CAAP Quarterly Report

Date of Report: *April 9, 2016*

Contract Number: *DTPH5614HCAP04*

Prepared for: *Arthur Buff, Project Manager, PHMSA/DOT*

Project Title: *Embedded Passive RF Tags towards Intrinsically Locatable Buried Plastic Material*

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Contact Information: *Dr. Yiming Deng (CU-Denver) and Dr. Prem Chahal (MSU)*

For quarterly period ending: *April 10, 2016*

Business and Activity Section

(a) Generated Commitments

Project abstract: Accurate and reliable locating, identifying and characterizing the buried plastic pipes from the ground surface in reducing the likelihood of hit them is critical and imperative to reduce the pipeline incidents. In this collaborative research, a new harmonic radar (frequency doubling) mechanism for smart RF tags design that can detect plastic pipes deeply buried in various soils conditions will be investigated, achieved through efficient tags and highly sensitive readers design, and coupled with intelligent signal processing. The proposed low-cost, small thin-film form passive RF tags can directly be embedded in plastic pipes. It will be able to withstand high temperature processing of plastics and stress involved with horizontal tunneling/drilling of buried pipes. The embedded RF tags have the capability to not only precisely locate the buried plastic pipes, but also have integrated sensing functionality, which can measure the strain-stress changes in the plastic materials. Finally, the vast amount of acquired sensing data from individual tags will be integrated to the advanced signal processing for better data categorization and mining. An innovative prognostics framework for better asset life-cycle management will be developed.

A complete solution is needed that helps in identifying individual buried pipes, their precise location, determining their integrity and sensing for leaks. Buried pipes are expected to have a lifetime of greater than 30 years that are designed to carry a range of liquid and gaseous materials. Among the many pipe technologies, demand for plastic pipes is growing largely because of their low-cost and potential for long life time. Any tags or sensors that are incorporated within these pipes should be able to withstand harsh conditions with a lifetime meeting or exceeding that of the pipes, and should be battery free (passive tag). Furthermore, the overall system should be compact, low-cost, and easy to operate. With advanced techniques to bury the pipes using tunneling approaches it is necessary that tags withstand the associated stress and handling during construction work. Typically, the pipes are buried 3 feet or deeper in the ground and thus the reader should be able to interrogate the tags at these and at higher depths (greater than 5ft is desired).

As summarized in Introduction section, significant advances have been made in the area of electronic tagging of buried objects. However, most of these tags are an afterthought as they are not integral part of the infrastructure. These tags are typically large and are buried along with the objects.

This is simple if open trenching is carried out. However, for plastic pipes that are buried using tunneling this approach will not suffice without making the tags an integral part of the plastic pipe. Furthermore, no RF tags are commercially available that will allow in sensing of the environment and the integrity of the buried object during its life time. Smart RF tag designs are necessary as power harvesting and storage techniques will also have limited life time as the rechargeable batteries (or capacitors) and the associated circuit (e.g., piezo power harvester) will have a limited lifetime. Meanwhile, no advanced data processing algorithms are available for optimally manage and use the vast amount of information embedded into the received RF signals from the proposed new tags. Under this three-year project, the specific technical objectives/goals of the proposed research are:

1) Design and development of new passive harmonic radar based smart RF tags with long range detection guided by industry partners;
2) Design robust and miniature tags such that they can directly be embedded in plastic pipes during manufacturing;
3) Investigate on-tag strain-stress sensing capabilities and efficient data transmission;
4) Investigate new massive RFID data mining, processing and classification algorithms with experimental testing;
5) Develop a Bayesian Learning based pipeline hazardous prognostics methodology using discrete sensing data;
6) Intrinsically locatable pipe materials demonstration and field testing using representative pipe specimens with GPGPU acceleration.

Another equally important objective of this proposed research is to engage MS and PhD students who may later seek careers in this field by exposing them to subject matter common to pipeline safety challenges. Since the project being kicked off, three PhD students from both universities and several MS students have been recruited and trained through this CAAP program and apply their engineering disciplines to pipeline safety and integrity research. The PIs think the educational component is a very important part of the CAAP project and will integrate with research activities with various educational activities to prepare the next generation engineers for gas and pipeline industry. The educational and research impacts sponsored by CAAP has been recognized within the university (see *support letter 3 from Associate Vice Chancellor of university*) and nationally (Two current CAAP-funded students at CU haven been recognized at ASNT annual research symposiums in 2014 and 2015). Specific educational objectives and goals are:

1) Guide and train graduate students at University of Colorado-Denver and Michigan State University for the pipe integrity assessment and risk mitigation;
2) Integrate with existing mechanisms for undergraduate research at University of Colorado-Denver and Michigan State University for early exposure of pipe industry research to potential engineers;
3) Improve the current curriculum teaching at University of Colorado-Denver (ELEC5644 Nondestructive Evaluation and ELEC3817 Engineering Probability and Statistics) and Michigan State University (ECE802-1 Microwave and Millimeter Wave Circuits and ECE802-2 Electronic Systems Packaging) using the achievement from the proposed research;
4) Invite pipe industry expert (see support letters later in this proposal) to deliver seminar/workshops to undergraduate/graduate students about the challenges and opportunities in gas and pipeline industry;
5) Encourage the involved students to apply internships at DOT and industry to gain practical experiences for the potential technology transfer of the developed methodologies.

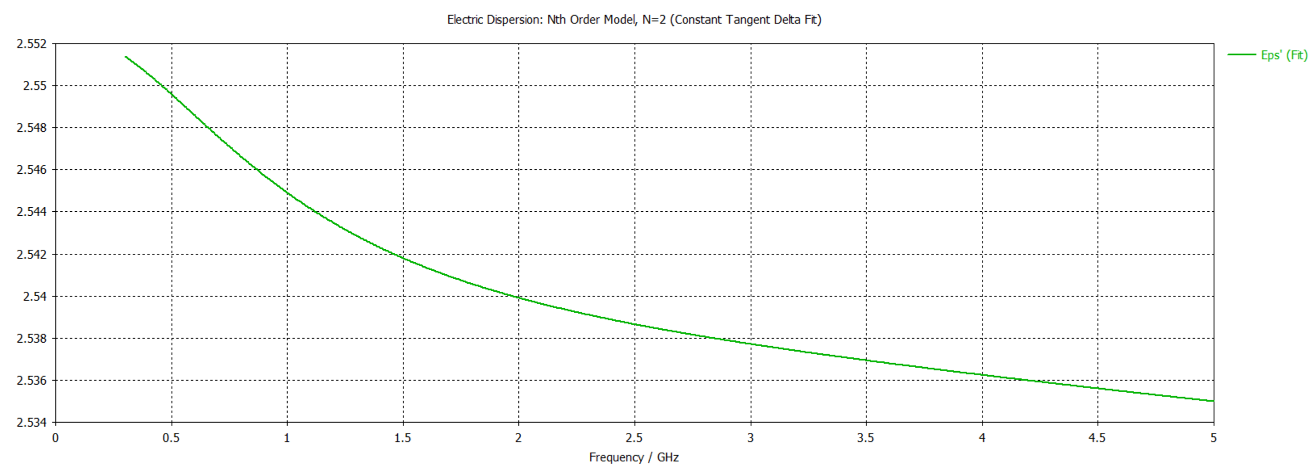
The above-mentioned goals and objectives of the proposed Competitive Academic Agreement Program (CAAP) project will be well addressed and supported by the proposed research tasks.

Development, demonstrations and potential standardization to ensure the integrity of pipeline facilities will be carried out with the collaborative effort among different universities and our industry partners. The quality of the research results will be overseen by the PIs and program manager and submitted to high-profile and peer-reviewed journals and leading conferences. The proposed collaborative work provides an excellent environment for integration of research and education as well as tremendous opportunities for two universities supported by this DOT CAAP funding mechanism. The graduate students supported by this CAAP research will be heavily exposed to reliability and engineering design topics for emerging pipeline R&D technologies. The PIs have been actively encouraging students to participate in past and ongoing DOT projects and presented papers at national and international conferences. Students who are not directly participating in the CAAP project will also benefit from the research findings through the undergraduate and graduate courses taught by the PIs and attending university-wide research symposium and workshop, e.g. RaCAS at CU-Denver. The proposed research involves pipeline industry to validate and demonstrate scientific results and quantify engineering principles by working closely with industry partners. They will also collaborate with the CAAP team on this research which may include but is not limited to information exchange, mutual meetings, providing CU and MSU with appropriate technical support for the target application.

(b) Status Update of Past Quarter Activities

Task 1.1 - Study the properties of different soil types for RFID data modeling

The study of different soil types from quarter 1 is extended to the change in electrical properties over the range of frequencies. The electric dispersion of sandy and loamy soil types are studied. In DRY and WET conditions, the change in properties of both soil types are similar. Fig.1a, 1b and Fig.2a, 2b shows the change in sandy and loamy soil over the frequency range (300 MHz- 5 GHz) respectively.



