CAAP Quarterly Report

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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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For quarterly period ending: *July 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 – Experimental setup at University of Colorado, Denver

A basic model of electromagnetic (EM) transmitter and receiver has been developed for the study of the transmitting medium. According to Q2-report, a circularly polarized patch antenna was used to interrogate the RFID tag in air. The result shows that the antenna is capable of reading tag's id from 15-ft (max) in the air with an input power of 30-dBm. The same patch antenna shown in fig.1 operating at 915-MHz is used for transmitting power into the medium for our new model. A small linearly polarized antenna shown in fig.2 is also used as a receiver. A fixed input power of 16-dBm is used to perform all experiments.

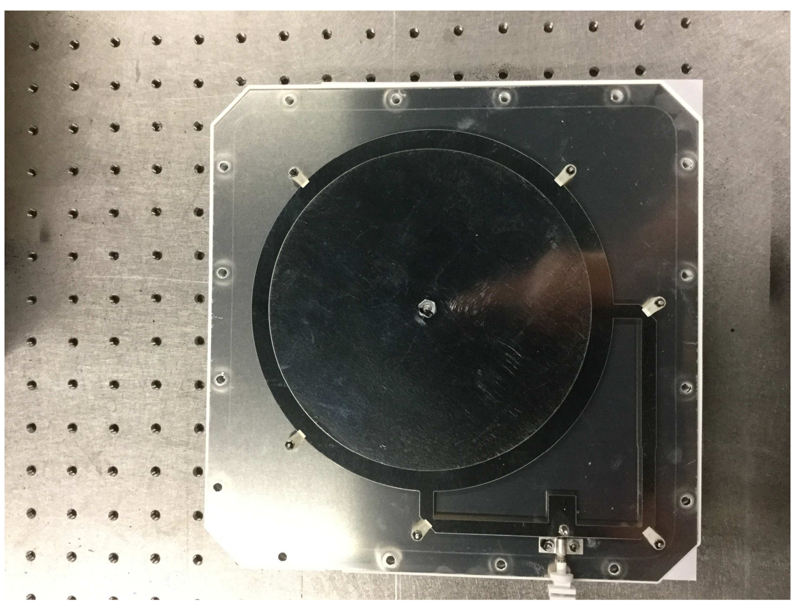


Fig.1 Circularly polarized patch antenna (T_x)

