags when a combination of the three tags was used and the reader was moved around all sides of the CTB. This 100% read rate was achieved when tag orientation was adjusted manually. If the items were arranged randomly within the CTB, there is a greater chance that some tags will be missed during the scan. We hypothesize that increasing the power output of the reader may reduce the need to either spin the CTB or move the reader around the CTB. An increase in power output may also reduce the chance of missing tags due to orientation issues and could potentially increase the read range.

As expected, the Gen 2 RFID tags still had some problems with liquid and metal based materials. Liquid and gel type materials proved to be much more detrimental than metal based materials, however, the tags designated for liquid and water materials easily overcame the readability issues.

8.0 Recommendations

It is the recommendation of the RfSCL Lab that Gen2 RFID tags can meet the requirements for IMS implementation when tag orientation is controlled within the CTB, a fixed, four-antenna reader configuration is used, and a combination of Omron Scorpion, Avery Dennison AD-820/821, and the Omni-ID tags are used depending on item characteristics. It would be desirable to investigate an increase of output power for the mobile reader to alleviate the need for manually orientating the tags.

ACKNOWLEDGEMENTS

We would like to acknowledge the efforts and contributions from team members Andrew Chu from NASA Johnson Space Center and Michael Vasquez from VerdaSee Solutions, Inc.

AUTHORS

Erick Jones is an assistant professor at the University of Nebraska and Director of the University of Nebraska's RFID Supply Chain Lab (www.unl.edu/rfscl) - His research studies include RFID, RTLS, and Satelite technology development and testing with respect to inventory control. Other research areas include Supply Chain Logistics, and Six Sigma Quality Engineering Management.

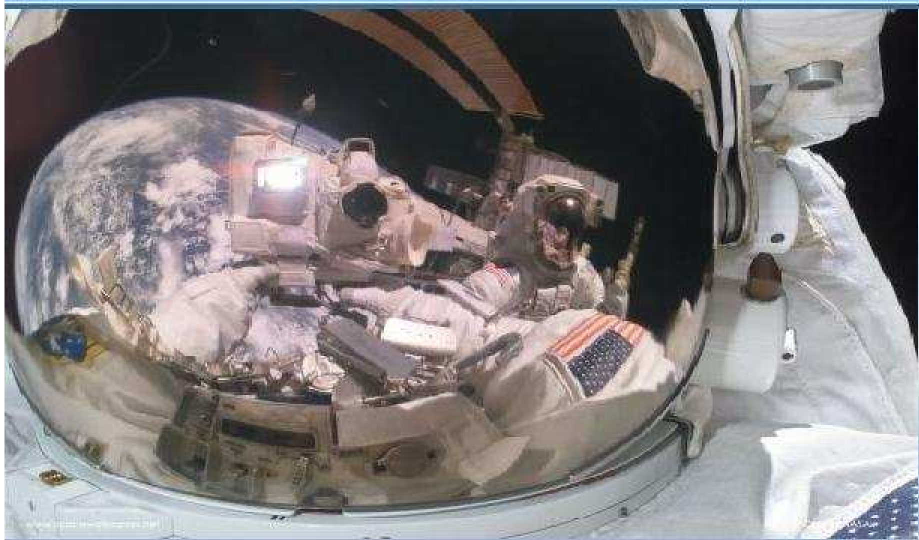
Casey Richards received his B.S. degree in Industrial and Management Systems Engineering from the University of Nebraska-Lincoln and is currently working there towards a M.S. degree in Industrial and Management Systems Engineering. His professional interests include Supply Chain Logistics, RFID and its applications, and Engineering Economics. He can be reached at cnr2003@gmail.com.

Kelli Herstein earned her B.S. in Industrial and Management Systems Engineering from the University of Nebraska – Lincoln and is currently working on her M.S. in Industrial and Management Systems Engineering. Her professional interests focus on Engineering Management, RFID applications for the Supply Chain, and Human Factors. She can be reached by e-mail at kelliherstein@gmail.com.

Rodrigo Franca received his B.S. in Industrial Engineering from the Universidade Federal do Ceará-Brazil and in the moment he is a candidate for the M.S. in Industrial and Management Systems Engineering from the University of Nebraska-Lincoln. His professional interests are Engineering Economy, Supply Chain Modeling, and RFID and its applications. He can be reached at rbfranca@yahoo.com.

Evan L. Yagoda is a NASA Johnson Space Center / ESCG Systems Engineer. He supports the Constellation program working Habitation Accommodations for the Orion vehicle. His professional background includes engineering management, thermal, and fluid dynamics work in space, military and commercial aircraft. Evan received both his B.S. and M.S. degrees in Aerospace Engineering at the University of Michigan, Ann Arbor.

Reuben Vasquez is President and CEO of VerdaSee Solutions, Inc. He was the Senior Vice President and General Manager of Moore North America, with P&L responsibility for RFID systems. He has held Several VP and general management positions in Moore in operations, manufacturing, logistics, and quality. He specializes is areas including information management, commercial bar code labels and applications, and advance tracking and tracing solutions.



NASA Constellation Program RFID Presentation

Team Introduction

- UNL Faculty
  - Dr. Erick C. Jones (Director)
- UNL Graduate Students
  - Casey Richards
  - Kelli Kopocis
  - Rodrigo Franca
- NASA Johnson Space Center
  - Evan Yagoda
  - Andrew Chu
- VerdaSee Solutions, Inc.
  - Reuben Vasquez
  - Michael Vasquez

Team Introduction
UNL Radio Frequency and Supply Chain Logistics Lab

- Mission:
  - *"Providing integrated solutions in logistics and other data driven environments through automatic data capture, real world prototypes, and analysis"*
- Equipment
  - Currently Active and Passive Tags/Readers and software (Matrics, Alien, Samsys), Hytrol conveyor and GCS WMS, HP5555 Mobile Active Reader and Software, RF Code Active tags, SAVI Tags/Reader, WMRM/WORM
- Other Notes
  - Currently awarded planning Grant to move forward on NSF Industry/University Co-op
  - Industry gets discount to do industry related research at UNL with respect to Logistics

University of Nebraska Lincoln

Project Definition

- To assist in implementation of RFID inventory tracking for the NASA Constellation Program (CxP)

- To find commercial off the shelf (COTS) solutions to create a more effective and user-friendly inventory management system (IMS)

Project Goal

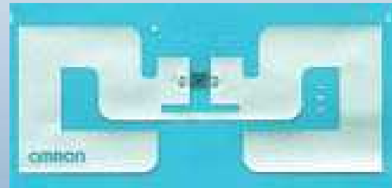
- The goals include:
  - Improving the speed and accuracy of inventory management and control
  - Evaluate how RFID can be used for tracking item locations in a space environment
  - Evaluate how RFID can benefit tracking of inventory on the ground

Sequential Design of Experiments

- Series of controlled experiments using Design of Experiments (DOE)
- Information used from current and previous experiments to alter factors to improve performance
- Eliminates testing of insignificant factors and helps determine optimal testing conditions

RFID – Passive Tags

- Tags selected for item level testing
  - *Omron Scorpion*
    - *www.omronrfid.com*
  - *Avery Dennison 820/821*
    - *Improved performance on metallic items*
    - *www.rfid.averydennison.com*
  - *Omni-ID Prox*
    - *Specialty liquid/metal tag*
    - *Much thicker than standard tags*
    - *www.omni-id.com*



Accuracy Testing

- Testing was performed to determine:
  - Ability to read multiple tags
  - Ability to read through CTB
  - Ability to read through crew consumable items
  - Items which would interfere with or absorb RFID signals

Accuracy – Summarized Results

- All RFID systems were capable of handling data from multiple tags simultaneously
  - Limiting factor for mobile reader is output power/antenna gain
- Omron Scorpion tags demonstrated good performance on a wide variety of non-liquid and non-metallic items
- AD 820/821 tags demonstrated a higher degree of readability on metallic items than the Omron Scorpion tag
- Omni-ID tags demonstrated superior readability on non-RF friendly items (liquids/metals)

Define > Measure > Analyze > Design > Identify

Accuracy – Summarized Results

- Shampoo, toothpaste, shave cream, X-static clothing and batteries caused large decreases in readability
  - To be expected, as these are some of the most notorious RFID enemies
  - Decrease in performance overcome by using Omni-ID tags
- RF signal cannot penetrate these items
  - Can be alleviated by:
    - Adjusting antenna configuration
    - Moving the mobile reader around
    - Spinning the CTB

Analyze – Fixed Reader Conclusion

- All items could be read regardless of material by using one of the three tags utilized in the study.
- Using multiple fixed antennas at close distances (1 – 2 feet from container) increases the probability of reading all items within the container
  - Orientation sensitivity is a critical factor. The data collected in this study was based on an ideal packing configuration. Random packing orientations may greatly reduce read rates.
- Portal antenna configurations performed much better than single side antenna configurations.

Analyze – Mobile Reader Conclusion

- The mobile handheld reader could read all items individually, but some problems still persist with reading the items in a CTB:
  - Output power/antenna gain of the reader requires the tags to be in close proximity to the reader (scans were performed within one foot of the container in order to read all items).
  - The reader must be moved around all sides of the container in order to read every item within the container. This could also be caused by inadequate output power or antenna gain.

Analyze – Tags

- Conclusion
  - **Omron Scorpion** tag should be used on all non-liquid or non-metallic items
  - **AD 820/821** tag should be used on semi-metallic materials (i.e., batteries, razor blades, and microcassettes)
  - **Omni-ID Prox** tag should be used on all other liquid and metallic items (i.e., shampoo, toothpaste, and mouthwash)

Analyze – Readers

- Range
  - Fixed passive readers are able to read tags accurately and consistently with proper antenna configurations.
  - Handheld devices typically have a shorter range.
- Implementation
  - Fixed readers need power, room to be mounted (door portals, smart shelves, etc.)
  - Handheld reader may require increased output power or a higher antenna gain for success.

Analyze – Mobile Readers

- Conclusion:
  - Little difference in performance between basic linear polarized antenna and large circular polarized antenna
    - Circular antenna showed slight increase in read rates
  - Circular polarized antenna is much bulkier and heavier

Analyze – Software

- VerdaSee Navigator fixed reader software could provide a basis platform and could potentially be integrated into existing IMS
- Handheld demo software is not inventory application specific.
  - Inventory management applications would need to be developed prior to implementation

Recommendations – Tracking

- Investigate the feasibility of increasing antenna gain and/or output power for mobile readers
- Investigate NASA defined portal configurations for fixed readers
- Investigate the feasibility of smart shelf configurations
- Investigate smart bag prototypes

Recommendations – Tracing

- Investigate the feasibility of RFID software to integrate with NASA inventory control systems
- Investigate the feasibility of creating a user friendly mobile reader application
  - Investigate a modified COTS approach

Recommendations – Locating

- Investigate RFID based Real Time Location Systems (RTLS) ability to locate items in NASA type containers including:
  - Rooms
  - Containers
  - CTB's
  - Boxes
- These technologies could include active RFID sensor tags or location using passive triangulation

Define Measure Analyze Design Identify

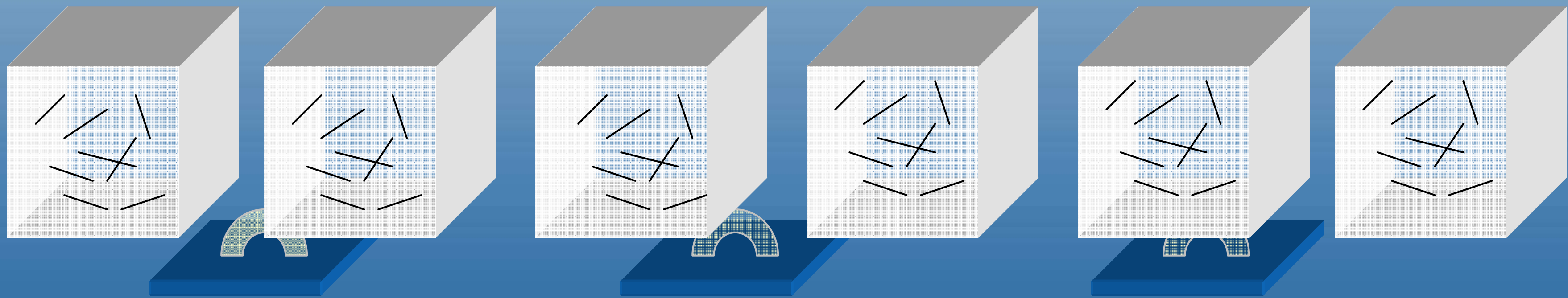
Recommendations – Hybrid Tracking and Locating

- Investigate an RFID active and semi-active technology configuration (Sensor Tag) that can be used with a container such as a CTB
  - Tracking capabilities use semi-active technology for scanning contents
  - Active technology provides battery assisted signals for location of the container

Define > *Measure* > *Analyze* > *Design* > *Identify*

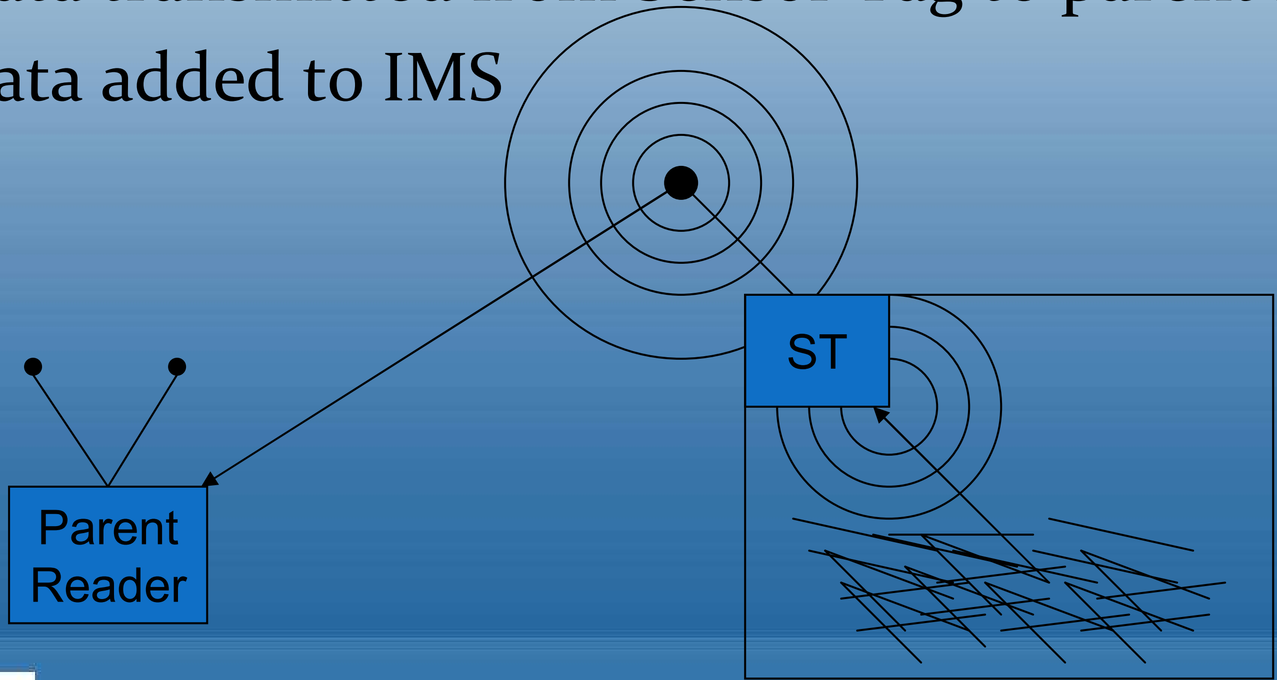
Smart Shelf

- Shelves are equipped with built in RFID readers
- The shelves periodically scan items
- Shelves then transfer data to computer to keep track of information
- Items can be easily located in a space environment