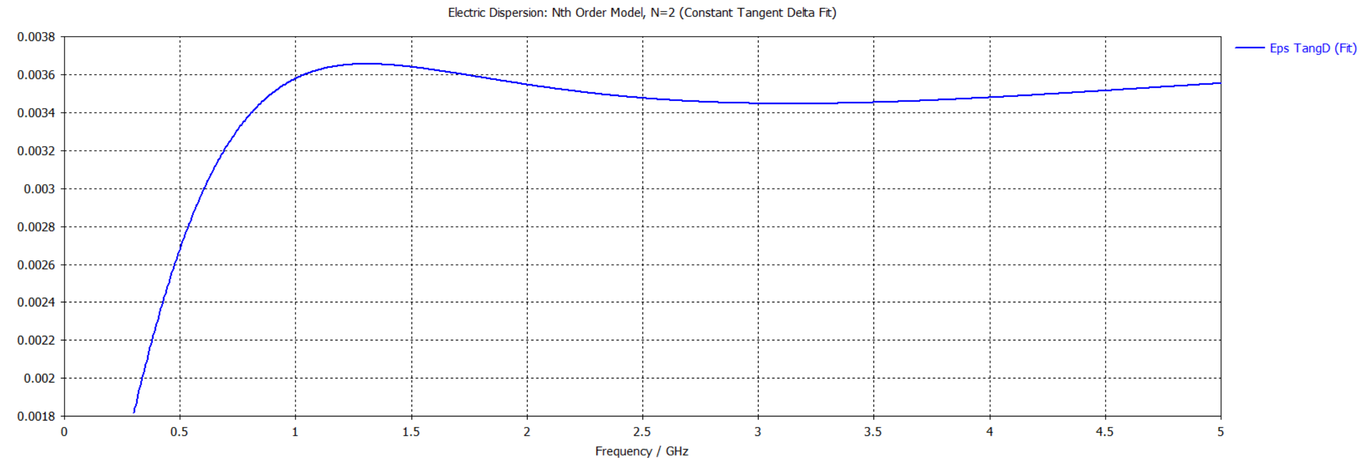


Fig. 1a Sandy Dry Soil

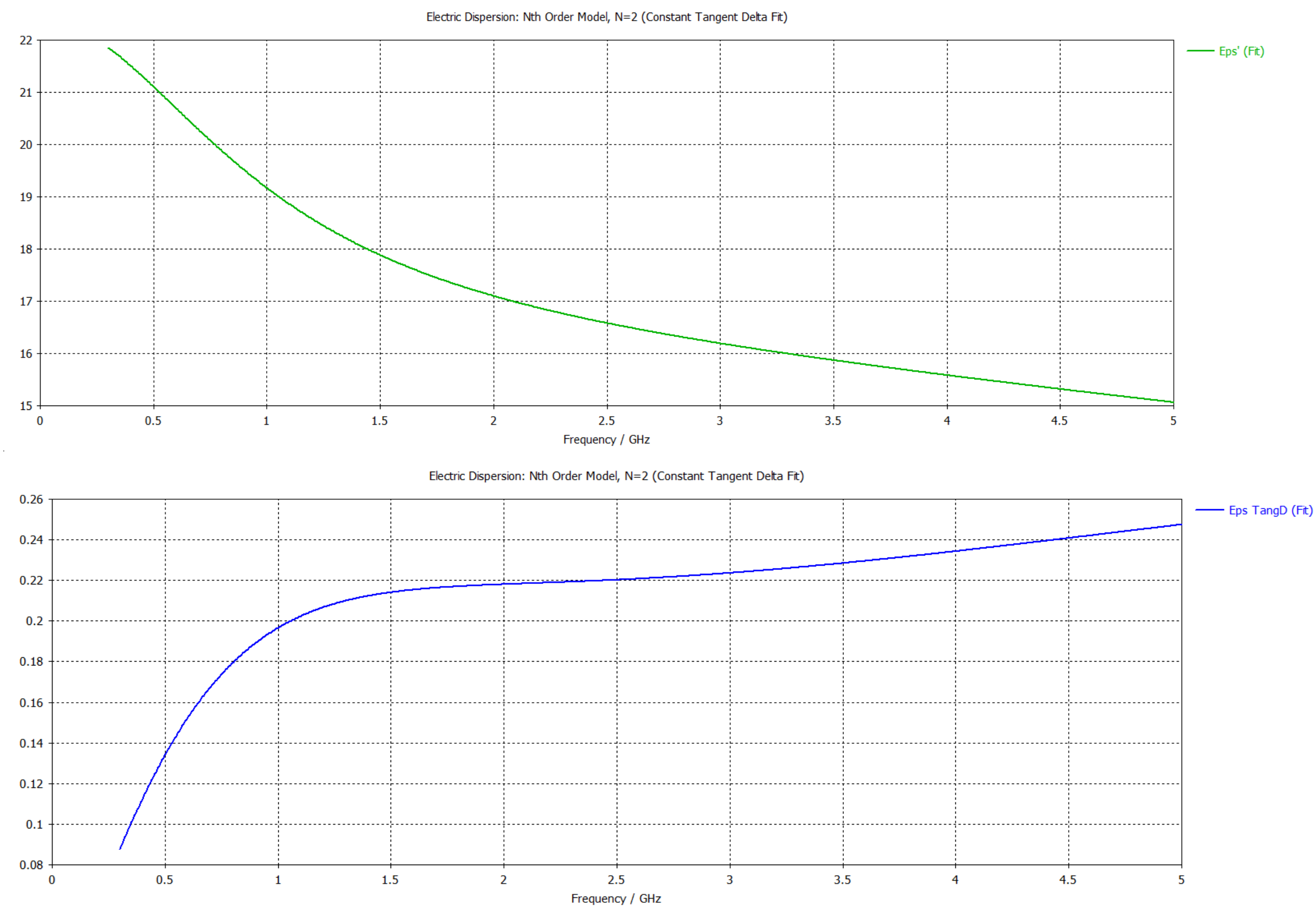


Fig. 1b Sandy Wet Soil

In Fig.1a the represented sandy dry soil didn't change much of its permittivity with frequency, so make us independent of selecting any frequency in range but the loss tangent is higher for high frequencies, which suggest to keep the system's operating lower for efficient long distance propagation.

In Fig.1b the properties show some significant change due to additional 18.8% of water contents.

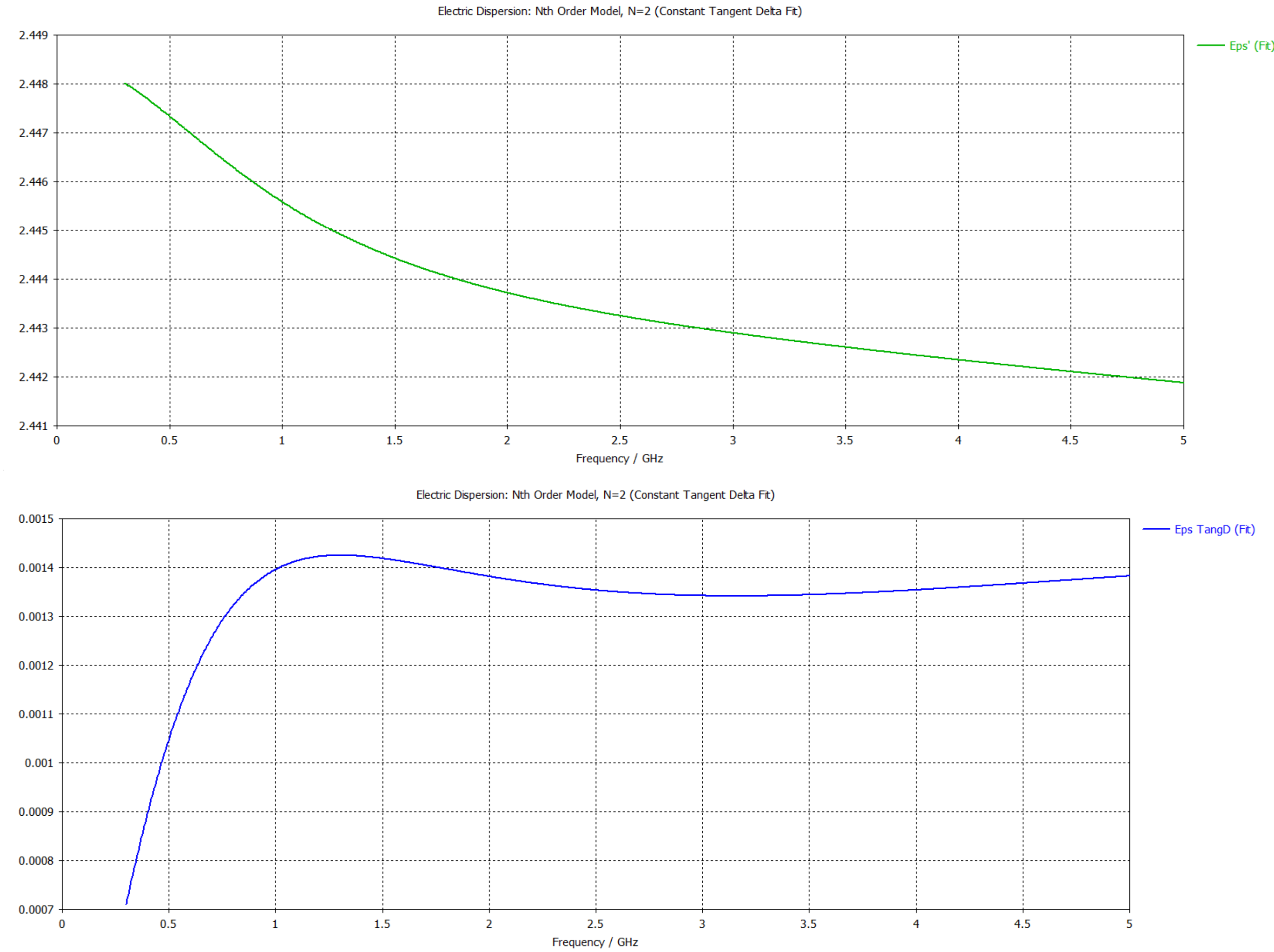
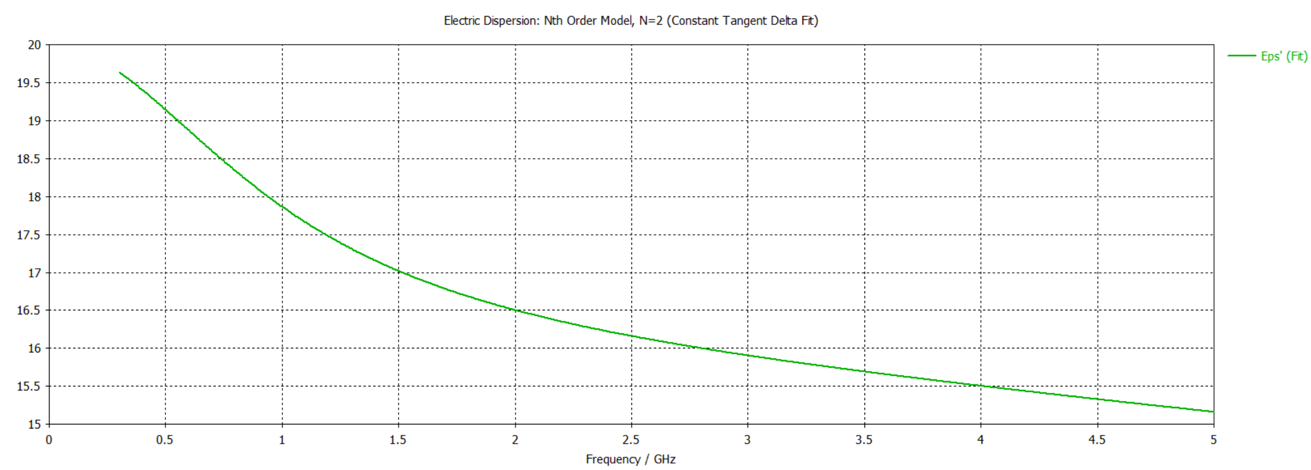