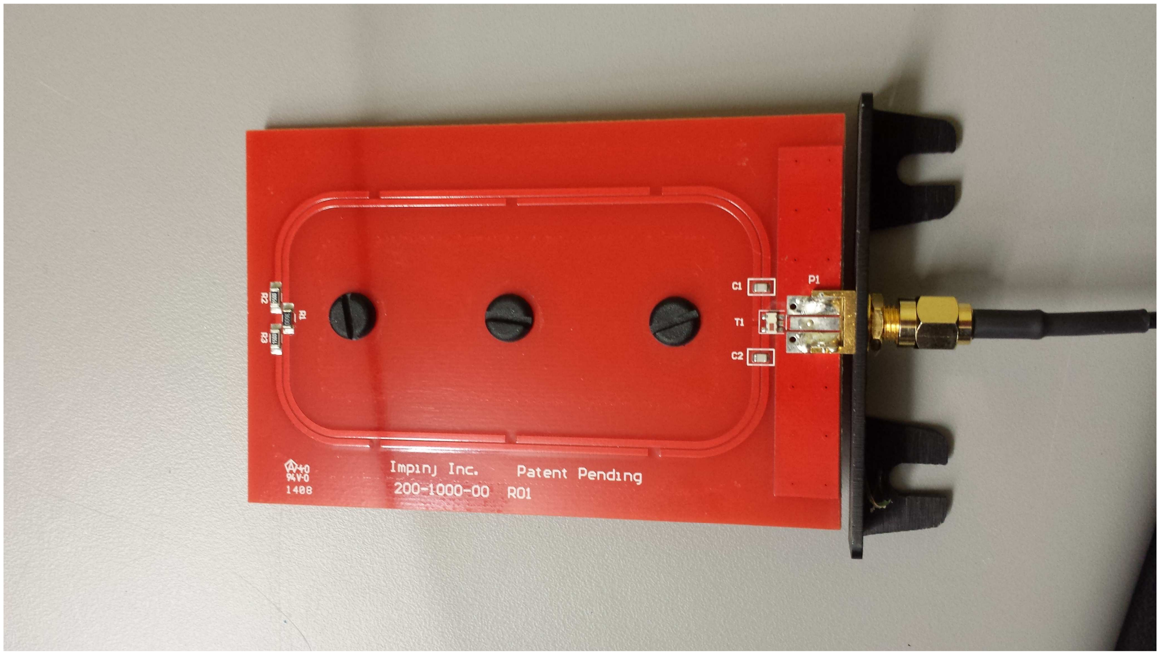


Fig.2 Linearly polarized receiving antenna (R_x)

For testing the reliability of experimental model and setting the reference point for different mediums, the initial experiment was performed in the air. It helps us understanding antenna's gain, directivity and efficiency. Fig.3 shows the power received vs. distance in the air.

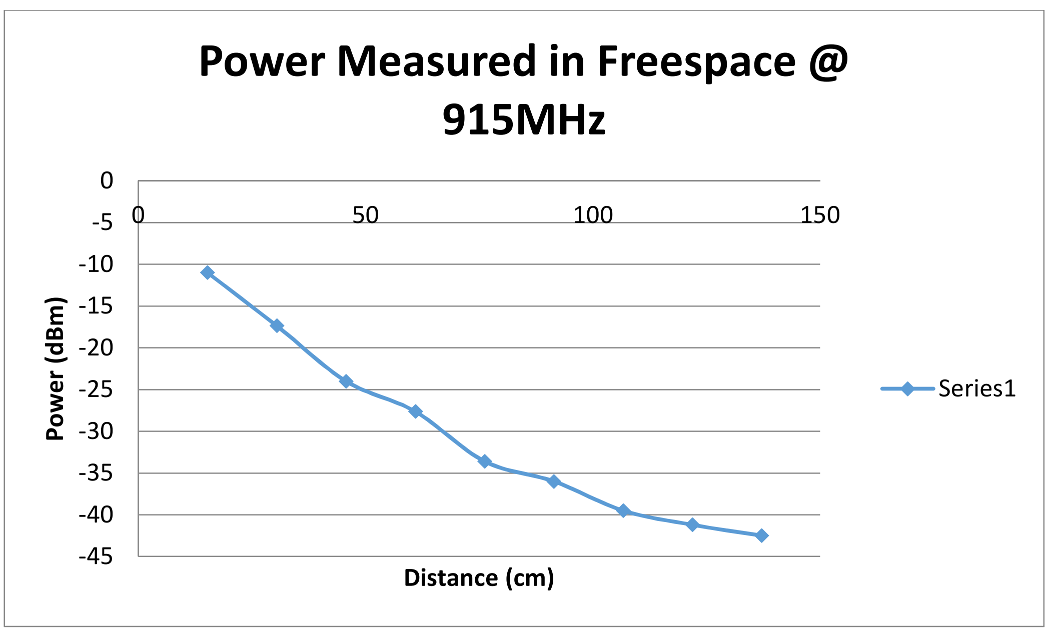


Fig.3 Power received vs. Distance in AIR

The experimental result shows that transmitter and receiver are working correctly as they follow the power transmission rule.

The next experiments are performed to study the behavior of EM waves with the dry sandy soil. The electromagnetic properties of the soil have been studied in the previous quarter, the relative permittivity $\epsilon_r = 2$ and the conductivity $\sigma = 0.002$.

The first setup was build to observe the change in EM strength of signal with respect to the distance. The source, patch antenna, has been fixed to one end of the soil container shown in fig.4 and the received power is recorded at different position/distance of the receiver antenna in the soil container.