Sensor Tag System – Concept

- Reader and Active Tag combine into one unit, creating Sensor Tag
- CTBs mounted with Sensor Tags interrogate passive tags on items
- Data transmitted from Sensor Tag to parent reader
- Data added to IMS



Define › Measure › Analyze › Design › Identify

Possible Phase II Solutions

- Review, update, and confirm NASA testing protocols and scenarios for testing RFID identified inventory
- Evaluate modified COTS RFID mobile and fixed readers for improved tracking in NASA space operations
- Investigate:
  - The feasibility of increasing antenna gain and/or output power for mobile readers
  - Smart shelves and smart bag prototypes

Define > *Measure* > *Analyze* > *Design* > *Identify*

Possible Phase II Solutions

- Evaluate modified COTS software for improved data capture and tracing purposes
- Investigate:
  - The feasibility of RFID software to integrate with NASA inventory control systems to trace inventory information
  - Creating a user friendly mobile reader application

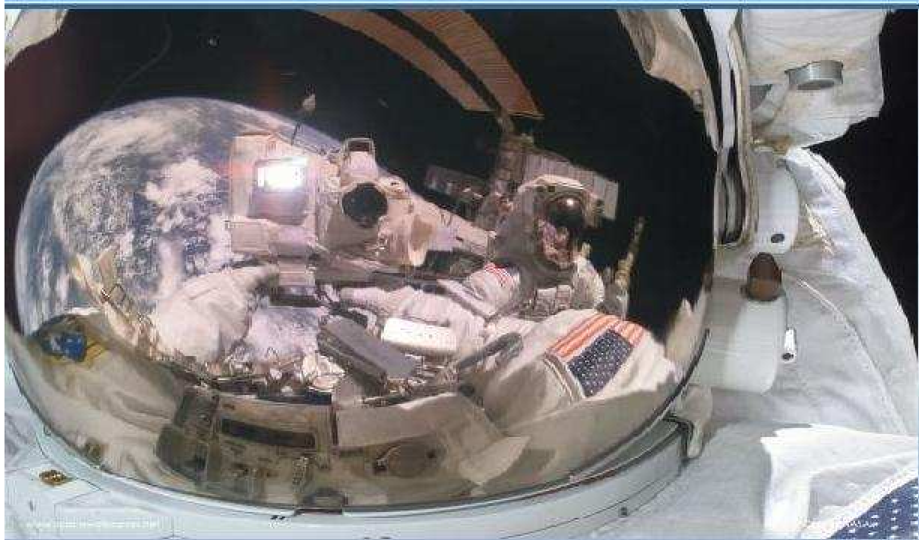
Questions?

Authors

- Dr. Erick Jones – University of Nebraska-Lincoln
  - ejones2@unl.edu
- Casey Richards – University of Nebraska-Lincoln
  - Graduate Assistant
  - cnr2003@gmail.com
- Evan Yagoda – NASA Johnson Space Center
  - Evan.L.Yagoda@nasa.gov
- Reuben Vasquez – VerdaSee Solutions, Inc.
  - reuben.vasquez@verdasee.com

Acknowledgements

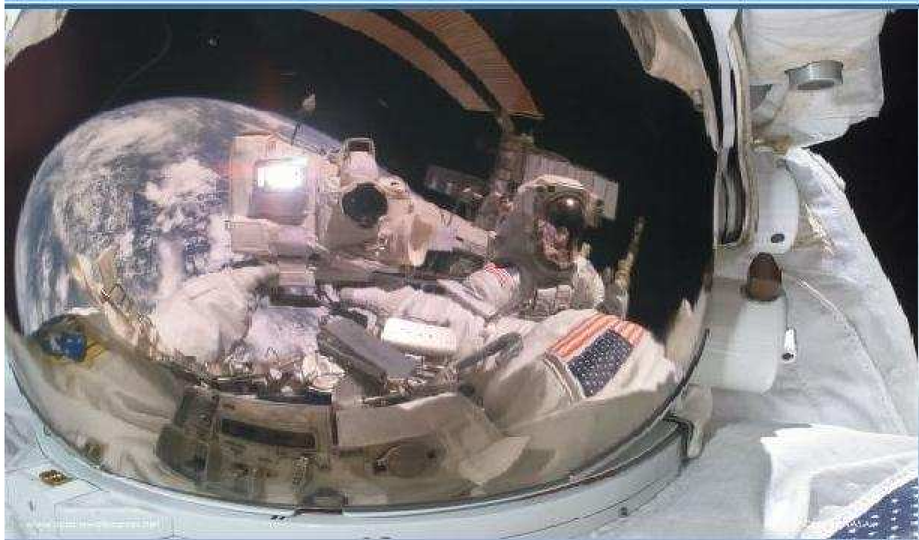
- Andrew Chu – NASA Johnson Space Center
- Michael Vasquez – VerdaSee Solutions, Inc.



NASA Constellation Program RFID Presentation

Presentation Outline

- Team Introduction
- Project Definition
- Project Approach
- Project Results
- Recommendations
- Next Steps



Team Introduction

Team Introduction UNL Faculty and Students

- Faculty
  - Dr. Erick C. Jones (Director)
- Graduate Students
  - Casey Richards
  - Kelli Kopocis
  - Rodrigo Franca

Team Introduction
Partners

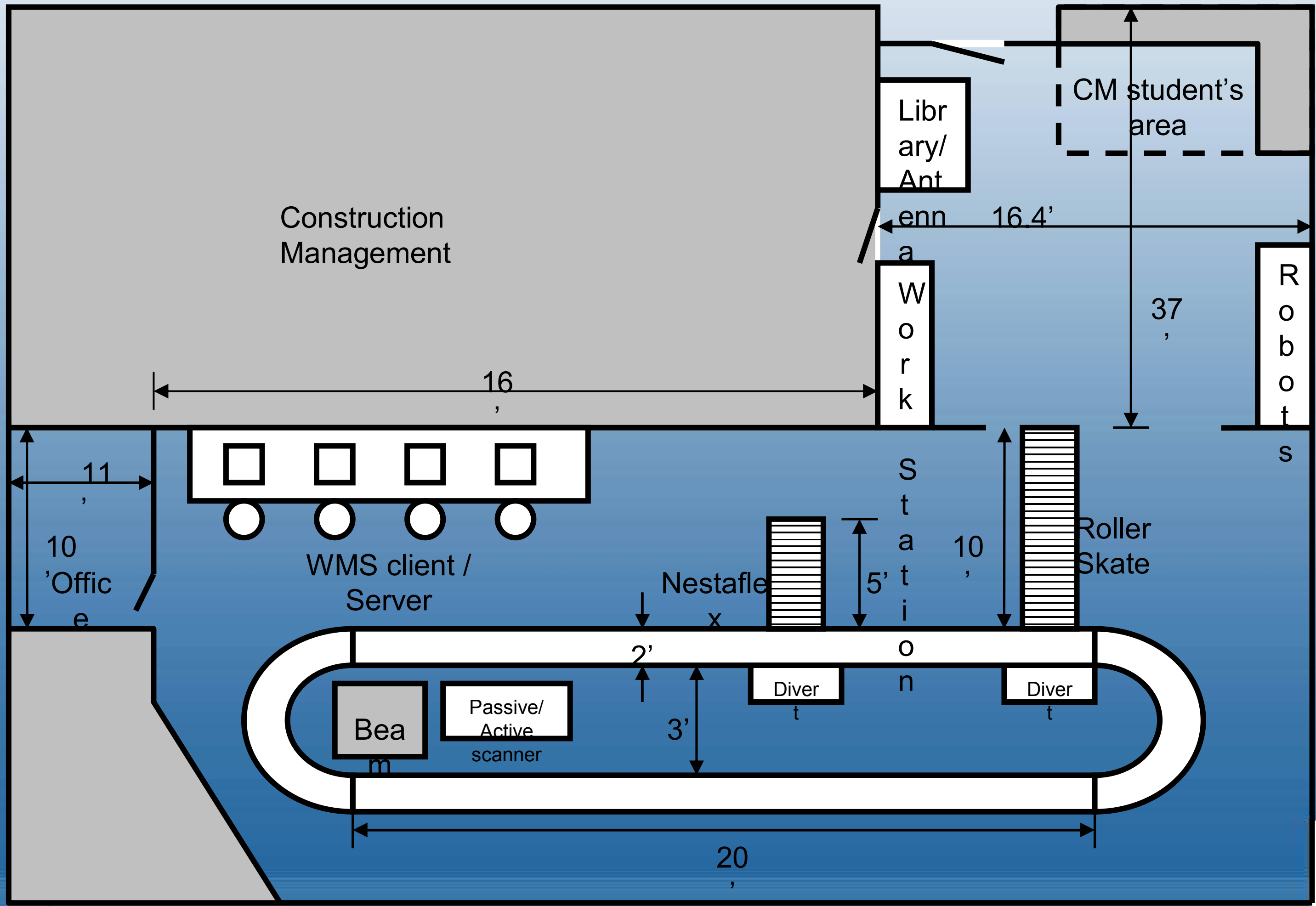
- NASA Johnson Space Center
  - Evan Yagoda
  - Andrew Chu

- VerdaSee Solutions, Inc.
  - Reuben Vasquez
  - Michael Vasquez

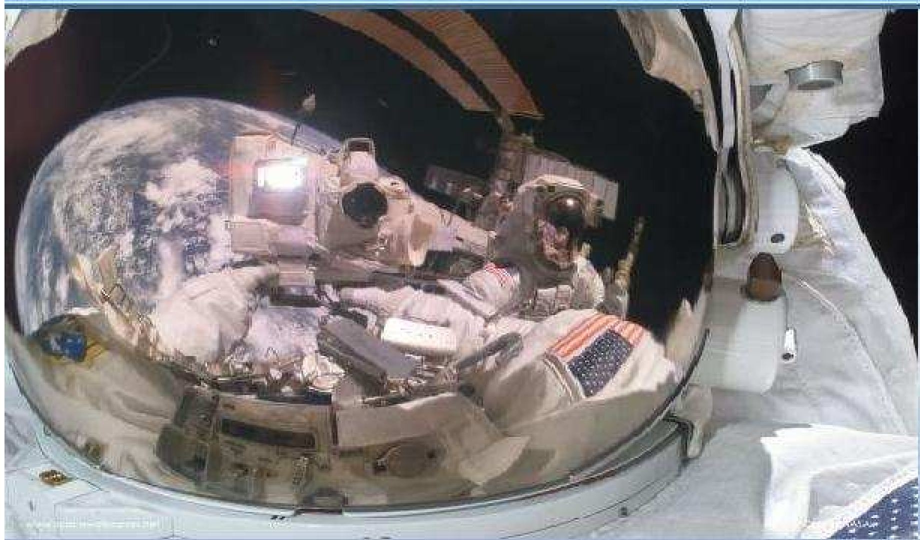
Team Introduction
UNL Radio Frequency and Supply Chain Logistics Lab

- Mission:
  - *"Providing integrated solutions in logistics and other data driven environments through automatic data capture, real world prototypes, and analysis"*
- Equipment
  - Currently Active and Passive Tags/Readers and software (Matrics, Alien, Samsys), Hytrol conveyor and GCS WMS, HP5555 Mobile Active Reader and Software, RF Code Active tags, SAVI Tags/Reader, WMRM/WORM
- Other Notes
  - Currently awarded planning Grant to move forward on NSF Industry/University Co-op
  - Industry gets discount to do industry related research at UNL with respect to Logistics

Team Introduction
UNL RfSCL Facility



Team Introduction
UNL RfSCL Facility



Project Definition

Project Definition

- To assist in implementation of RFID inventory tracking for the NASA Constellation Program (CxP)

- To find commercial off the shelf (COTS) solutions to create a more effective and user-friendly inventory management system (IMS)

Problem Statement

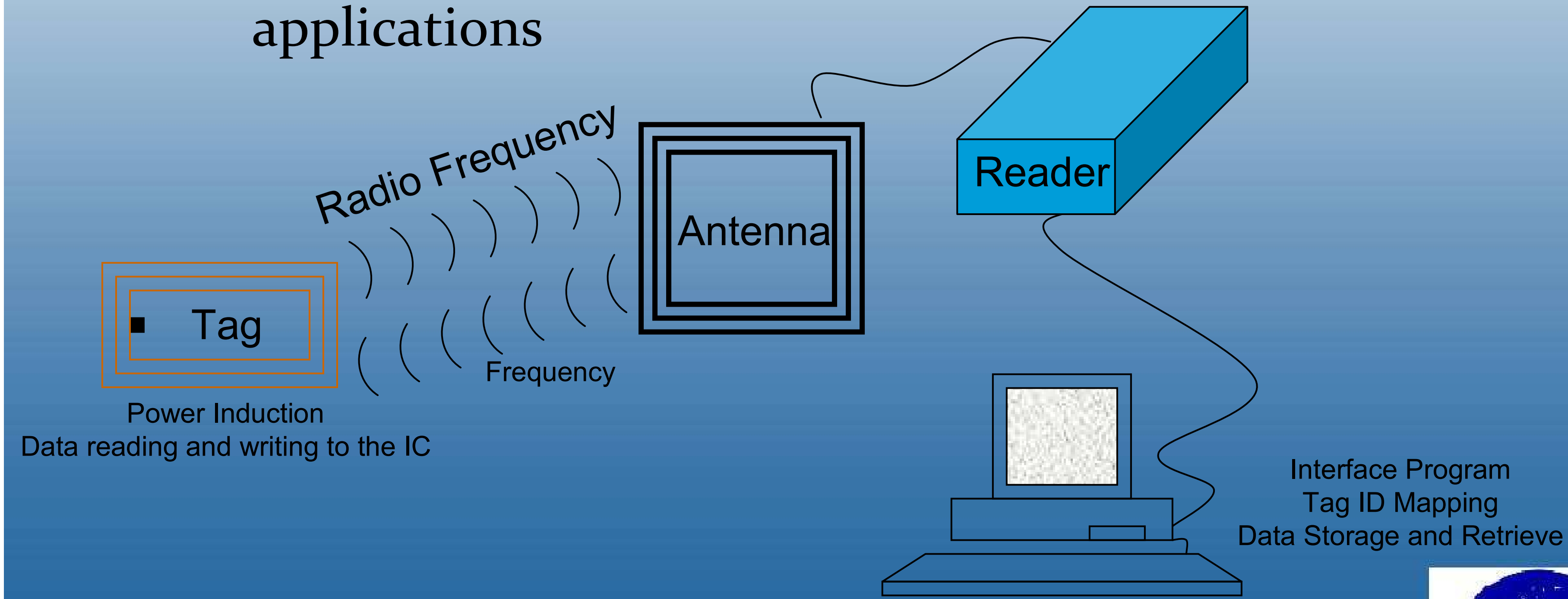
- Current inventory kept by barcode
  - All items hand scanned
  - Data fed to IMS software
  - Difficult to keep accurate inventory
- Periodic inventory audits
  - Labor intensive
  - Time consuming
  - Only as accurate as data input by crew

Project Goal

- The goals include:
  - Improving the speed and accuracy of inventory management and control
  - Evaluate how RFID can be used for tracking item locations in a space environment
  - Evaluate how RFID can benefit tracking of inventory on the ground

What is RFID?