Fig. 2a Loamy Dry Soil



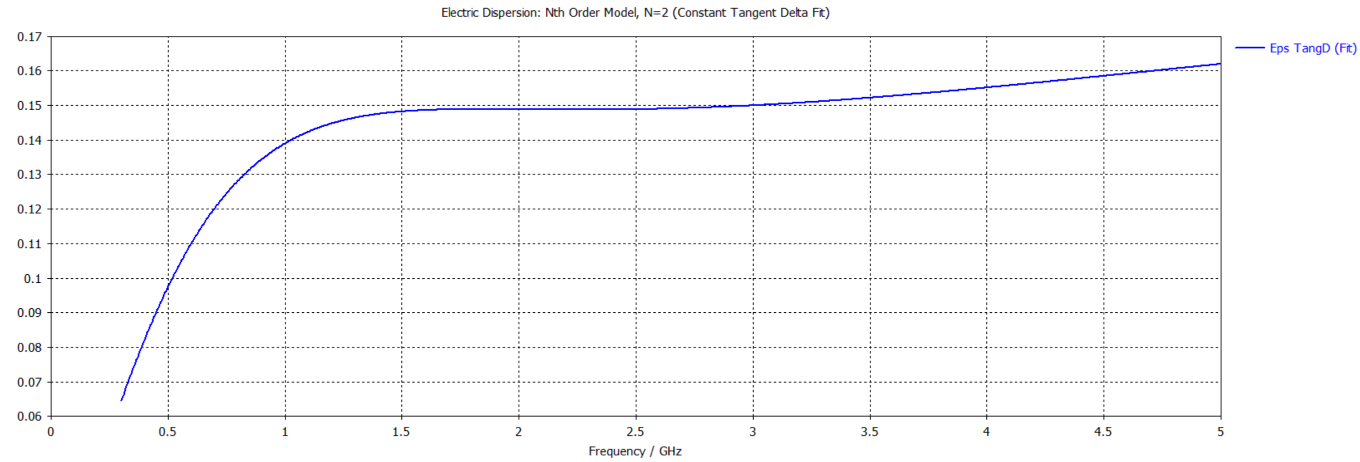


Fig. 2b Loamy Wet Soil

The sandy soil and loamy soil has some difference in electrical properties, the change is similar and both soil types behave in same way by increasing loss tangent with additional water contents.

The percentage of water contents in sandy-wet and loamy-wet soils are 18.8% and 13.7% respectively. The conclusion drawn from above data is that the electric permittivity of dry soil isn't very high and didn't vary much as well with the change in frequency, but the wet soil shows the high values with large change. The loss tangent represent the conductivity of the soil type is higher as expected for wet soil that leads to more dispersion and losses. Using this data we can set upper and lower bound to the permittivity (2-22) and conductivity (0.0018- 0.26), now we can try to solve the problem with these properties of soil. The range is wide for both parameters, but the effects of change in permittivity are way less than the change in conductivity.

Analytical model of power propagation into soil with different relative permittivity and conductivity is shown in Fig.3. The following data plot is of power received at different depth in dry sandy soil. The transmitted power is $1W,\ \epsilon_r = 2\ and\ \sigma = 0.002$.

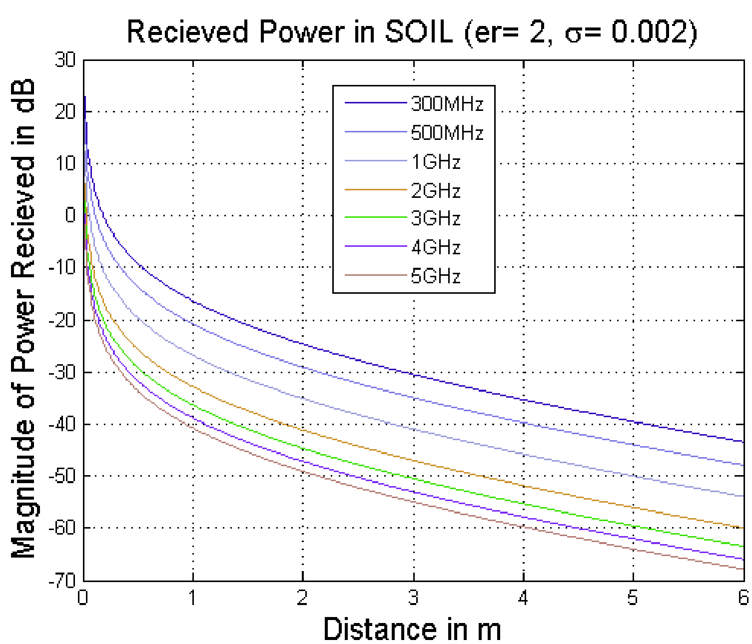


Fig.3 Power transmission in soil with $\sigma = 0.002$

If we keep the same model and increase the conductivity of soil means add water contents in the soil, the magnitude of transmitted power decreases significantly. Shown in Fig.4.

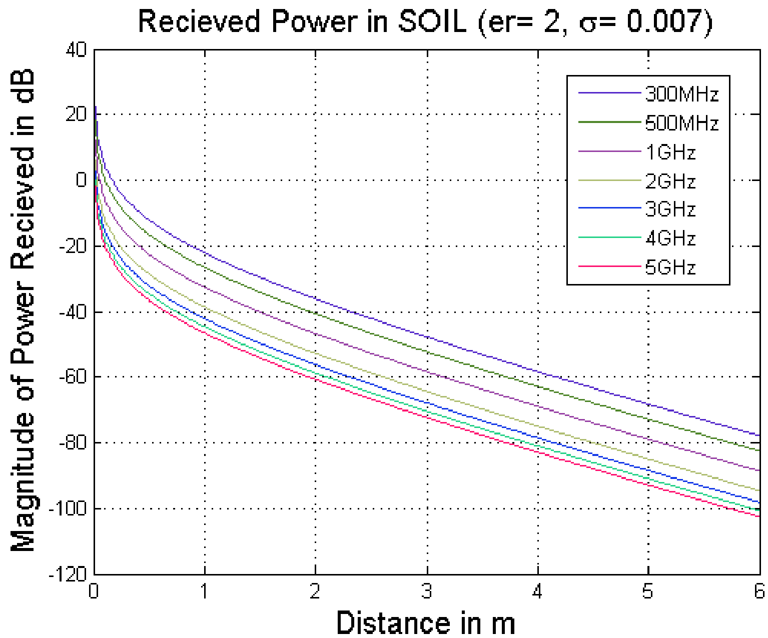


Fig.4 Power transmission in soil with $\sigma = 0.007$

Whereas the change in relative permittivity didn't effect much over power transmission, supported by Fig.5