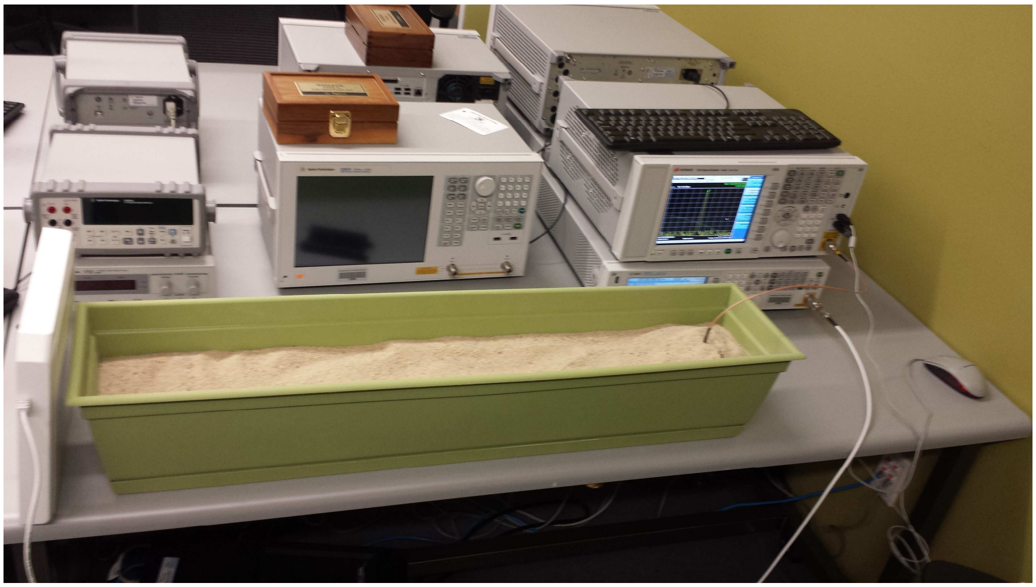
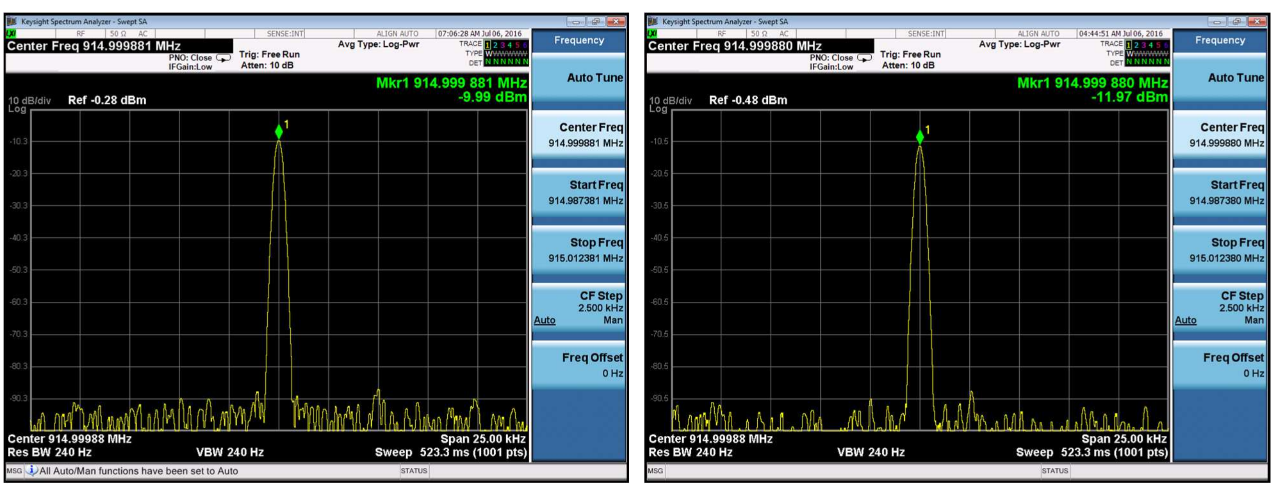


Fig.4 Soil Container 1

The EM waves should lose more power in soil than in air as its denser and conductive. The recorded data for the dry sandy soil medium doesn't show correlation with the previously calculated power w.r.t. distance. The received power at 18-inches and 32-inches in free space is -23.54 dBm and -34.36 dBm respectively. But in the soil the power didn't attenuate according to its properties rather it increases. Fig.5 shows the received power at 18-inches and 32-inches away from the source in soil.



(a) -9.99 dBm @ 18-in (b) -11.97 dBm @ 32-in

Fig.5 Received power

The second setup was a bucket shown in fig.6 with multiple holes for different depth readings.