- Radio Frequency Identification
  - Antenna sends signal to RFID tag
  - RFID tag responds with unique frequency
  - Antenna sends data to reader, which uses it for various applications



Benefits of RFID

- No line of site required
  - Radio waves pass through many objects
  - Multiple tags scanned simultaneously
- More data storage than barcode
  - Passive tags average 96 bits of information
  - Active tags can range to 200 kilobytes

Project Requirements

- Bag/container scanned within 10-15 seconds
- Accuracy greater than or equal to 99%
- Tag size not to exceed 3” x 2”
- Tagged items in each bag/container must be representative of actual items used by NASA personnel

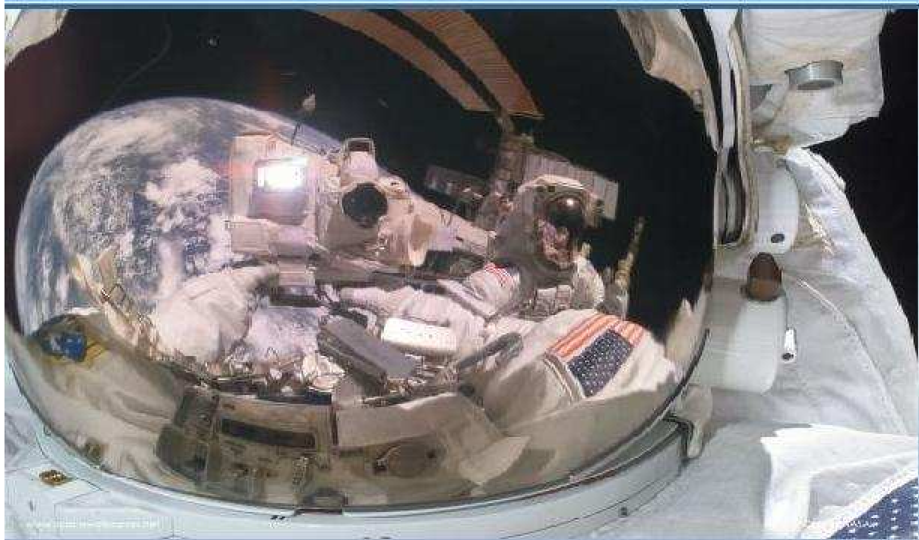
UNIVERSITY OF Nebraska Lincoln

Unique Project Obstacles

- 360 degree tag orientation range possible
- Non-systematic packing
  - Packing done by staff on ground
  - No organized groupings of items
- Wide range of items
- Need to integrate with current systems

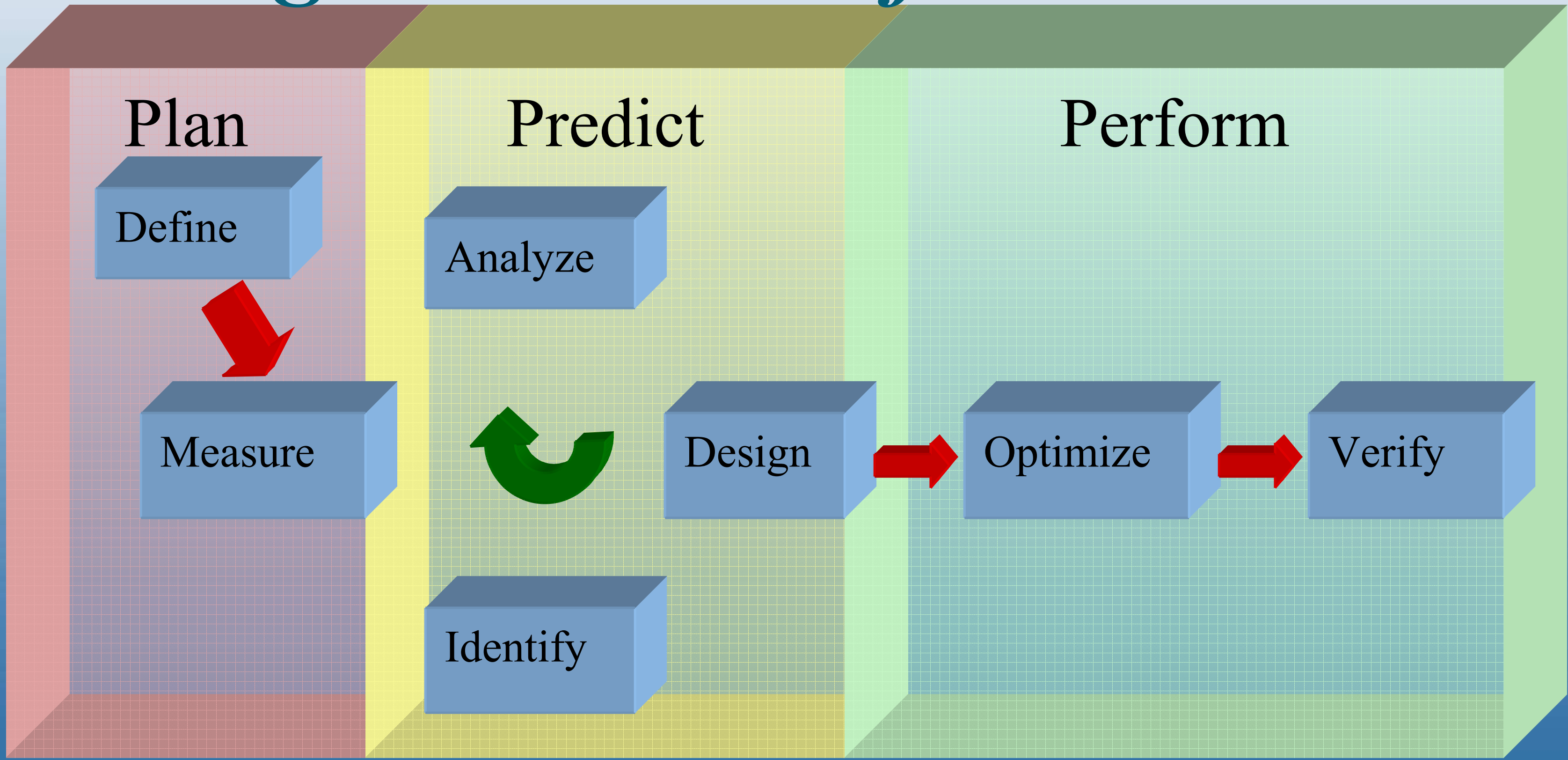
Project Hardware

- RFID tags and equipment were limited to commercial off the shelf (COTS) technology
- Tags were manufactured by:
  - Omron
  - Avery Dennison
  - Omni-ID
- Reader and antennas were manufactured by:
  - Omron
  - Psion Teklogix



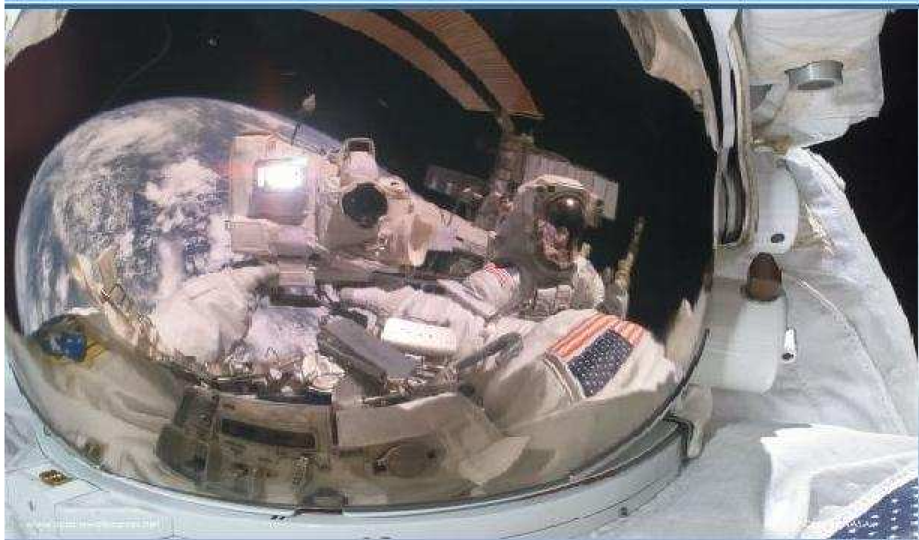
Project Approach

Applied Research Methodology
> Integrated DFSS for Research



Sequential Design of Experiments

- Series of controlled experiments using Design of Experiments (DOE)
- Information used from current and previous experiments to alter factors to improve performance
- Eliminates testing of insignificant factors and helps determine optimal testing conditions



Experiment 1 – Define

Define

- Compare performance of 10 different passive Gen 2 RFID tags from Omron and Avery Dennison
- Experimental design with 3 factors
  - Material type to be tagged
    - Cardboard, Metal, Liquid

  - Tag orientation with respect to reader ante
  - Read distance
    - 5 ft. and 10 ft.

Define

- Tags placed on a wooden stand at the same height as the reader antenna

Define > *Measure* > *Analyze* > *Design* > *Identify*

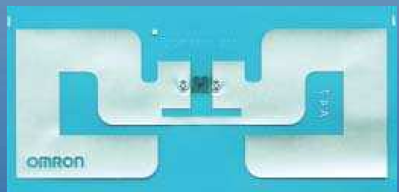
Tag List – Gen 2 COTS Tags

Omron

Ninja

Wave
(inlay & label form)

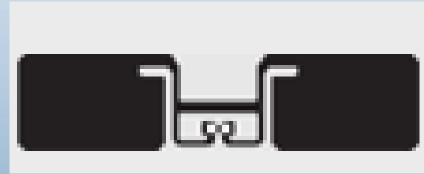
Loop



Scorpion

Avery Dennison

AD 222



AD 431

AD 622

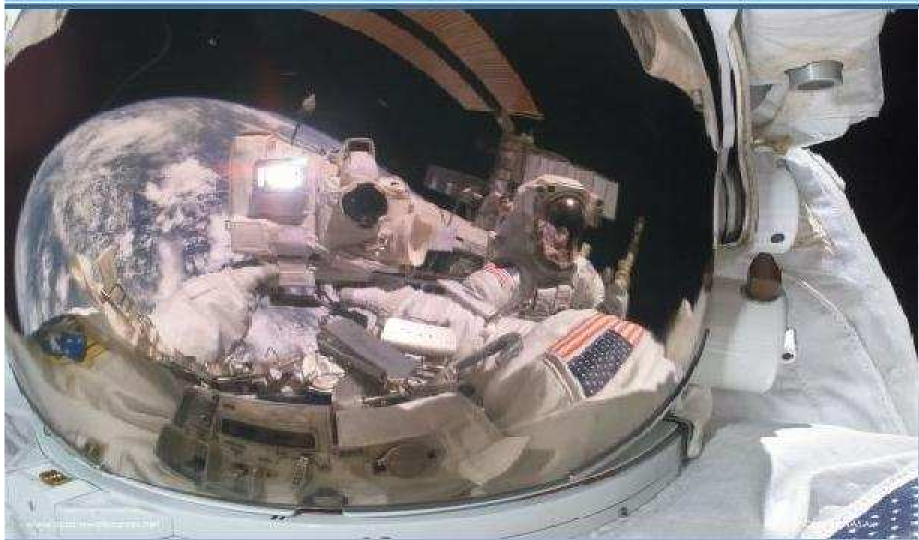
AD 811/812

AD 820/821

Hardware/Software Configuration

- Omron V750 UHF Passive RFID Reader
  - Fixed Reader
  - Single Omron V740 Mono Static Antenna
    - Circular Polarized

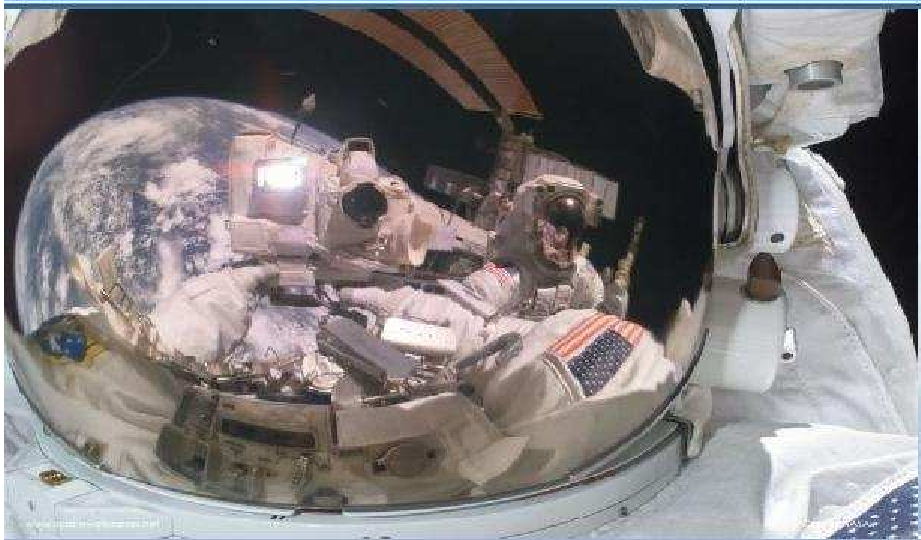
- VerdaSee Navigator 2008 Device Testing Software
  - Tag IDs are matched with inventory items
  - Useable with all tags



Experiment 1 – Measure

Measure

- Dependent Variables
  - Read Rate (Reads per Second)
  - Percentage of Successful Reads
- Independent Variables
  - Distance
  - Tag
  - Material
  - Orientation
- 36 data points collected for each of the 10 tags
  - 3 materials x 6 orientations x 2 distances