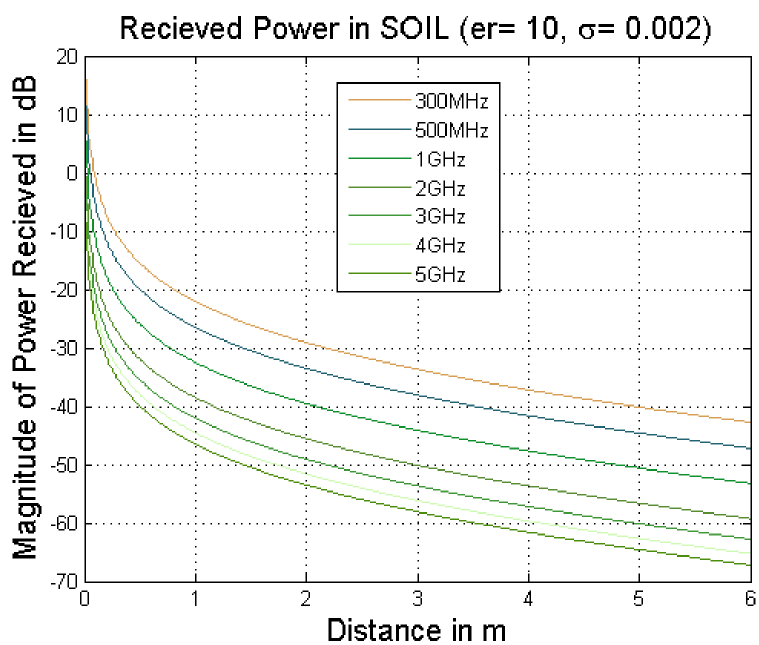


Fig.5 Power transmission in soil with $\epsilon_r = 10$

Additionally, a simulation model is created in COMSOL for supporting our argument that the choice of lower frequency will help us penetrating deeper into ground. Fig. 6 explains the setup we modeled.

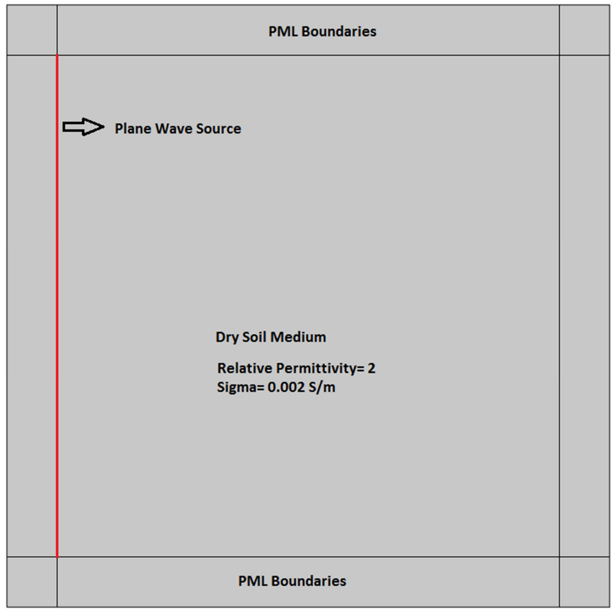
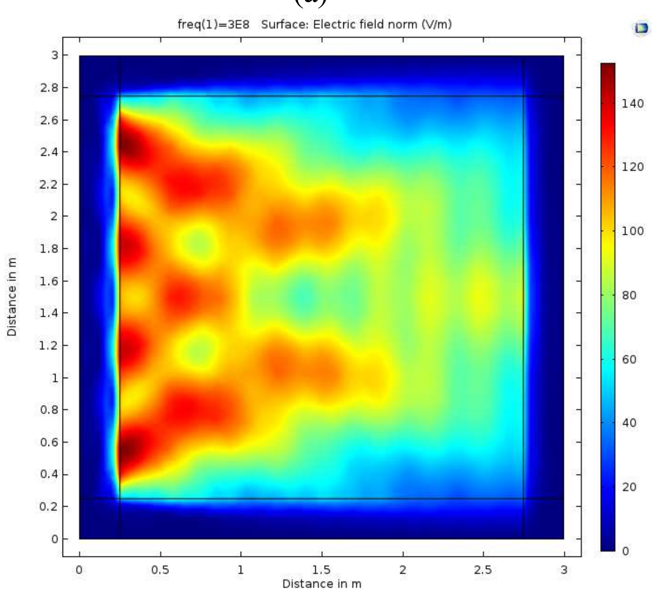


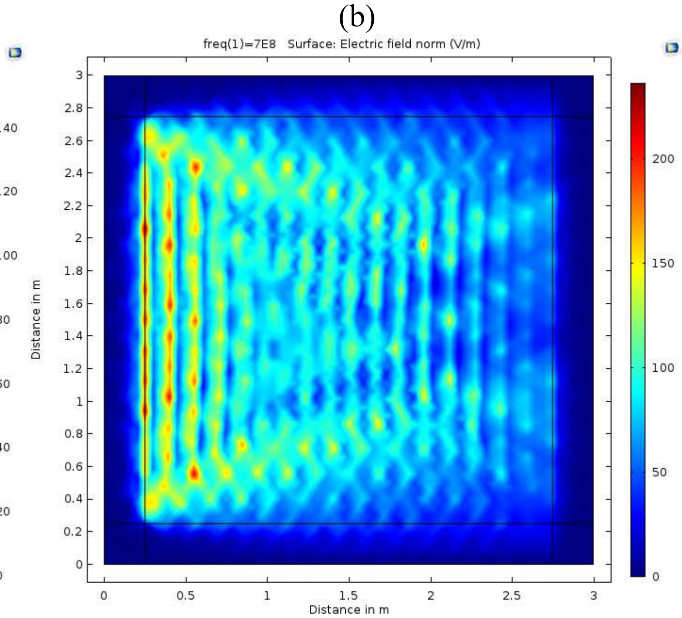
Fig.6 COMSOL model

The medium is excited with a plane wave source that is selected for simplicity and just to check the power transmission. The electrical parameters of the material are kept same as $\epsilon_r = 2 \; and \; \sigma = 0.002$. The 2D simulation is run over some different frequencies and the results are as follows:

(a)



(b)



(c)

(d)

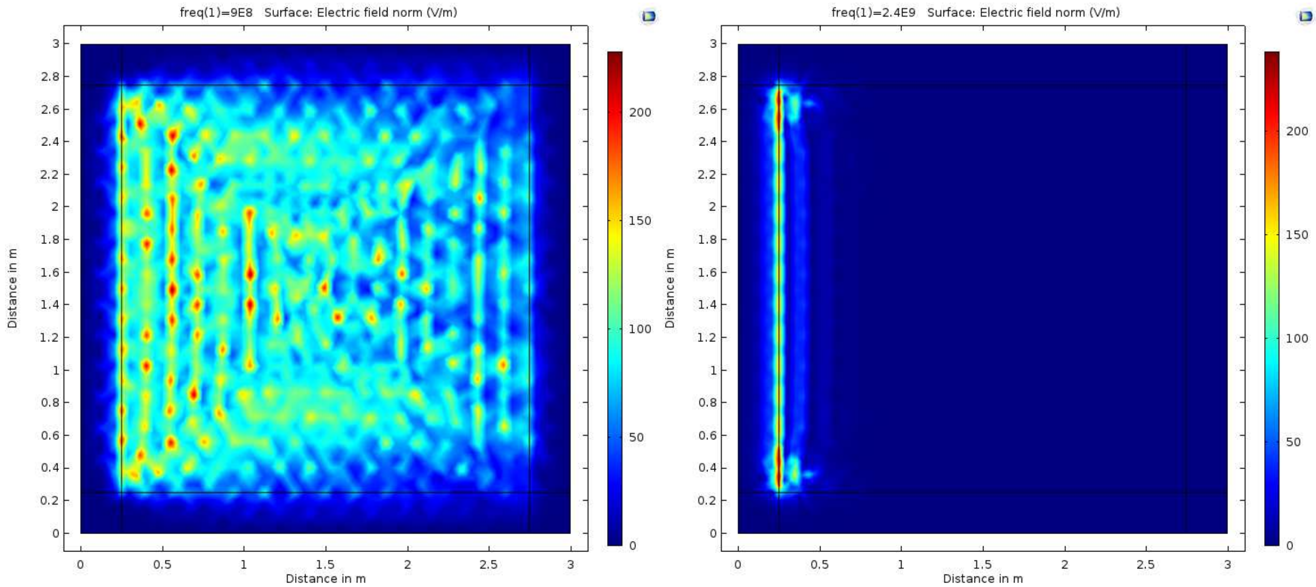


Fig.7 (a) 300 MHz, (b) 700 MHz, (c) 900 MHz and (d) 2.4GHz

Fig.7 shows the behavior of dry soil type with different source of frequency. Conclusion drawn from this also supports the facts that lower frequency trails further into medium. If we use (a), (b) or (c) frequency model we can easily see some power down at 3m distance, but the (d) 2.4GHz frequency only propagated up till only half a meter.

The lower frequencies promises better results than higher frequencies but they have a problem with antenna size. If we go lower in frequency (increases wavelength) it leads to design a much bigger size antenna. There is a tradeoff between efficient power transmission and size of antenna.
The application of this technology will be mainly for tracking pipes of different sizes and it's difficult to mount the bigger size antenna over a small pipe.

900 MHz band is selected for the initial development of system, selecting this band is advantageous due to the massive previous researches and some commercially available tools for further development. Huge section of current passive RFID infrastructure uses this band for communication and has already developed some efficient and optimized systems. We will take these systems as basic building blocks and create new method that will provide considerably good results for underground RFID tag communication system up to 10ft.