Fig.6 Soil Container 2

The transmitting power is being measured from 5-40 cm burial depth inside the soil container 2. The measured data is shown in fig.7. The interaction of EM waves with soil is similar to the soil container 1 as the receiving power levels are still higher than the free space.

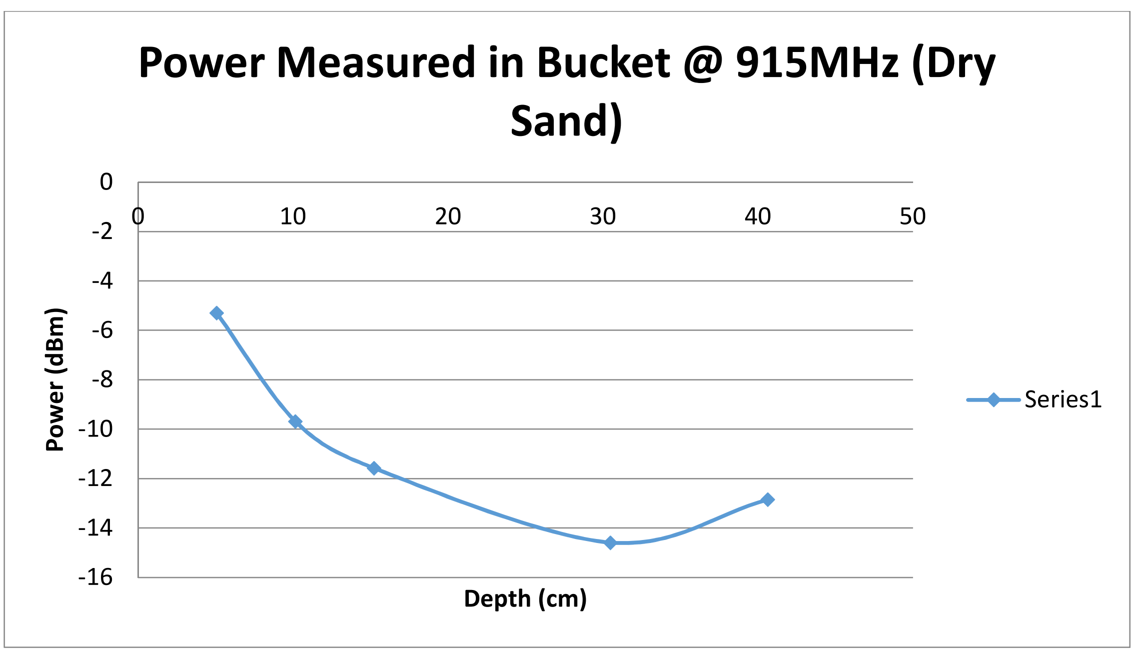


Fig.7 Power received vs. Distance in Soil

The soil containers used in the above experiments are small compared to the wavelength of 915MHz. Since these containers are small relative to the wavelength, the containers introduce near-field effects onto the receiving antenna. The reflections within the containers increase the power density of EM waves in the soil. This leads to an increased power received of the receiving antenna when compared to free space.

Based on the previous experiments a larger container is designed to reduce the near-field effects of the container walls. The dimensions of the container are 18" x 18" x 60". Half inch thick acrylic is used to build the container. This material was chosen to minimize reflections at the air interface and also to be strong enough to hold a large amount of various soil types. The follow figures show the designed container.