Experiment 1 - Analyze

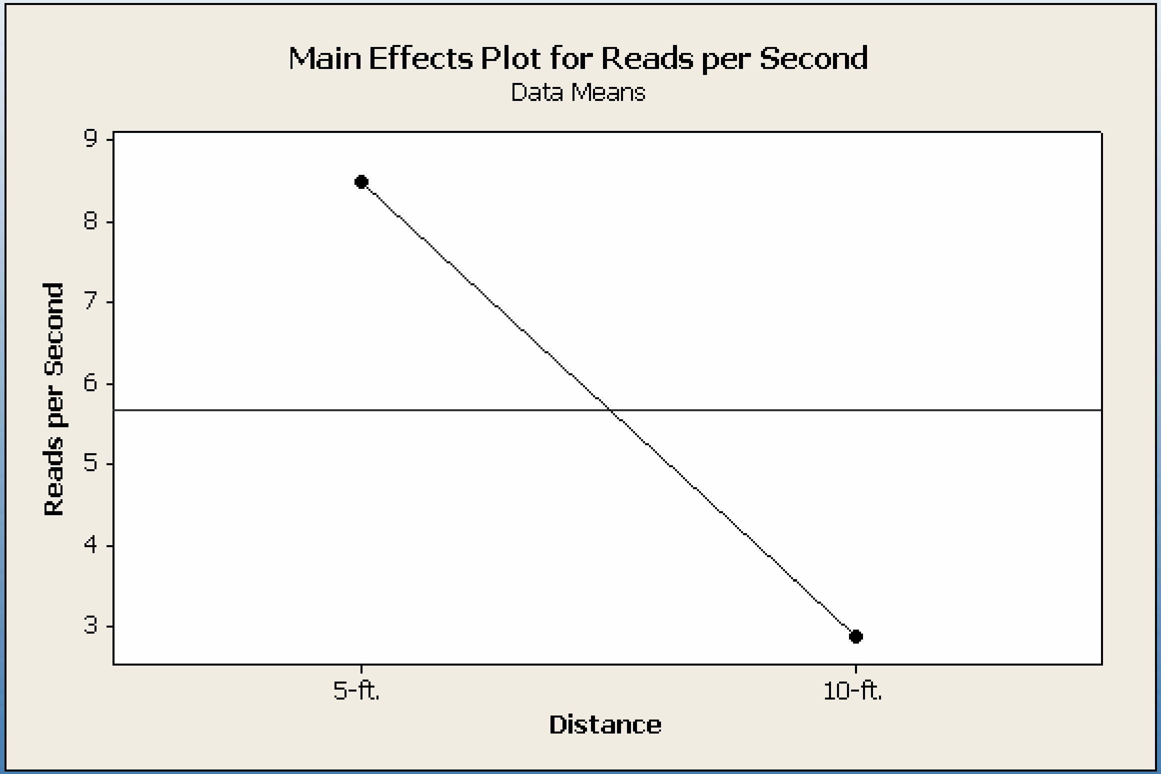
Analyze

- Analysis performed using Minitab 14.1 to determine significant variables
- All four factors found to be significant using an alpha value of 0.05 (P-value < 0.05)

Analysis of Variance for Reads per Second, using Adjusted SS for Tests

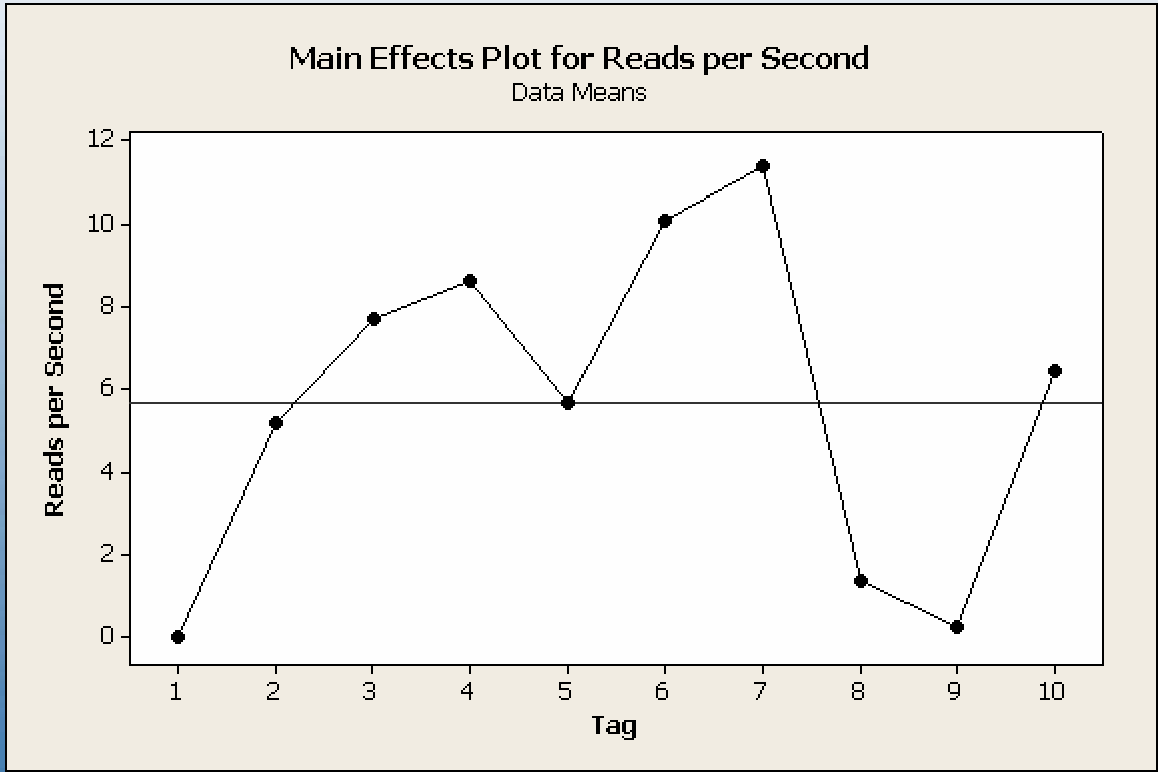
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Distance	1	2855.5	2855.5	2855.5	29.52	0.000
Tag	9	5260.0	5260.0	584.4	6.04	0.000
Material	2	18603.6	18603.6	9301.8	96.18	0.000
Orientation	5	1872.8	1872.8	374.6	3.87	0.002
Error	342	33077.1	33077.1	96.7		
Total	359	61669.1				

Analyze – Distance



Read rates decreased by more than half as the distance from the tag to the reader antenna increased from 5 feet to 10 feet.

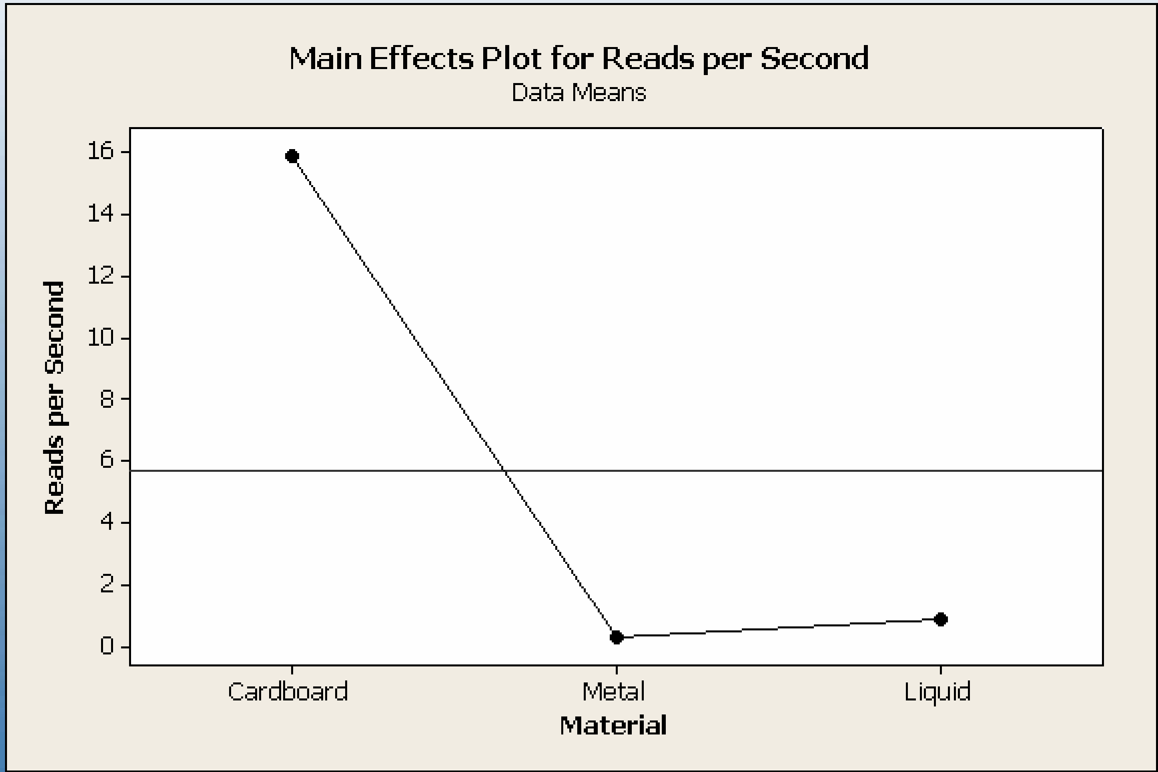
Analyze – Tag



Two tags were significantly better than the rest when all factors were taken into account. Five tags were considered average and three tags performed very poorly.

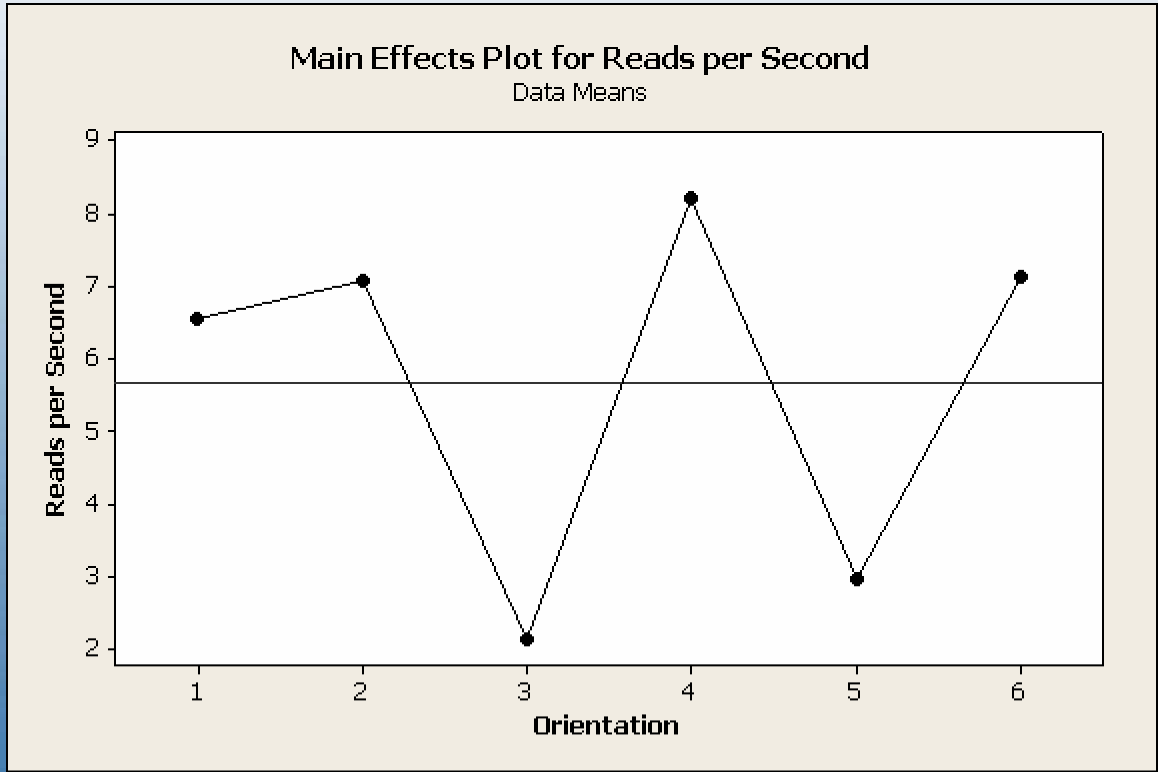
Define *Measure* *Analyze* *Design* *Identify*

Analyze – Material



A significant decrease in read rates was experienced between the cardboard trials and the metal and liquid trials. This was expected, however, and some tags were able to produce reads on all materials.

Analyze - Orientation



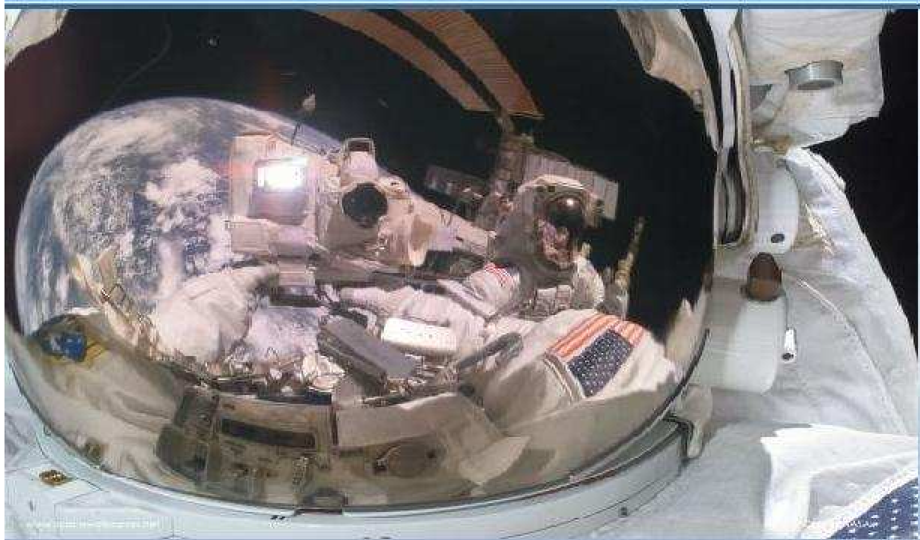
Orientation of the tag with respect to the reader had a significant effect when the tag was placed in a horizontal position. These two positions (3 and 5) created the least amount of antenna surface area for the RF signal to contact.