Task 1.2 Current working RFID setup at University of Colorado Denver:

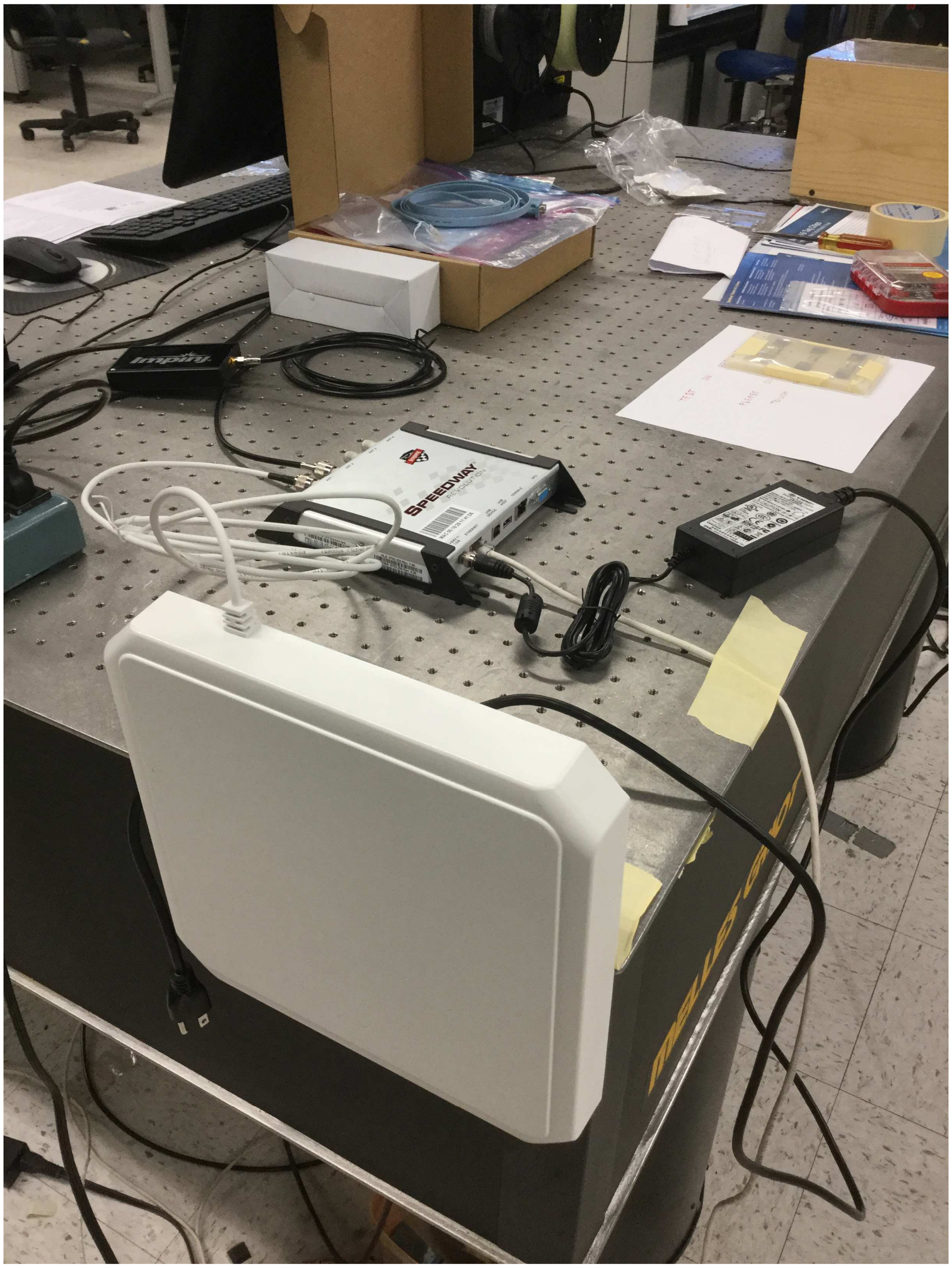


Fig 8. Lab Set-up of Antennas, Antenna-Source/Acquisition Hardware

Source:

Fig.9 Antenna Source and acquisition hardware

Speedway R420 is a commercially available RFID system by Impinj operated in UHF band. It can be connected with 4 monostatic antennas at a time and has -82 dBm of receiving sensitivity. Return loss for all ports is 10 dB.

Transceiver Antenna:

Transceiver antenna is circularly polarized panel that operates in 902-928 MHz frequency band.
<u>Antenna Specifications:</u>

Gain	9 dBic
Max VSWR	1.3:1
Front to Back ratio	20 dB
Max Input Power	10 W
Input Impedance	50 ohm
Axial Ratio	1 dB
3 dB beamwidth- Azimuth	70 degree

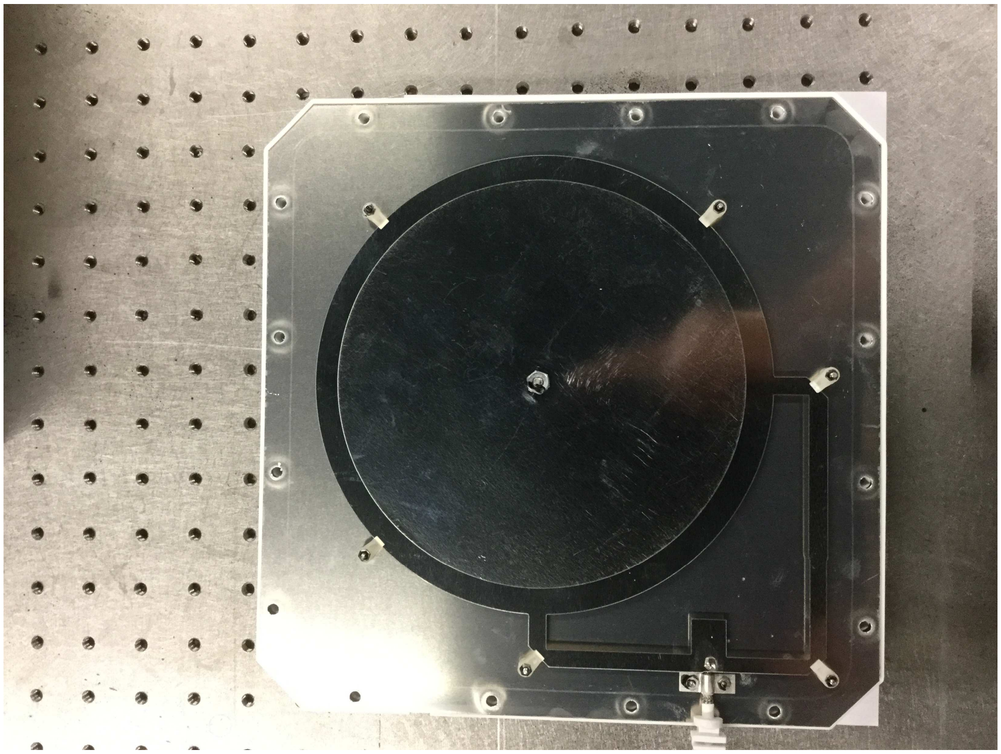


Fig.10 Circularly Polarized RFID Antenna

<u>Radiation Pattern of Antenna:</u>

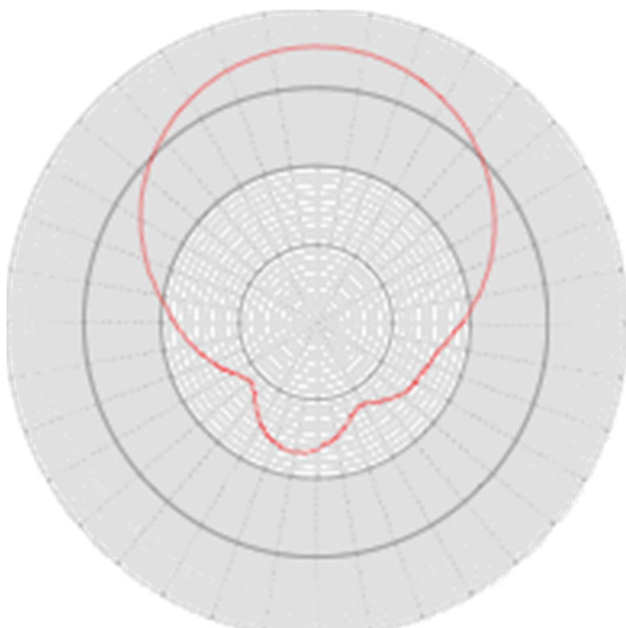


Fig.11 Radiation Pattern of Antenna

Tag/Transponder:

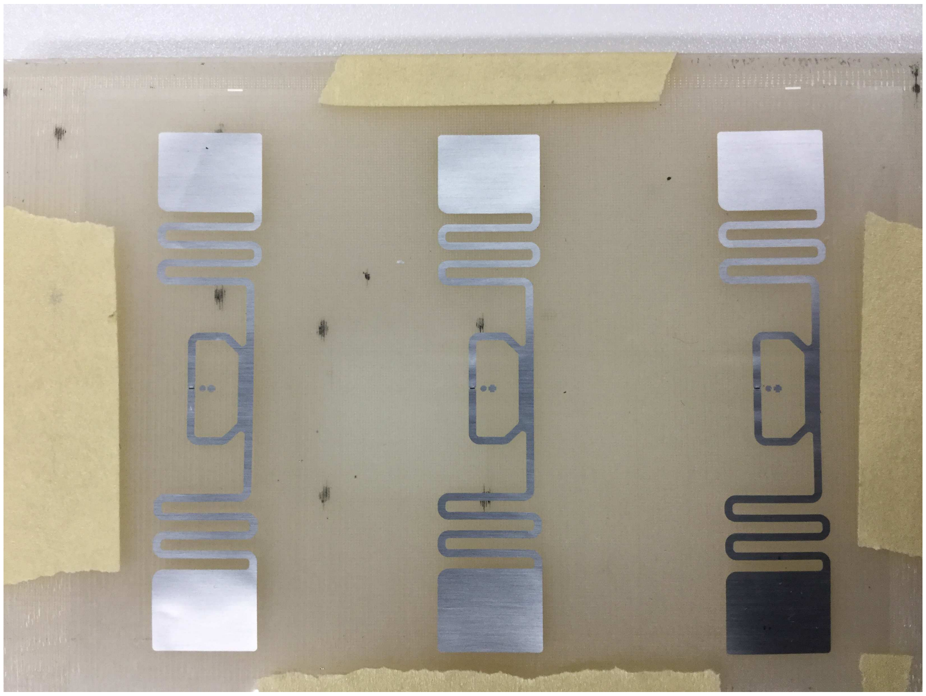


Fig.12 Tags for 900 MHz

Software Interface:

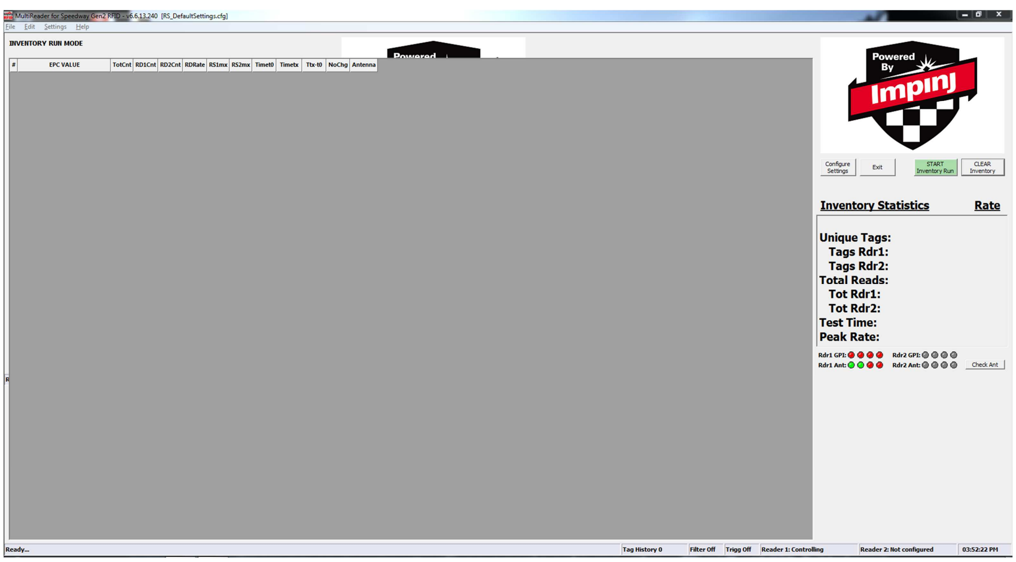


Fig.13 Software GUI for Reader

The RFID system by Impinj provides software GUI that is capable of reading passive tags within its operating frequency. Figure 13 is a snapshot of the GUI provided by the software. Once enabled, the provided software reads the EPC tag value or TAG ID, the total number of tag reads, the number of total tag reads per each reader, the tag read rate, max tag RSSI on each reader, the first and last time the tag was read, and the time between the first and last reads. Figure 14 shows the active tags being read by the Software. When tags are no longer detectable, the software highlights non-active tags in red as shown in Figure 13.

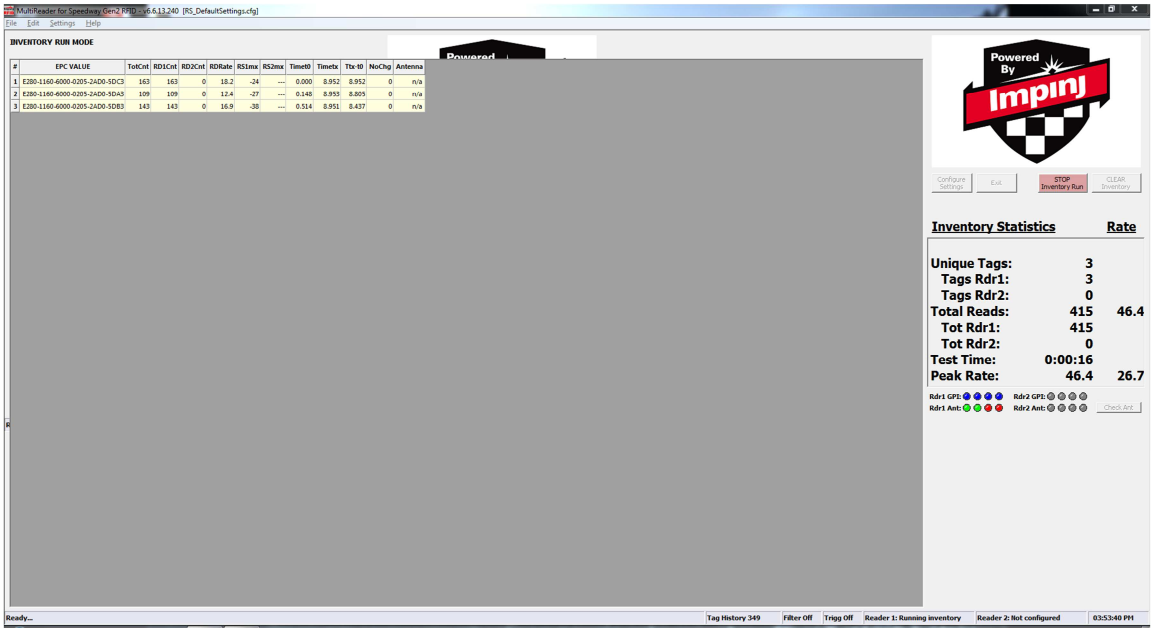


Fig.14 Software – Tags being read

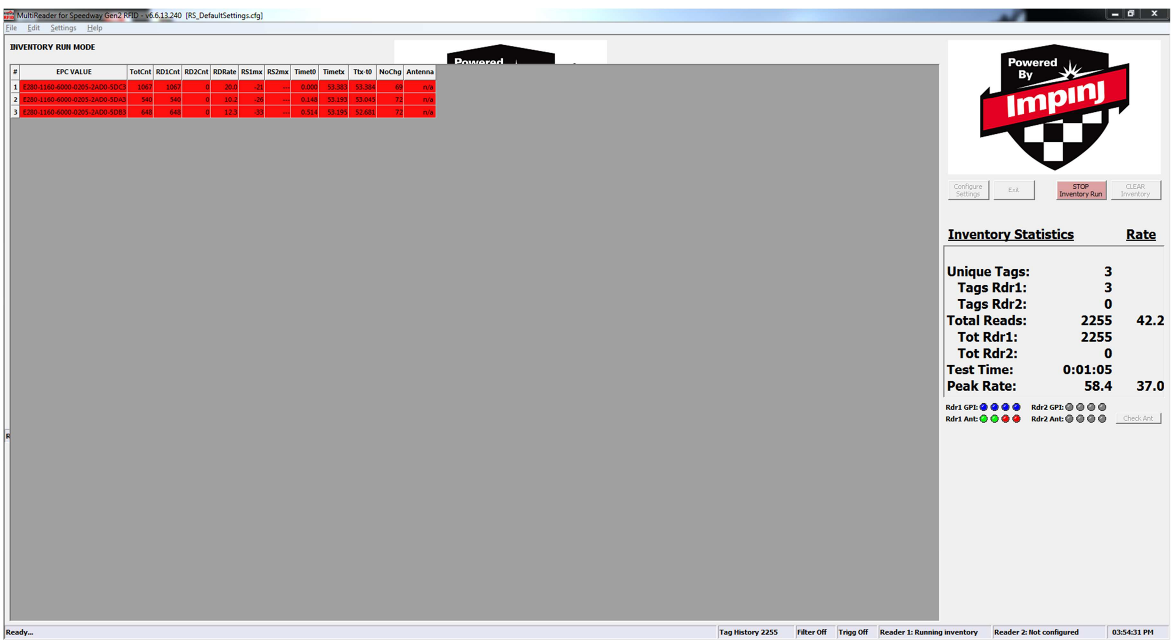
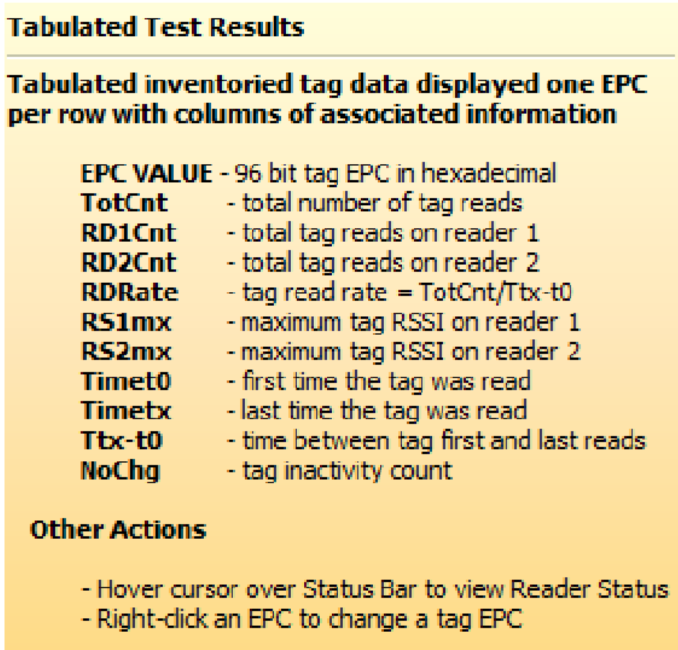


Fig.15 Software – Tags not available or cannot be read

The follow table provided in Figure 16 shows what information the reader is providing once the tag is identified.