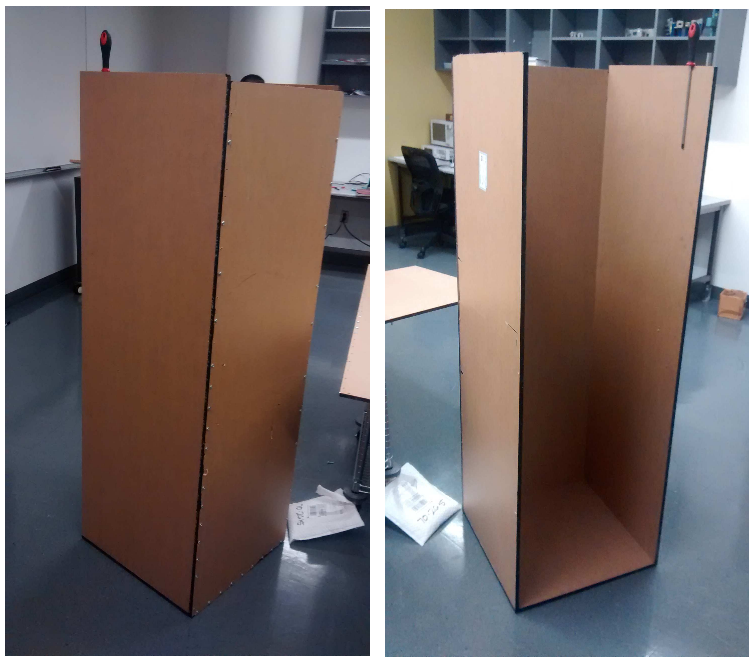


Fig.8 Soil Container 3

Experiments were performed to compare the effects of the container walls versus free space. The images of the experiment and the data are shown in the figure below.

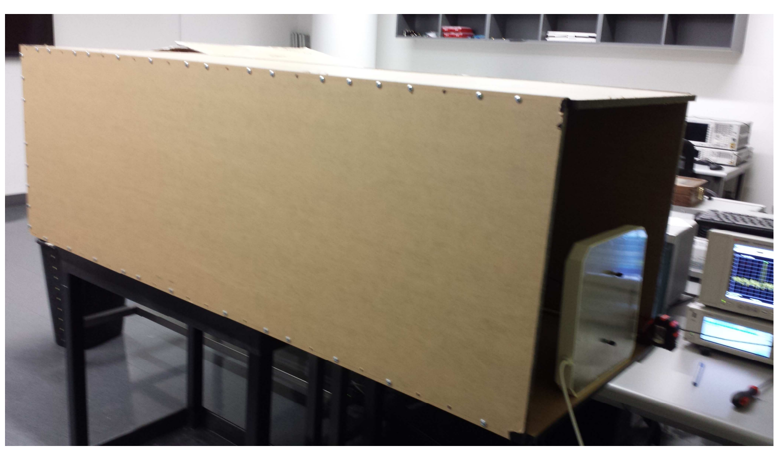


Fig.9 Experiment Setup (a)

Fig.9 Experiment Setup (b)

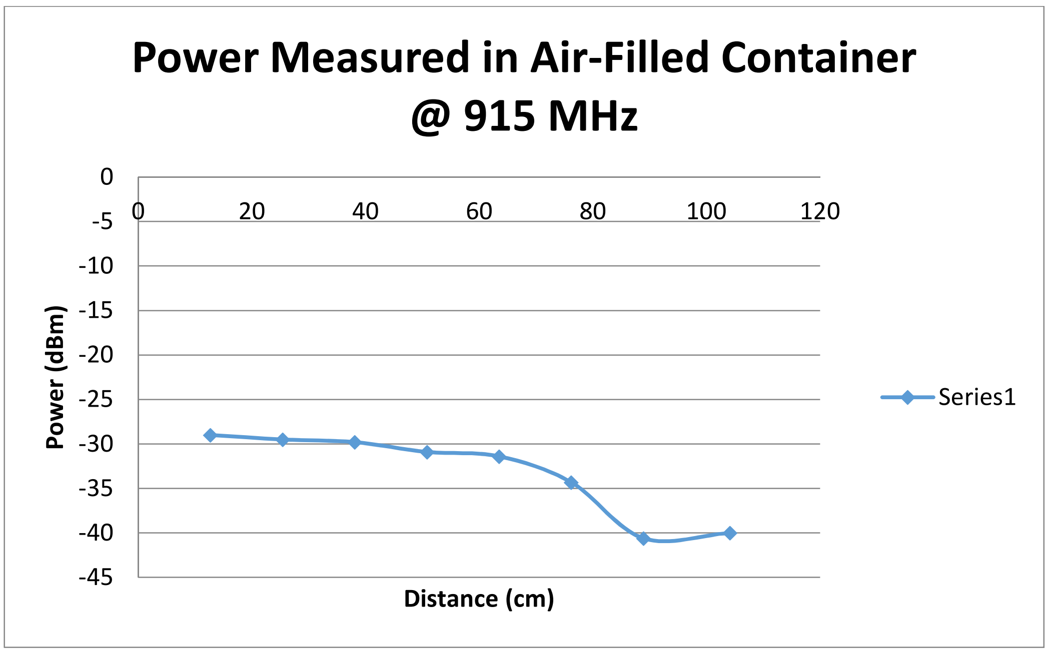


Fig.10 Power received vs. Distance in empty container

It is observed that the power measured is closer to free space when the receiving antenna is further away. For depths less then 60 cm, there is a significant difference in the power measured when compared to open-air free space.