Results

- Tags selected for item level testing were chosen based upon performance on all three material types
- Three tags with the best performance were:
  - Omron Scorpion
  - Avery Dennison 820/821
  - Avery Dennison 622
    - AD 622 did not meet size requirements and was not selected for further testing
    - Omni-ID Prox was selected instead, which is a liquid/metal specialty tag (the Prox tag was not available during Experiment 1 and was added later)

University of Nebraska Lincoln

Define > Measure > Analyze > Design > Identify



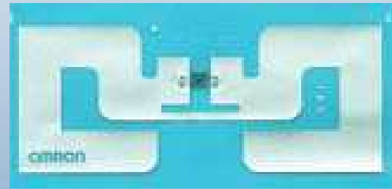
Experiment 2 – Define

Define

- Evaluate best performing tags from Experiment 1 at the item level
- Items are representative of clothing and supplies used by NASA personnel
- Each item to be individually tagged and packed into a cargo transport bag (CTB)

RFID – Passive Tags

- Tags selected for item level testing
  - *Omron Scorpion*
    - *www.omronrfid.com*
  - *Avery Dennison 820/821*
    - *Improved performance on metallic items*
    - *www.rfid.averydennison.com*
  - *Omni-ID Prox*
    - *Specialty liquid/metal tag*
    - *Much thicker than standard tags*
    - *www.omni-id.com*




RFID – Tag Summary

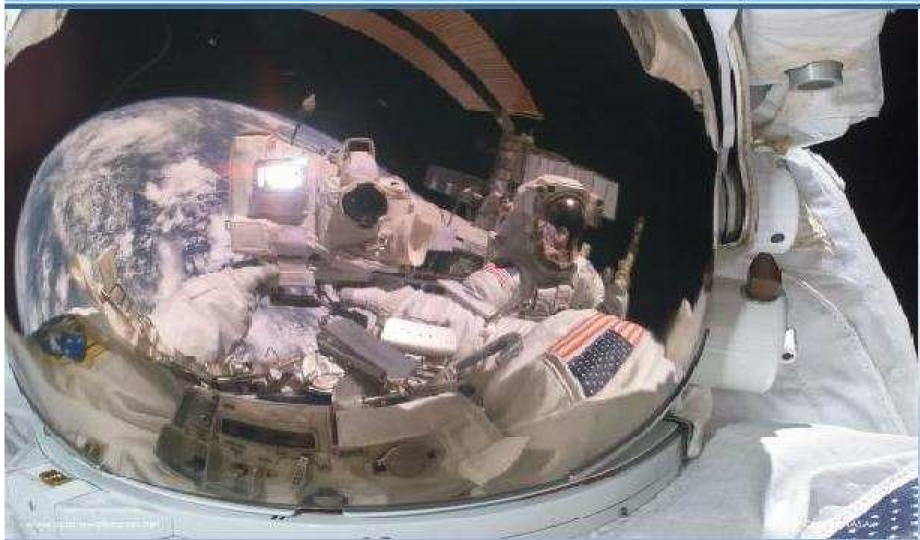
	Dimensions	Max Read Range
Omron Scorpion	1.10 in. x 2.68 in. x 0.04 in.	13 ft.
AD 820/821	1.18 in. x 2.83 in. x 0.04 in.	-
Omni-ID Prox	0.39 in. x 1.38 in. x 0.16 in.	8 ft.

RFID – Passive Readers

- Omron V750 UHF RFID Reader
  - Fixed Reader
  - Four Omron V740 Mono Static Antennas
    - Circular Polarized
- Psion Teklogix Workabout Pro
  - Mobile Reader
  - Linear Polarized Antenna
- Psion Teklogix Workabout Pro
  - Mobile Reader
  - RD7950 UHF Circular Polarized Antenna

RFID – Software

- VerdaSee Navigator
  - Tag IDs are matched with inventory items
  - Useable with all tags
- WJ Technologies MPR Demo Software
  - Very baseline, no inventory tracking component
  - Useable with all tags



Experiment 2 – Measure

Measure – Independent Variables

- Main Factors to Test
  - Mobile reader vs. fixed reader
  - Number of fixed antennas used and configuration
  - Read distance
  - Tag type and placement on items

Measure – Dependent Variable

- Read Accuracy
  - Percentage of tags within a cargo transport bag (CTB) that are read during a single scan

- Goal is to read 100% of tags within a CTB

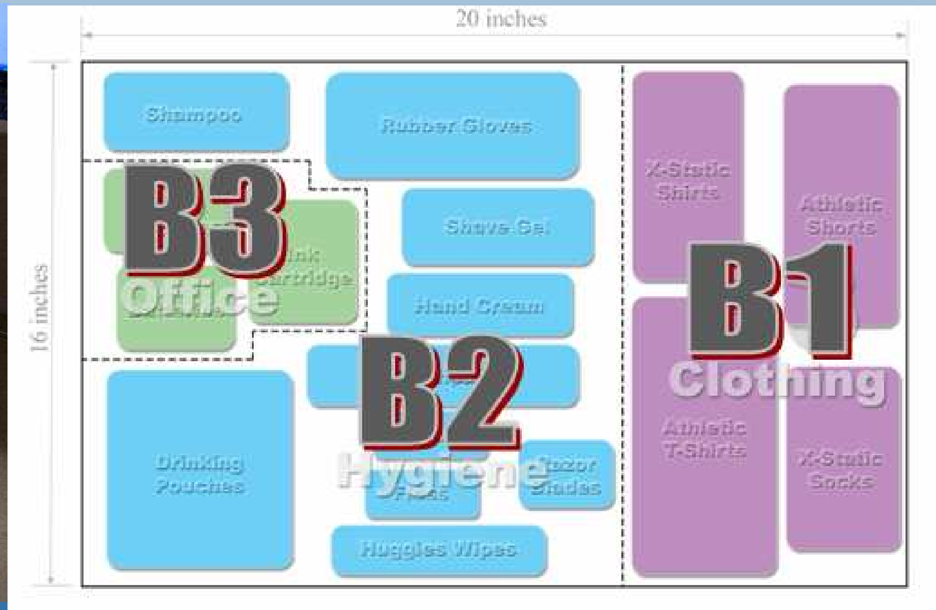
Define | Measure | Analyze | Design | Identify

Orientation Issues

- Items were adjusted throughout pre-trial testing to alleviate blocking and attenuation issues between close proximity tags
- Once an acceptable arrangement was determined where no tags were completely blocked by others, the items were packed according to this configuration for all trials

Packing Configuration in CTB

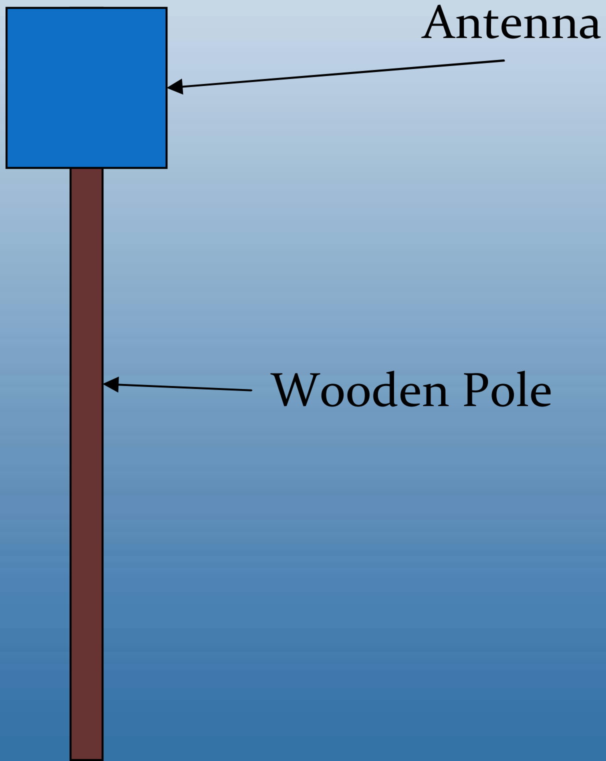
- Items grouped according to type:
  - Clothing / Hygiene / Office Supplies



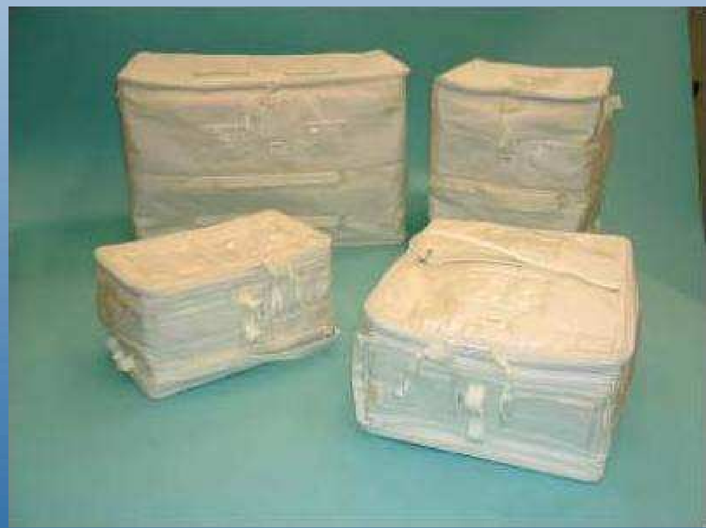
Experiment Setup

- The experiment was setup with four different configurations for the fixed reader
  - One Antenna
  - Two Antennae, same side
  - Two Antennae, opposite sides
  - Four Antennae, two per side
- Items were tested in both a CTB and a cardboard box to determine if the container had an effect on read rates

Setup – Factors and Symbols

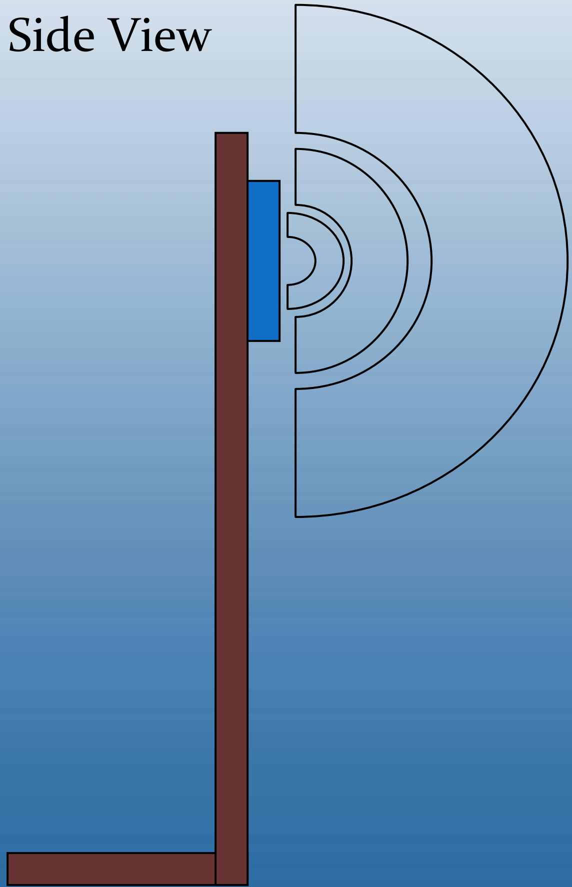


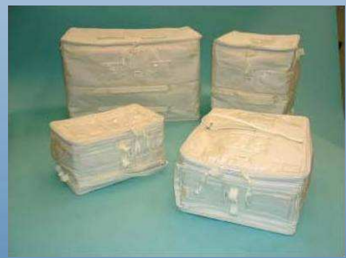
NASA Cargo Transport Bag (CTB)