Tabulated Test Results

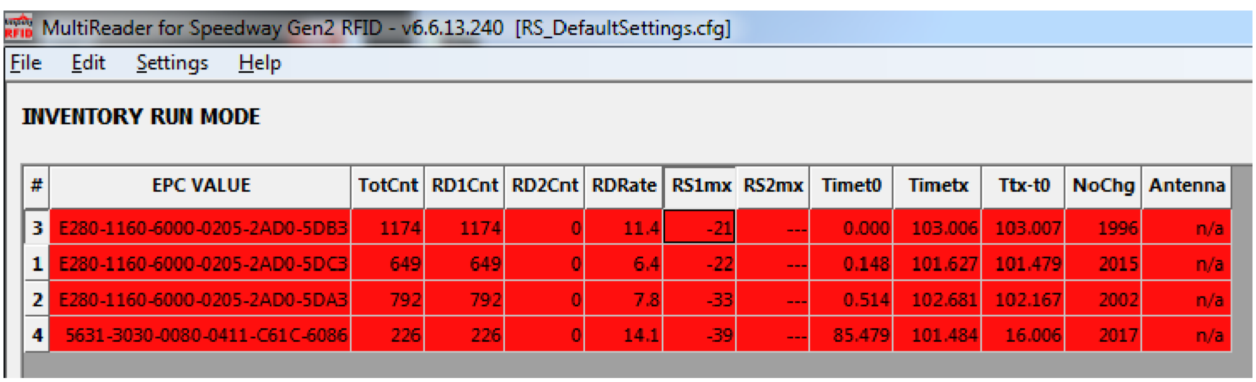
Tabulated inventoried tag data displayed one EPC per row with columns of associated information

EPC VALUE - 96 bit tag EPC in hexadecimal
TotCnt - total number of tag reads
RD1Cnt - total tag reads on reader 1
RD2Cnt - total tag reads on reader 2
RDRate - tag read rate = TotCnt/Ttx-t0
RS1mx - maximum tag RSSI on reader 1
RS2mx - maximum tag RSSI on reader 2
Timet0 - first time the tag was read
Timetx - last time the tag was read
Ttx-t0 - time between tag first and last reads
NoChg - tag inactivity count

Other Actions

- Hover cursor over Status Bar to view Reader Status
- Right-click an EPC to change a tag EPC

Fig.16 Table Results of Information Provided By Software


MultiReader for Speedway Gen2 RFID - v6.6.13.240 [RS_DefaultSettings.cfg]

File Edit Settings Help

INVENTORY RUN MODE

#	EPC VALUE	TotCnt	RD1Cnt	RD2Cnt	RDRate	RS1mx	RS2mx	Timet0	Timetx	Ttx-t0	NoChg	Antenna
3	E280-1160-6000-0205-2AD0-5DB3	1174	1174	0	11.4	-21	---	0.000	103.006	103.007	1996	n/a
1	E280-1160-6000-0205-2AD0-5DC3	649	649	0	6.4	-22	---	0.148	101.627	101.479	2015	n/a
2	E280-1160-6000-0205-2AD0-5DA3	792	792	0	7.8	-33	---	0.514	102.681	102.167	2002	n/a
4	5631-3030-0080-0411-C61C-6086	226	226	0	14.1	-39	---	85.479	101.484	16.006	2017	n/a

Fig.17 Example of Results Provided

Fig.17 is an example of how the software represents the information provided from the tag and reader.

Task 2 – Design and development of passive harmonic radar based smart RF tags

This task 2 demonstrates the use of passive harmonic tags (transponder) as markers for buried plastic pipes in Q2. In the previous report, we demonstrated the concept of harmonic frequency doubler using bow tie antennas. Here we present a new and improved design that uses dual band slot dipole antennas, see Figure 18. The tag converts an incoming 2.5 GHz frequency to a 5GHz output frequency. The antenna was fabricated on 1.52 mm thick substrate of dielectric constant 3. The fabricated tag was embedded in a plastic casing which represent wall of a plastic pipe as shown in Figure 18. The casing was 3D printed using polylactic acid (PLA) dielectric material. Two harmonic tag designs based on double slot antenna are presented here: one embedded tag with a metal back reflector and the other without the metal backing.

Fig. 18 Top: photograph of the tag placed in 3D printed plastic casing before bonding. Bottom: cross sectional view of the embedded tag with a metal reflector on the back.

In the following section, six set of experiments were carried out to demonstrate the functionality of the developed tag. The first experiment is to verify the frequencies of operation of both the designs (with and without back reflector). Both of the tags works at 2.5 GHz and 5 GHz range as shown in Figure 19. In this experimental setup, the antenna performance is measured on a vector network analyzer (VNA) by directly connecting the antennas to a VNA using a coaxial cable. From the measured return loss (S11) two operational bands can be observed. One is near 2.5 GHz and the other near 5 GHz. The operational band near 5 GHz was made wideband to accommodate fabrication tolerances. Following the return loss measurements, a diode was mounted in the structure for the generation to harmonics.

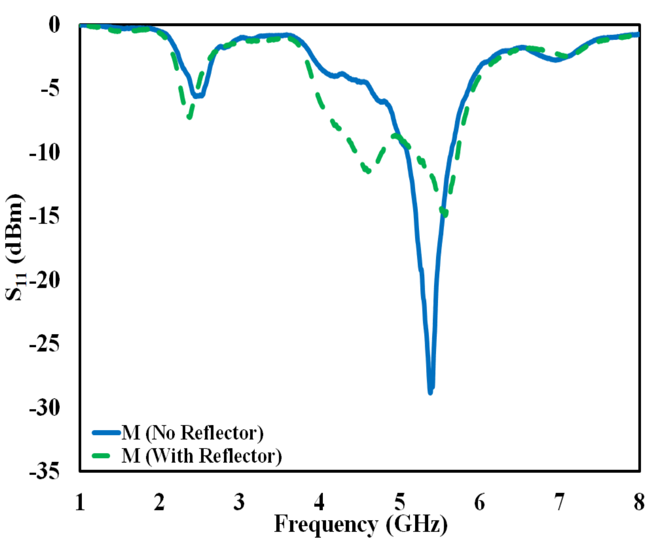


Fig. 19 Measured reflection coefficient of the RF tags (with and without a reflecting layer).

After mounting the diode, a second set of experiments were performed to find the optimal frequency of operation. Measurements on the tags were carried out as a function of input frequency (f_o with fixed power) versus output power at $2f_o$. The measured results are shown in Figure 20 for both the tag designs. The results show that the addition of the reflector behind the tag provides better performance, which is largely due to improvement in the gain of the antennas. The performance of the tag with reflector has 10 - 30 dB higher output power than the tag without the reflector. In addition, Figure 20 also shows the best optimal fundamental frequency is at 2.5 GHz.

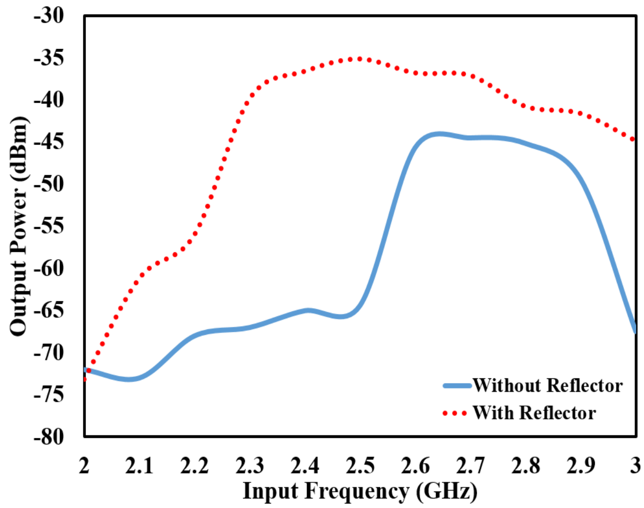


Fig. 20 Output power versus Input frequency for RF tag with and without reflector layer.

A third set of experiments were performed to demonstrate the long range interrogation of the tags in free space. Figure 21 shows the measured return signal for the two tag designs as a function of interrogation distance. It shows that the received power decreases as a function of interrogation distance. The tag with the reflector provides better detection capability compared to the tag without the reflector due to better gain. The noise floor in the measurement is near -90dBm. Thus, the measured results show that the signal to noise ratio (S/N) is high for these tag designs. In other words, the interrogation distance can be much longer than the measured range demonstrated here.