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

Under this quarterly report, Task 2 demonstrates an improved version of the passive harmonic tag (transponder) as markers for buried plastic pipes in Q3. In the previous report, we presented two harmonic tag designs based on double slot antenna design: one tag with metal back reflector and the other without the metal reflector as shown in Fig 11. The improved version of the tag is shown in Fig 12. Here, the antenna designs were optimized to achieve better impedance matching with the active element.

Fig. 11 Left: photograph of the tag placed in 3D printed plastic casing before encasing in plastic. Right: cross sectional view of the embedded tag with a metal reflector on the back of the plastic casing.

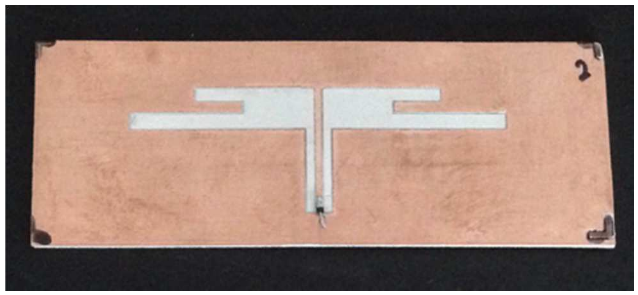


Fig. 12 Improved version of the tag.

In the following sections, four sets of experiments were carried out to demonstrate the functionality of the improved tag. In the first set of experiments, measurements on the tags with and without reflector were carried out as a function of input frequency (f_o) at fixed power versus return power at $2f_o$. The comparison of the measured results is shown in Fig. 13 for previous and improved tag design. The bandwidth of the new tag is more than the old design, and also the performance of the new tag has 2-5 dB higher output power than the old version.

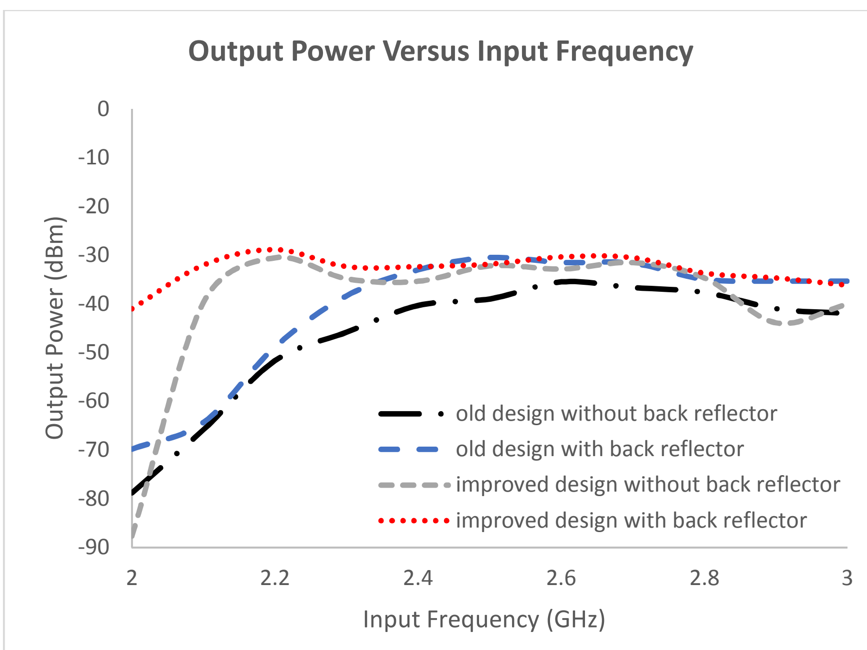


Fig. 13: Comparison of old and improved version of tags: return power (at $2f_o$) versus input frequency for fixed input power.