Setup – One Antenna Configuration

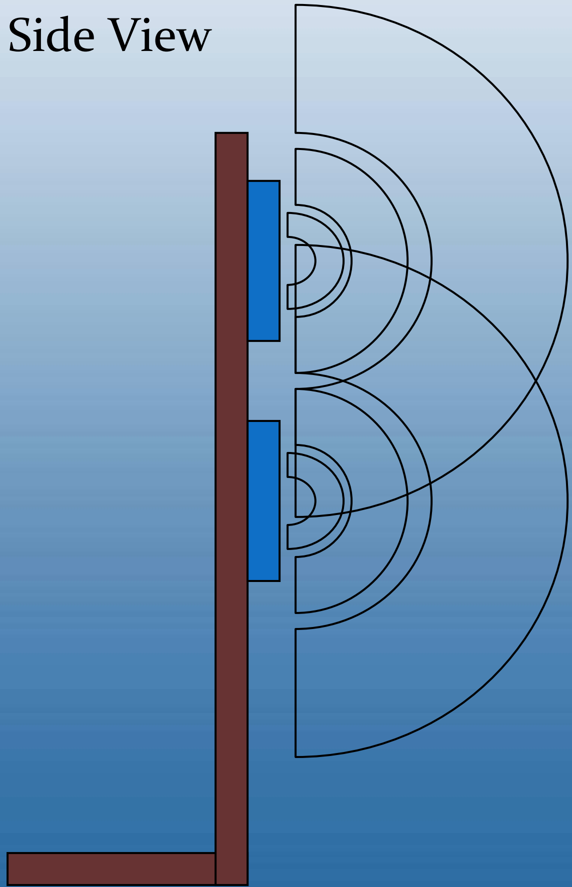
Side View

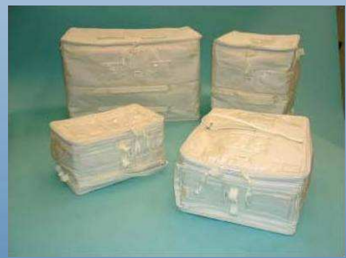




Setup – Two Antenna Configuration – Same Side

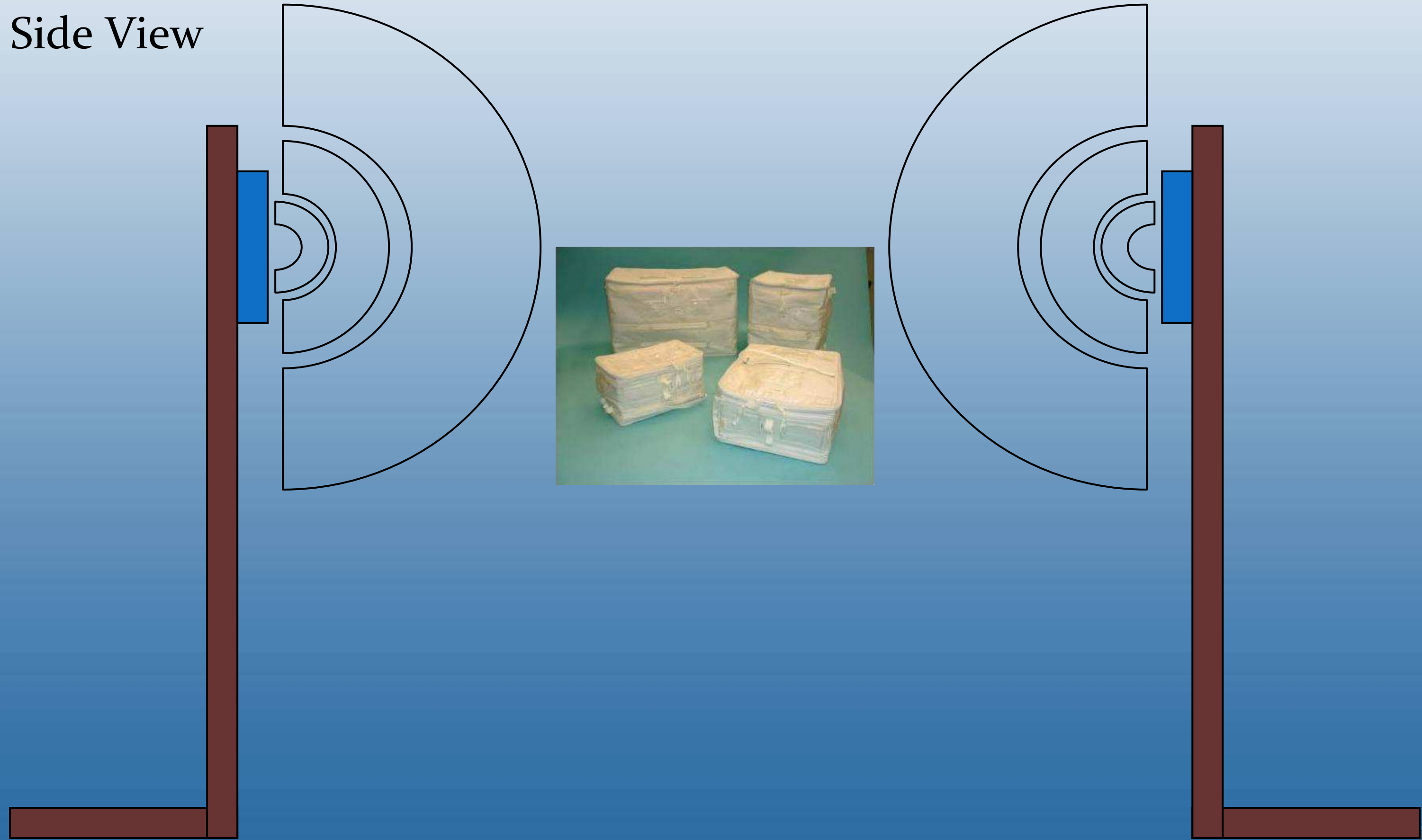
Side View



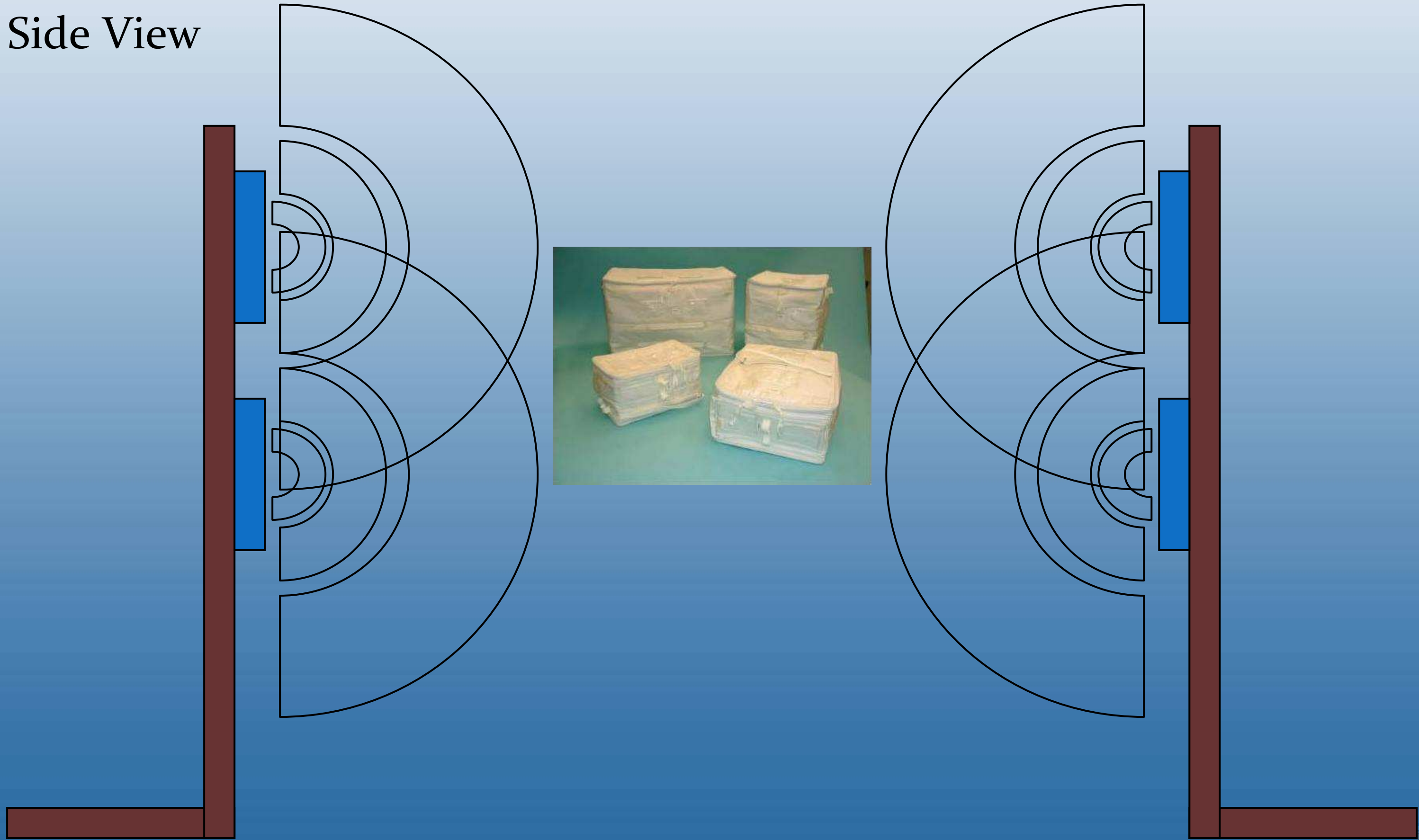


Define > Measure > Analyze > Design > Identify

Setup – Two Antenna Configuration – Opposite Sides



Setup – Four Antenna Configuration – Two Per Side



Tagging Progression

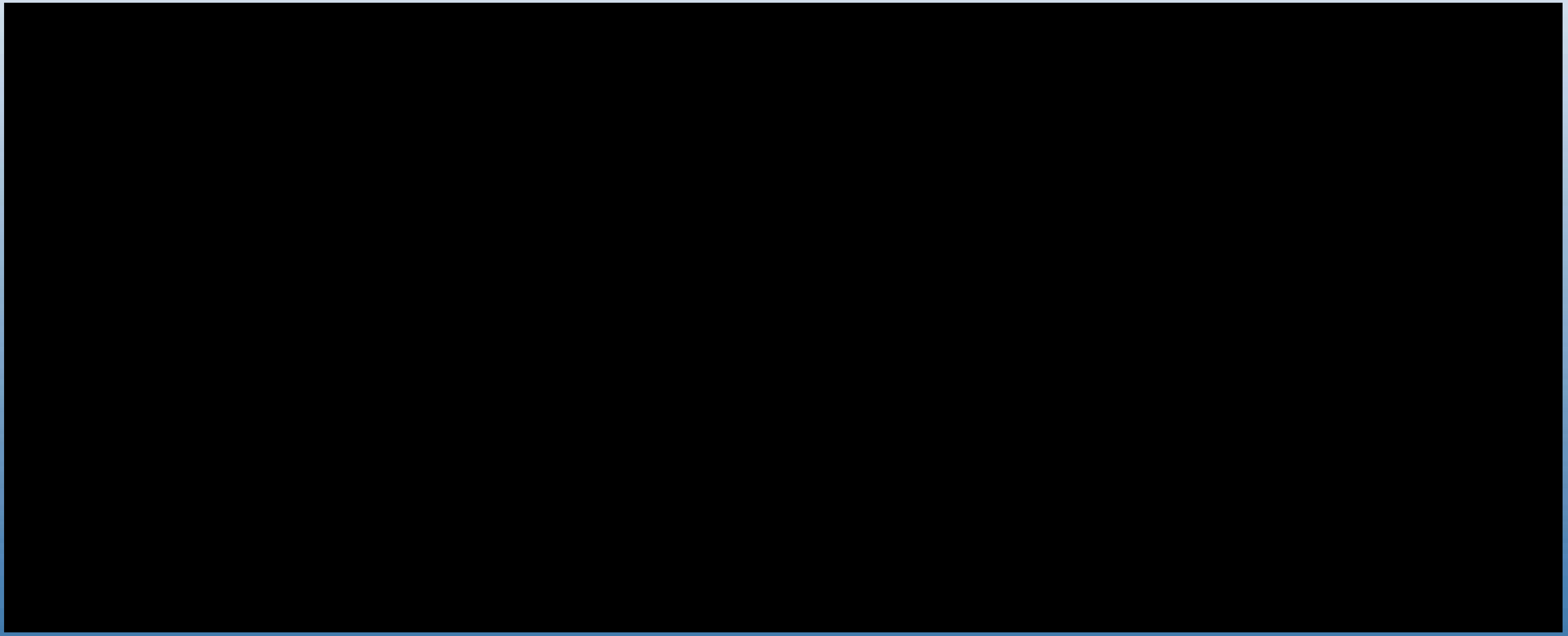
- All items initially tagged with Omron Scorpion tag
- If item was not readable, the Omron tag was substituted with the Avery Dennison 820/821
- If still not readable, Omni-ID Prox tags used
  - Designed specially for difficult to read items (liquid, paste, metals)

Accuracy Testing

- Testing was performed to determine:
  - Ability to read multiple tags
  - Ability to read through CTB
  - Ability to read through crew consumable items
  - Items which would interfere with or absorb RFID signals

Measure – CTB Results

- 100% read rate achieved in 2 trials



Measure – Cardboard Box Results

- 100% read rate achieved in 5 trials

The cardboard box outperformed the CTB due to the sequential design of the testing. Throughout each of the trials, adjustments to the tags used and the positioning of the tags were made. CTB trials were conducted first, followed by the cardboard trials and by the end of the cardboard trials all items had been attached with the most suitable tag.

Measure – Mobile Reader Results

Reader Type	Trial	B1(Clothing)	B2(Hygiene)	B3(Office)	Total
(Tag on Ziploc® bag)	1	88%	92%	67%	87%
(Tag on Ziploc® bag)	2	63%	50%	67%	57%
(Tag on Ziploc® bag)	3	75%	75%	33%	70%
(Tag on Ziploc® bag)	4	100%	67%	67%	78%
(Tag directly on item)	5	63%	50%	33%	52%
(Tag directly on item)	6	100%	83%	33%	83%
(Tag directly on item)	7	88%	75%	67%	78%
(Tag directly on item)	8	100%	92%	100%	96%

The initial testing of the mobile reader using only Omron Scorpion tags produced no reads on some items. This indicates that a combination of Omron, Avery Dennison, and Omni-ID tags would be required to achieve 100% read rates.

Measure – Mobile Reader Results

Trial	Reader Type	
	Psion (Linear)	Psion (Circular)
1	87%	80%
2	73%	87%
3	87%	93%
4	88%	94%
5	88%	88%
6	94%	88%
Total	86%	88%

Using the same tagging configuration as the fixed trials, the CTB was tested using both the linear and circular polarized mobile readers. The circular antenna showed a 2% increase over the linear antenna, but was much bulkier and heavier.

University of Nebraska Lincoln

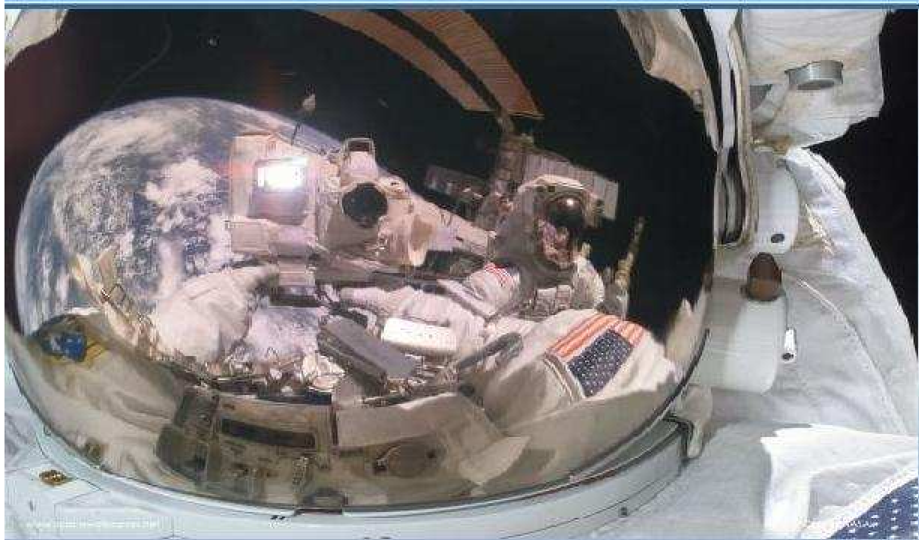
Define › Measure › Analyze › Design › Identify

Accuracy – Summarized Results

- All RFID systems were capable of handling data from multiple tags simultaneously
  - Limiting factor for mobile reader is output power/antenna gain
- Omron Scorpion tags demonstrated good performance on a wide variety of items
- AD 820/821 tags demonstrated a higher degree of readability on metallic items than the Omron Scorpion tag
- Omni-ID tags demonstrated superior readability on non-RF friendly items (liquids/metals)

Accuracy – Summarized Results

- Shampoo, toothpaste, shave cream, X-static clothing and batteries caused large decreases in readability
  - To be expected, as these are some of the most notorious RFID enemies
  - Decrease in performance overcome by using Omni-ID tags
- RF signal cannot penetrate these items
  - Can be alleviated by:
    - Adjusting antenna configuration
    - Moving the mobile reader around
    - Spinning the CTB



Experiment 2 – Analyze

Analyze – Fixed Reader
Analysis of Variance (ANOVA)

Table 1: Analysis of Variance for Read Rates: Fixed Reader Setup

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Container Type	1	0.003097	0.000398	0.000398	0.06	0.805
Distance	1	0.035832	0.044501	0.044501	6.96	0.014
Number of Antennas	2	0.031502	0.045980	0.022990	3.59	0.042
Movement of Items	1	0.120746	0.120746	0.120746	18.87	0.000
Error	25	0.159958	0.159958	0.006398		
Total	30	0.351135				