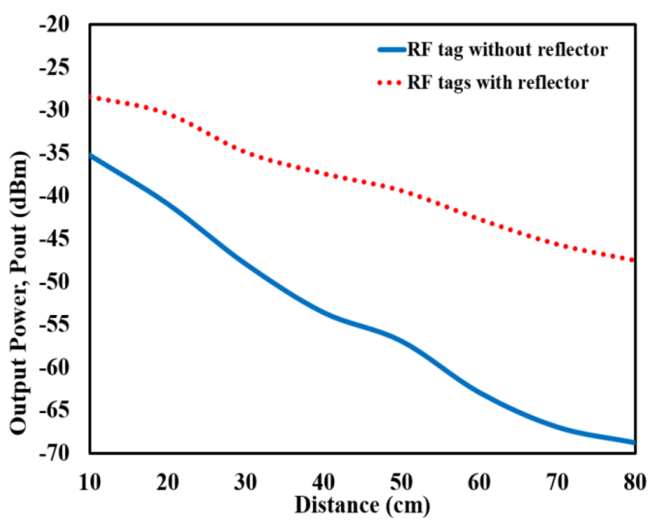


Fig. 21 Output Power versus Distance at 2.5 GHz fundamental frequency.

A fourth set of experiments were performed to demonstrate the functionality of the tag (with reflector) when buried under layers of wet soil (~ 10% moisture content). Figure 22 shows the experimental setup. An RF absorber is placed on the backside to absorb stray signals and minimize reflected signal from the cement ground floor. The soil used consists of sand, clay, rock and other organic material that are naturally found in the backyard in Michigan, USA. In the measurements, the thickness of the soil layers on top of the tag was increased and the return signal was measured as a function of soil depth. Figure 22 also shows the measured results; here the received signal from the tag decreases as a function of increase in thickness of the soil layer covering the tag. The data is presented here as a function of signal above the noise floor (-90dBm).

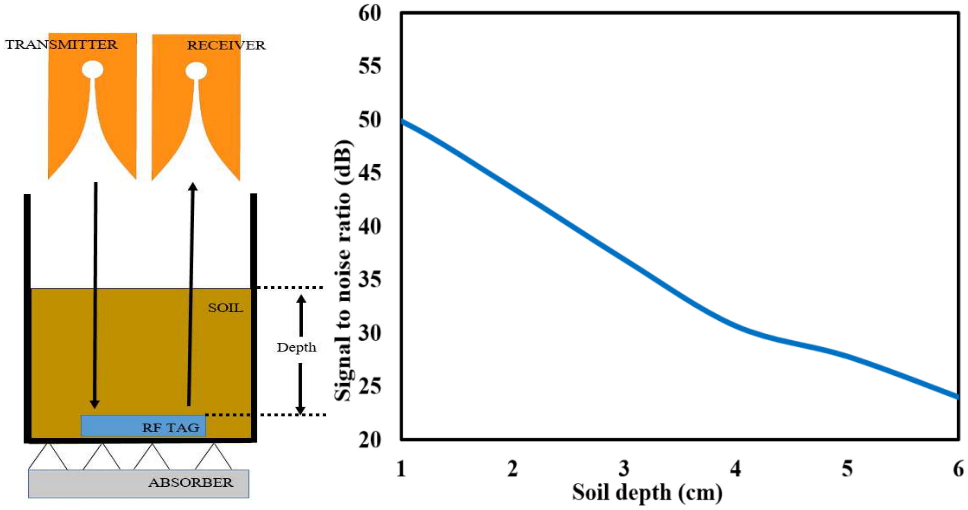


Fig. 22 On the left: Illustration of the experiment setup. On the right: Signal to noise ratio versus soil depth.

A fifth set of experiments were carried out to determine the direction of the buried pipes by using the polarization of the tag as a marker. The slot antennas are linearly polarized and the extinction ratio of the tag was measured while buried under soil. Figure 23 shows the return signal as a function of angle between the transmitting (interrogator) Vivaldi antenna and the tag. The measured results show that polarization extinction ratio of the tag is >40 dB. This is sufficient for tagging the direction of underground buried pipes.

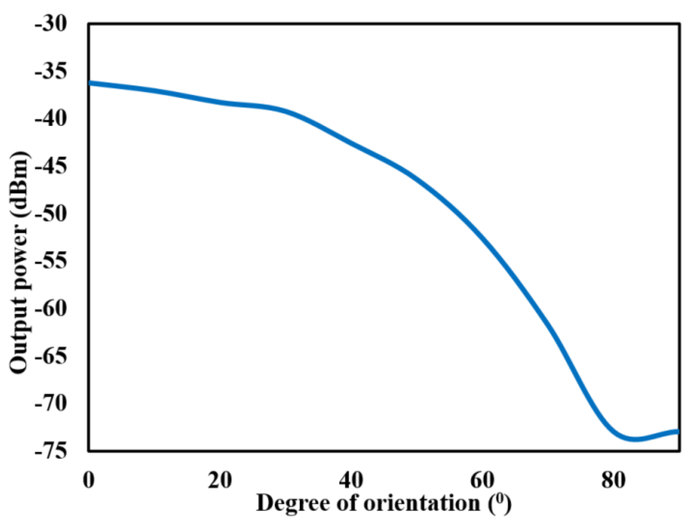


Fig. 23 Measured return signal as a function of polarization angle between the interrogator (transmit/receive) antennas and the tag antennas

The sixth sets of experiments demonstrate the ability to detect the tag at certain distance and angle. In this experiment, the tag was buried in the middle of a large sand box. The interrogator was moved across the sand box and the return signal was measured. An illustration of this experiment is shown in Figure 24. Measurement was carried out at an increment distance of 3cm in the horizontal direction. Figure 24 also shows the measured results as the interrogator crosses over the buried tag. It is plotted as a function of angle between the interrogator and the tag. Signal strength increase as the interrogator moves nearer to the tag or as the interrogation angle decreases. Maximum signal is when the interrogator is right above the tag. This approach coupled with time-gating of signal can be used to determine the precise location of the tag.

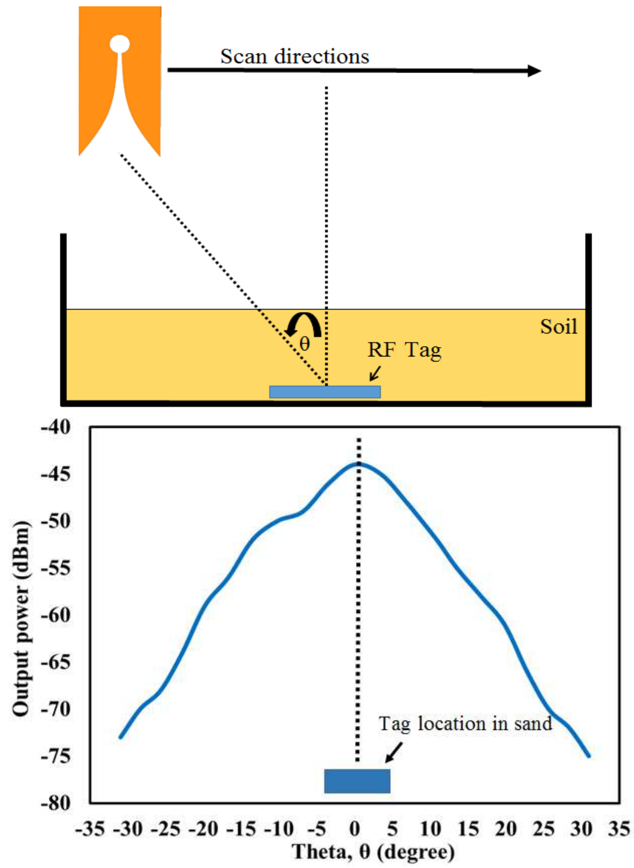


Fig. 24 Top: Illustration of the experiment of locating the RF tag embedded in plastic under buried sand. It was interrogated from a height of 50 cm. Bottom: Position versus return power from a buried antenna (under 3 cm thick sand).

(c) Planned Activities for the Next Quarters

Besides the planned activities mentioned in section (b), here is the future work for the next quarter:

CU: PASSIVE RF TAG DESIGN:

- Improvement in the existing design to increase the range of detection.
- Redesign the tag to be more compact with higher efficiency.

CU: ON-TAG SENSING, DATA MINING AND PROCESSING SETUP:

- Setup the environment for RFID communication in soil medium.
- Burial depth and orientation of tag will be taken into account.
- Investigate new massive RFID data mining, processing and classification algorithm.
- Check the integrity of system using Bayesian based methodologies.

MSU: NEW PASSIVE RFID TAG DESIGN:

- Power budget analysis of the system setup.
- Further improve the tag design to achieve longer range detection.

- Begin work on a breadboard interrogator circuit.
- Submit conference papers

(d) CAAP Students Activities

The students' activities in the 2nd quarter at both universities are summarized below:

CU-Denver:

- Deepak Kumar and Quang Than worked on the numerical modeling and data analysis for RF/Soil interaction
- Deepak Kumar and Quang Than worked on the RFID experimental testing facilities design and implementation
- Laura Spellman, Deepak Kumar and Quang Than conducted the passive RFID tags testing, data acquisition and mining
- Deepak Kumar wrote the Q2 report

MSU:

- Mohd Ifwat Mohd Ghazali and Saranraj Karuppuswami worked together on the design and measurement of RF tags
- Saranraj Karuppuswami also worked on the integration of sensor elements within the tag element.