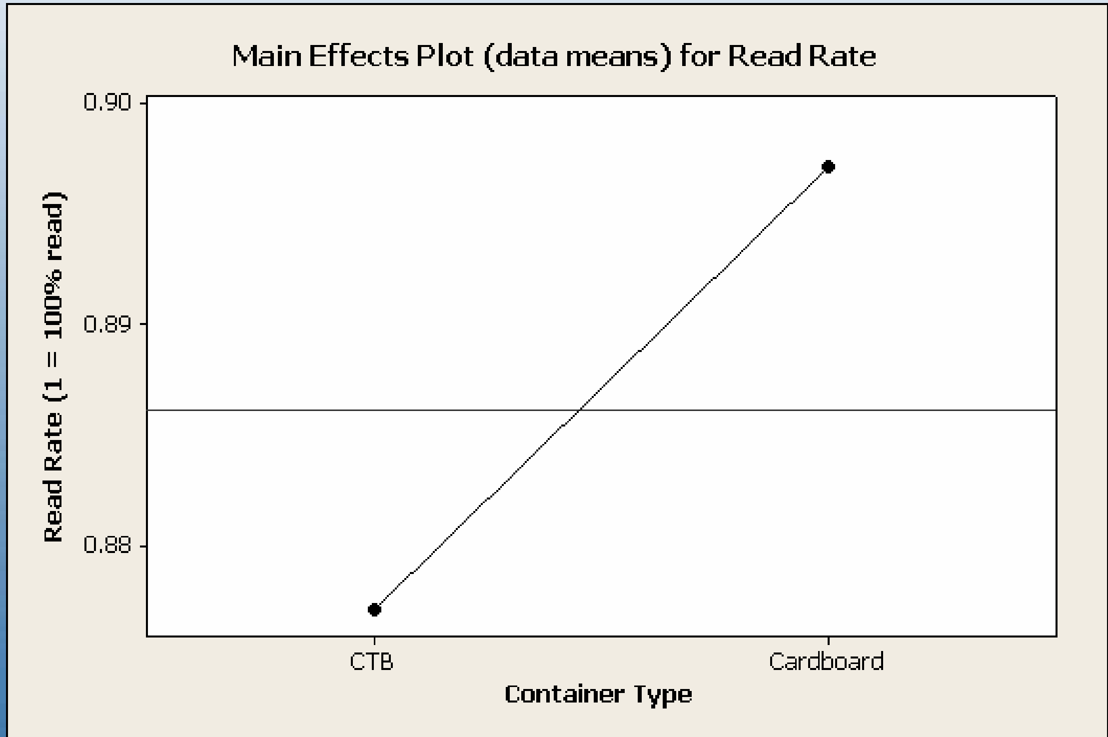
S = 0.0799896   R-Sq = 54.45%   R-Sq(adj) = 45.33%

As indicated by the P-values obtained from the data, all of the Main Effects were significant (alpha = 0.05) except the container type. This means that the container type, whether a cardboard box or CTB, does not have a significant effect on the read rates of the contents.

University of Nebraska Lincoln

Define › *Measure* › *Analyze* › *Design* › *Identify*

Analyze – Fixed Reader Container Type



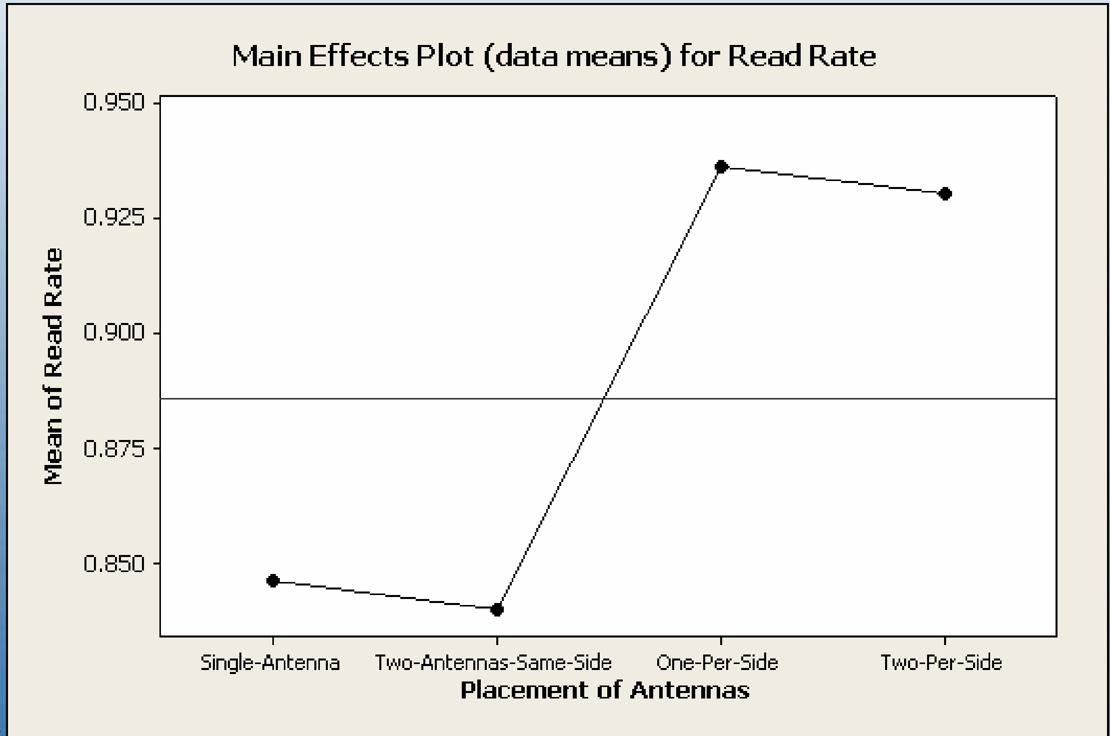
There was less than a 2% difference in the read rates between the CTB and the cardboard container. This shows that the material composition of the CTB has little effect on the RF signal as it passes through the container.

Analyze – Fixed Reader Distance

A significant decrease in read rates was noted as the distance between the container and the reader antennas increased. Read rates decreased from 92% at one foot away to 85% at a distance of three feet.

Define | Measure | Analyze | Design | Identify

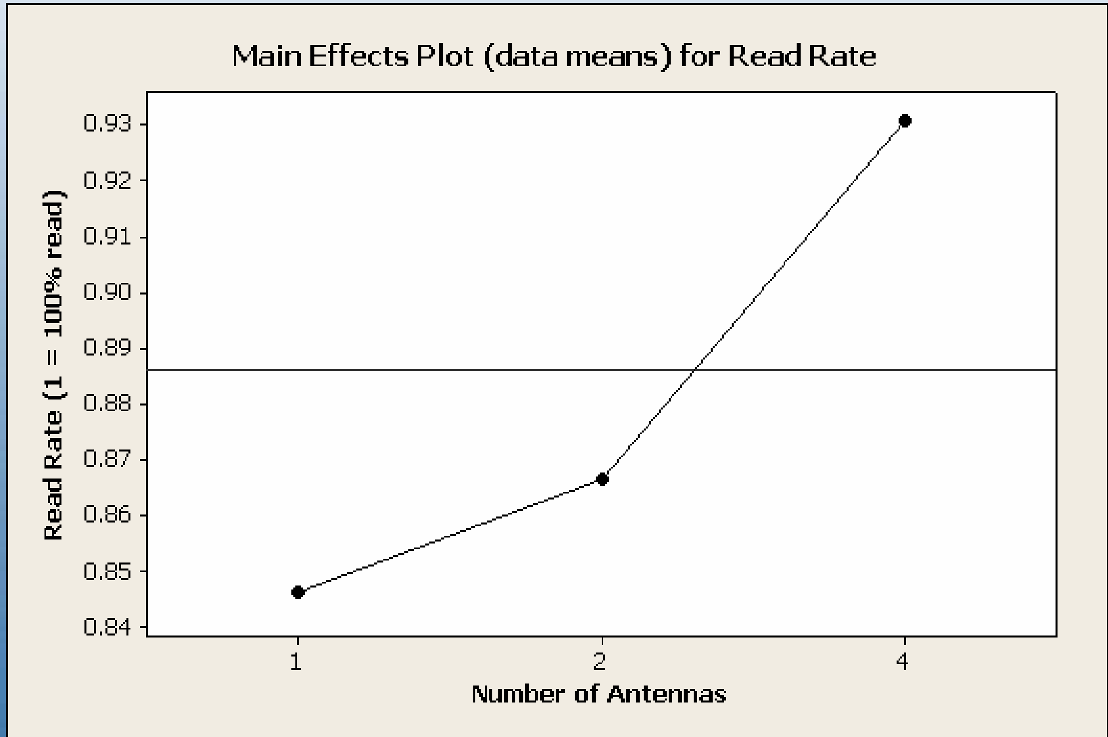
Analyze – Fixed Reader Antenna Placement



There is a significant improvement by placing antennas on opposite sides of the container. By creating a portal-type configuration (antennas on opposite sides) some of the issues with blocking and attenuation are alleviated.

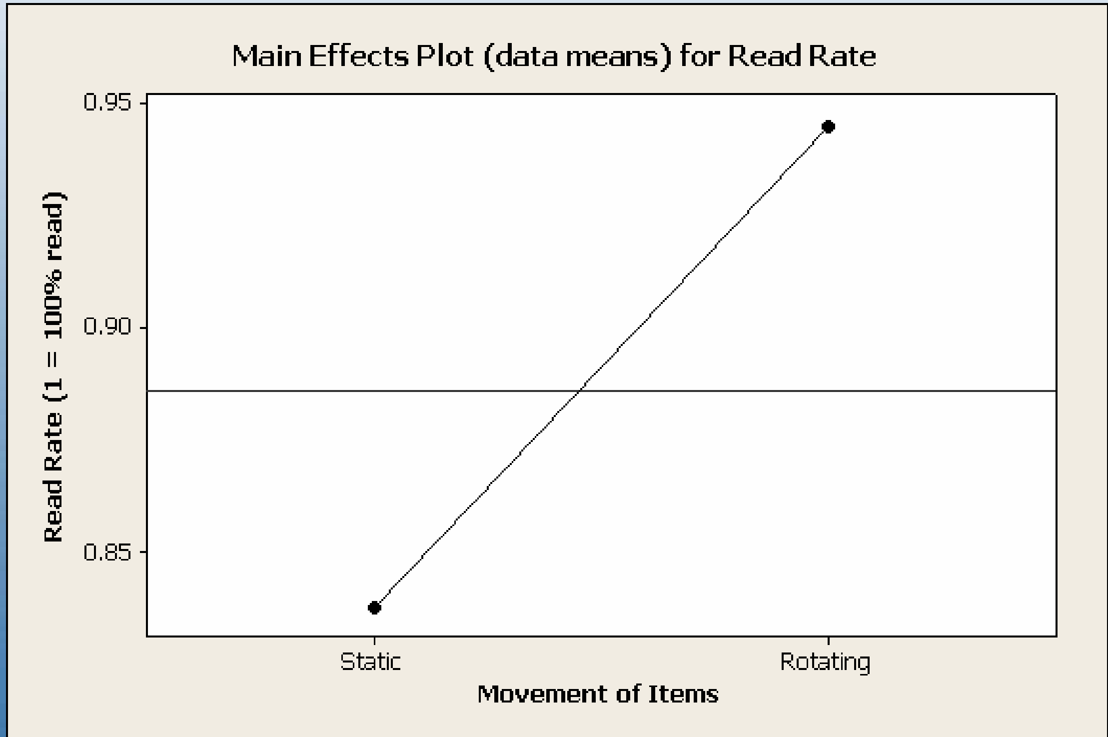
Define | Measure | Analyze | Design | Identify

Analyze – Fixed Reader Number of Antennas



Another look at the breakdown of data by reader antenna shows a strong increase as the number of antennas increase.

Analyze – Fixed Reader Movement of Items



When the data is separated by static and rotating trials for the fixed setup, a 10% difference was noted in the read rate. Rotating the container will help alleviate any orientation, attenuation, or blocking issues present.

Analyze – Fixed Reader Conclusion

- All items could be read regardless of material by using one of the three tags utilized in the study.
- Using multiple fixed antennas at close distances (1 – 2 feet from container) increases the probability of reading all items within the container
  - Orientation sensitivity is a critical factor. The data collected in this study was based on an ideal packing configuration. Random packing orientations may greatly reduce read rates.
- Portal antenna configurations performed much better than single side antenna configurations.

Analyze – Mobile Reader Conclusion

- The mobile handheld reader could read all items individually, but some problems still persist with reading the items in a CTB:
  - Output power/antenna gain of the reader requires the tags to be in close proximity to the reader (scans were performed within one foot of the container in order to read all items).
  - The reader must be moved around all sides of the container in order to read every item within the container. This could also be caused by inadequate output power or antenna gain.

Analyze – Tags

- Size
  - All three tags fit within specifications from initial proposal
    - AD 820/821 and Omron Scorpion are flat tags and can easily be attached via pressure sensitive labels.
    - Omni-ID Prox tag is small, but is very thick due to improved antenna design for liquid and metal materials

Analyze – Tags

- Conclusion
  - **Omron Scorpion** tag should be used on all non-liquid or non-metallic items
  - **AD 820/821** tag should be used on semi-metallic materials (i.e., batteries, razor blades, and microcassettes)
  - **Omni-ID Prox** tag should be used on all other liquid and metallic items (i.e., shampoo, toothpaste, and mouthwash)

Analyze – Readers

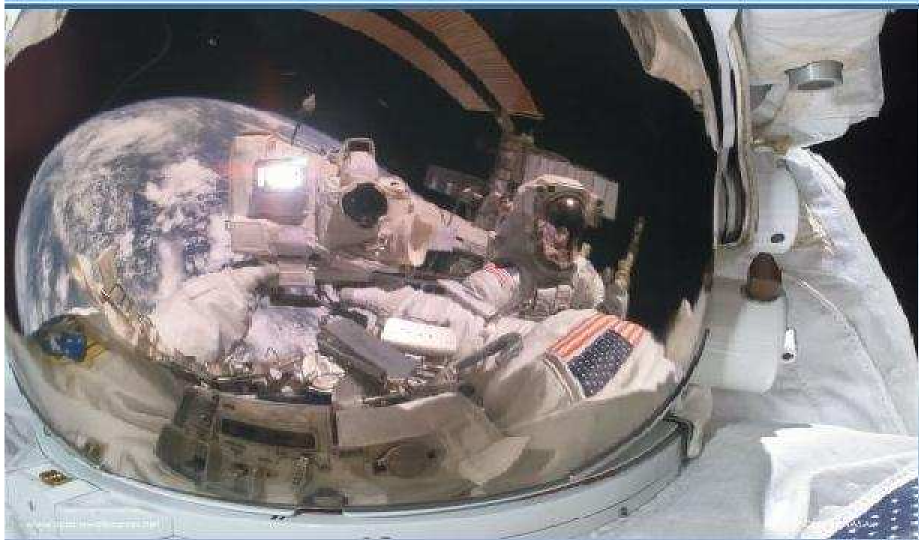
- Range
  - Fixed passive readers are able to read tags accurately and consistently with proper antenna configurations.
  - Handheld devices typically have a shorter range.
- Implementation
  - Fixed readers need power, room to be mounted (door portals, smart shelves, etc.)
  - Handheld reader may require increased output power or a higher antenna gain for success.

Analyze – Mobile Readers

- Conclusion:
  - Little difference in performance between basic linear polarized antenna and large circular polarized antenna
    - Circular antenna showed slight increase in read rates
  - Circular polarized antenna is much bulkier and heavier

Analyze – Software

- VerdaSee Navigator fixed reader software could provide a basis platform and could potentially be integrated into existing IMS
- Handheld demo software is not inventory application specific.
  - Inventory management applications would need to be developed prior to implementation



Summarized Results

Results – Experiment 1

- Slight decrease in performance as distance increased from 5 ft. to 10 ft.
- Read rates dropped significantly when tags were placed on metal and liquid
  - Only three tags produced reads on these materials
  - Gen 2 specialty tags such as the Omni-ID Prox tag have shown significant improvements over Gen 1 tags on these types of items
- Tag orientation had only a minimal effect on read rates

Results – Experiment 1

- Tags with the best performance on all materials that were chosen for Experiment 2
  - Omron Scorpion
  - Avery Dennison 820/821
  - Omni-ID Prox

Results – Experiment 2

- Scan containers within 10-15 seconds
  - If a tag is going to be read at all, it is read almost instantaneously by all RFID systems
- Accuracy ≥ 99%
  - Under optimal conditions, the fixed reader setup meets this requirement
  - Mobile reader still at only 94%
- Tag Size Smaller than 3" x 2"
  - All tags tested in Experiment 2 fall within this range

Results – Experiment 2

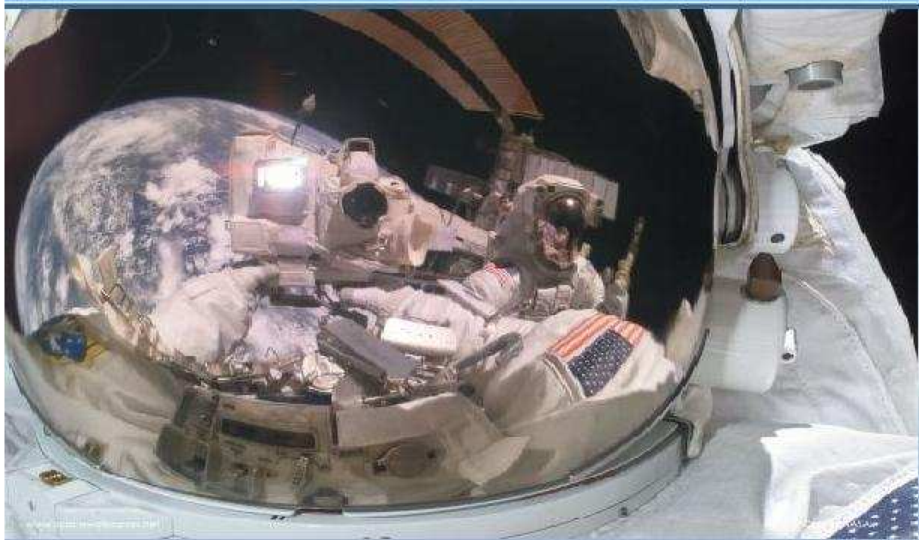
- Optimal Conditions for Fixed Reader Configuration
  - Organized packing within the CTB
  - Multiple antenna setup
    - Portal configuration so CTB is scanned from multiple directions
  - Reader antennas within close range of CTB (1 – 2 ft.)

Nebraska University of Lincoln

Define > Measure > Analyze > Design > Identify

Results – Experiment 2

- Number of tagged items in each bag/container comparable to flight data provided
  - With IMS or similar middleware, tag IDs can be matched up to individual consumables on ground
  - Matching acquired tag IDs from RFID reader to IMS will ensure that system meets this requirement
- Determine items which will interfere with RFID signals
  - Metal and liquid are chronic RFID problems
    - Not a key issue due to the development of Gen 2 liquid/metal specialty tags
  - All items were readable using one of the three tags from Experiment 2



Recommendations

Recommendations – Tracking

- Investigate the feasibility of increasing antenna gain and/or output power for mobile readers
- Investigate NASA defined portal configurations for fixed readers
- Investigate the feasibility of smart shelf configurations
- Investigate smart bag prototypes

Recommendations – Tracing

- Investigate the feasibility of RFID software to integrate with NASA inventory control systems
- Investigate the feasibility of creating a user friendly mobile reader application
  - Investigate a modified COTS approach

Define › *Measure* › *Analyze* › *Design* › *Identify*

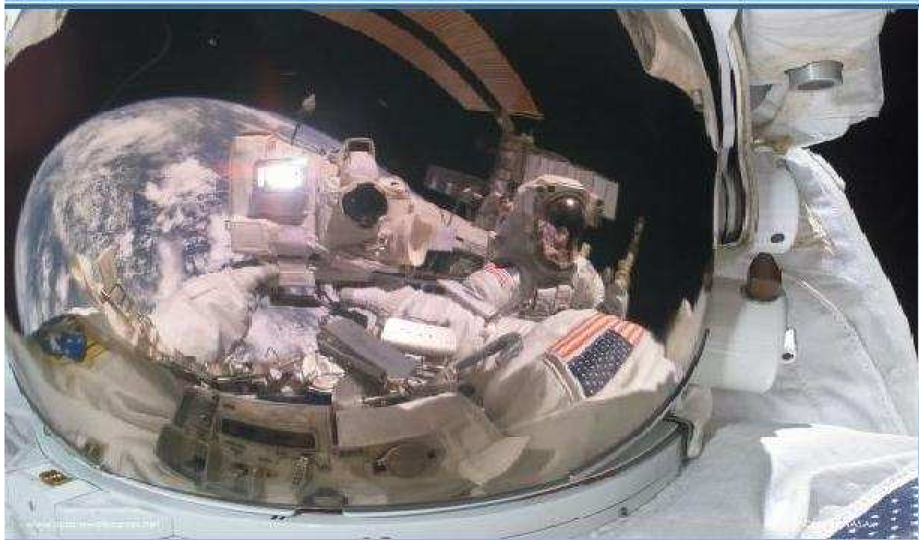
Recommendations – Locating

- Investigate RFID based Real Time Location Systems (RTLS) ability to locate items in NASA type containers including:
  - Rooms
  - Containers
  - CTB's
  - Boxes
- These technologies could include active RFID sensor tags or location using passive triangulation

Define > Measure > Analyze > Design > Identify

Recommendations – Hybrid Tracking and Locating

- Investigate an RFID active and semi-active technology configuration (Sensor Tag) that can be used with a container such as a CTB
  - Tracking capabilities use semi-active technology for scanning contents
  - Active technology provides battery assisted signals for location of the container

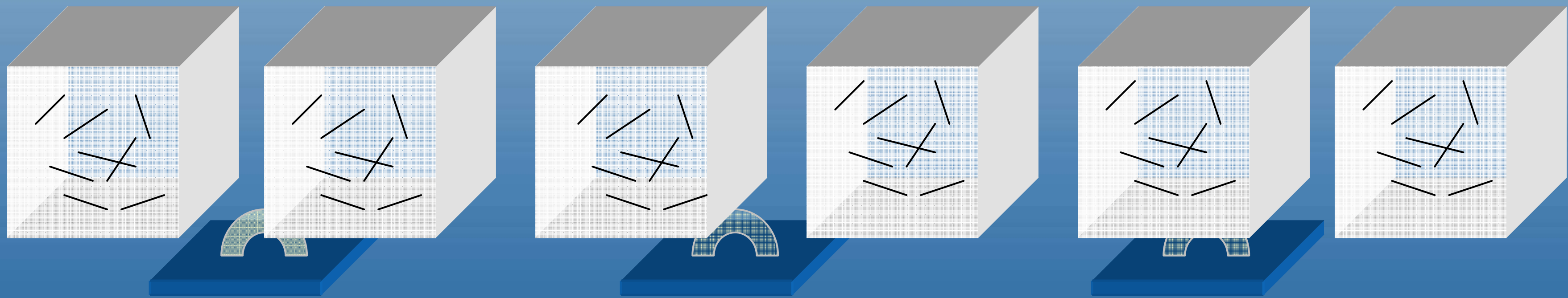


Design

Theoretical Phase II System Design Options

Smart Shelf

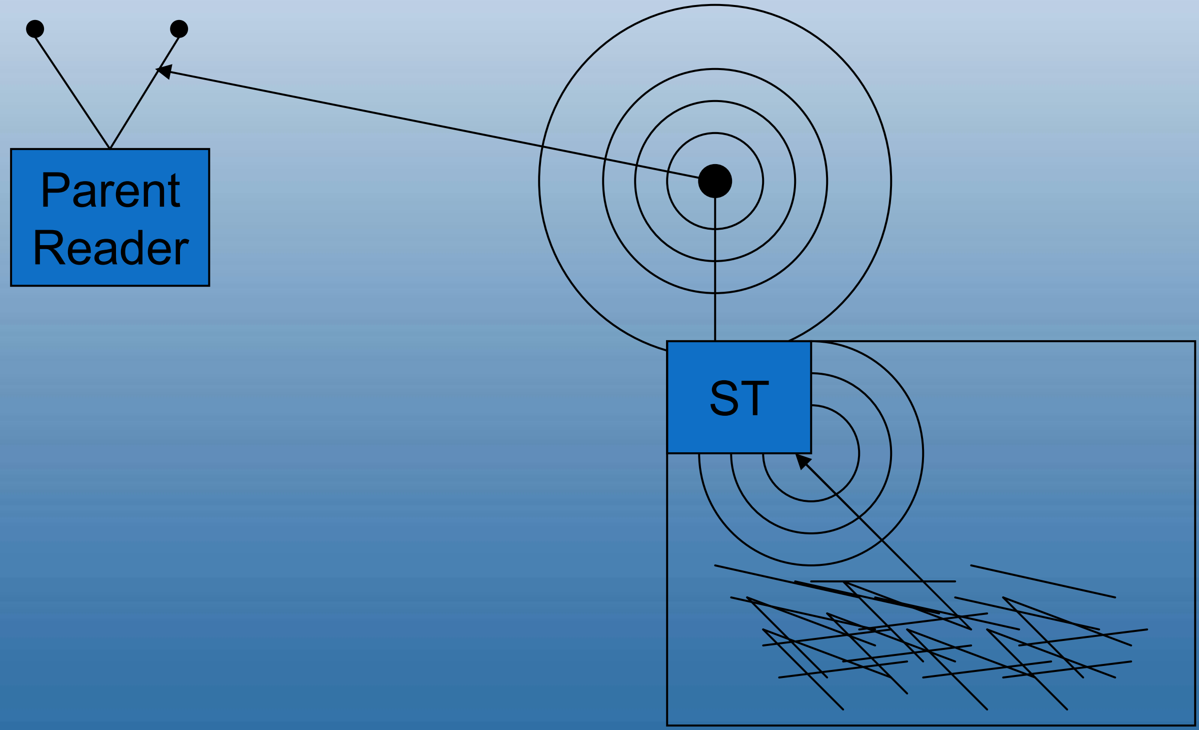
- Shelves are equipped with built in RFID readers
- The shelves periodically scan items
- Shelves then transfer data to computer to keep track of information
- Items can be easily located in a space environment



Sensor Tag System – Concept

- Reader and Active Tag combine into one unit, creating Sensor Tag
- CTBs mounted with Sensor Tags interrogate passive tags on items
- Data transmitted from Sensor Tag to parent reader
- Data added to IMS

Sensor Tag – Diagram

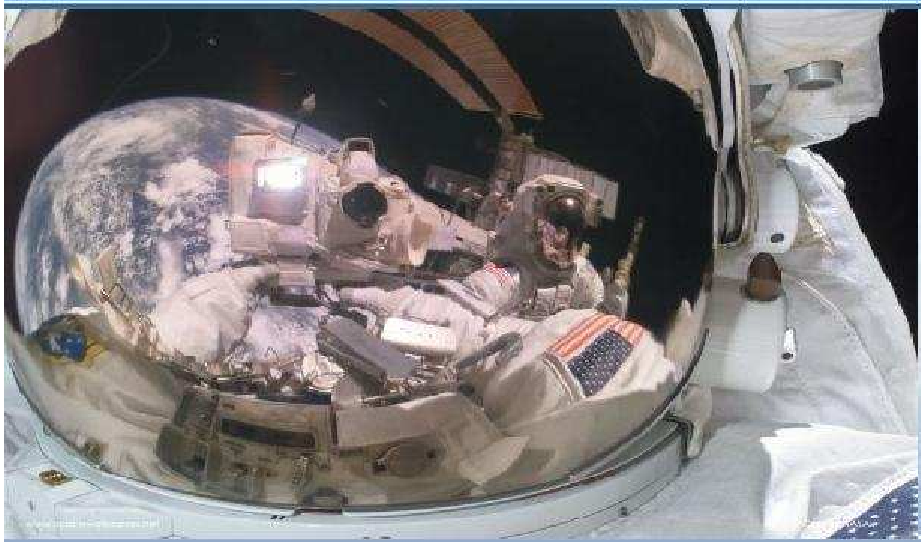


Sensor Tag – Benefits

- Total asset visibility
  - Up to the minute knowledge of how many items are onboard
  - Provides built in locating capabilities
- Limited to no crew intervention
  - System can be set up to be completely automated or to be dormant until queried from parent
- Little change to current infrastructure

Sensor Tag – Challenges

- No available COTS
  - Theoretically uses COTS components, but actual sensor tag will need to be developed
- Each CTB would contain active RFID components
  - May increase radiation output
- Long distance communication
  - Many metal surfaces, background radiation, etc.
- Design of prototype must be completed before testing can begin
  - Will require combination of COTS components



Identify – Next Steps

Phase II Research Opportunities

Possible Phase II Solutions

- Review, update, and confirm NASA testing protocols and scenarios for testing RFID identified inventory
- Evaluate modified COTS RFID mobile and fixed readers for improved tracking in NASA space operations
- Investigate:
  - The feasibility of increasing antenna gain and/or output power for mobile readers
  - Smart shelves and smart bag prototypes

Possible Phase II Solutions

- Evaluate modified COTS software for improved data capture and tracing purposes
- Investigate:
  - The feasibility of RFID software to integrate with NASA inventory control systems to trace inventory information
  - Creating a user friendly mobile reader application

Questions?

Authors

- Dr. Erick Jones – University of Nebraska-Lincoln
  - ejones2@unl.edu
- Casey Richards – University of Nebraska-Lincoln
  - Graduate Assistant
  - cnr2003@gmail.com
- Evan Yagoda – NASA Johnson Space Center
  - Evan.L.Yagoda@nasa.gov
- Reuben Vasquez – VerdaSee Solutions, Inc.
  - reuben.vasquez@verdasee.com

Acknowledgements

- Andrew Chu – NASA Johnson Space Center
- Michael Vasquez – VerdaSee Solutions, Inc.