A second set of experiments were carried out to determine the direction of the buried pipes by using the polarization of the tag as a marker. Fig. 14 shows the comparison of the return signal as a function of angle between the transmitting (interrogator) Vivaldi antenna and the improved tag and the old tag design. The results show that the new tag has good extinction ratio, sufficient enough for using polarization as a marker for tagging the direction of the buried pipe.

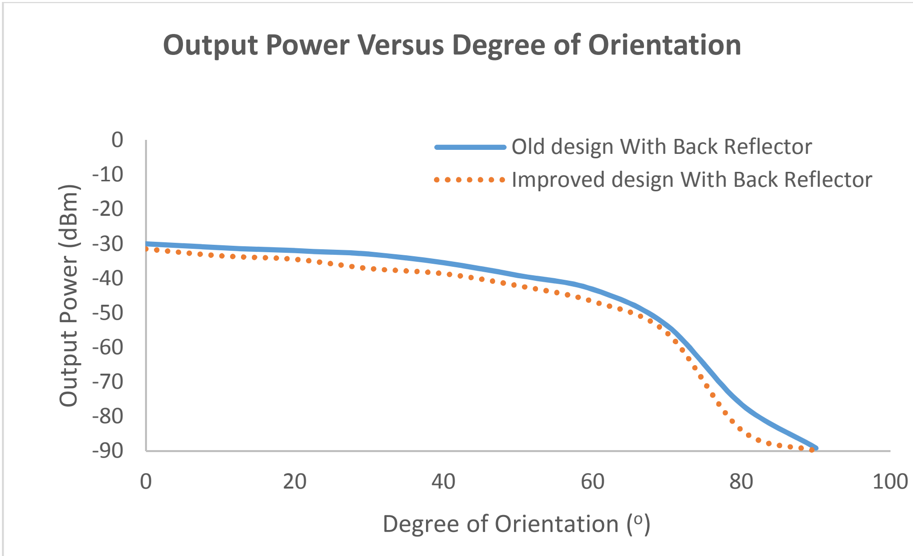


Fig. 14: Measured return signal as a function of polarization angle between interrogator and the tag.

A third set of experiments were performed to demonstrate the long range interrogation of the tags in free space. Fig. 15 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 as expected due to the square power law. The modified tag has better return signal as a function of distance in comparison to the old design as shown in fig.15.

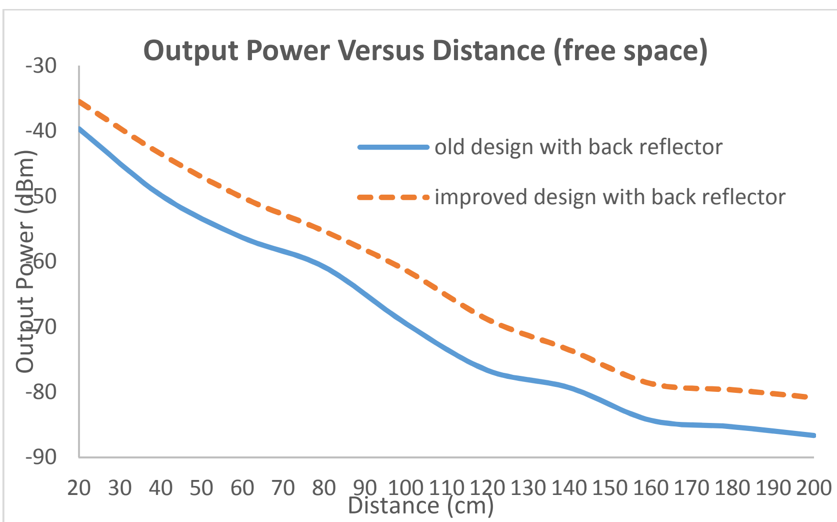


Fig. 15 Output Power versus Distance at 2.5 GHz fundamental frequency for old and improved designs.

A fourth set of experiments were performed to demonstrate the functionality of the tag (with reflector) when buried under layers of soil. The tag was placed in a large plastic container filled with soil. An RF absorber is placed on the backside of the tag to absorb stray signals and minimize reflected signal from the back side of the plastic container and the cement ground floor. Figure 6 shows the comparison of output power versus soil depth (buried depth of the tag) for both the designs. It can be seen that the improved design has higher output power than the old design as a function of soil depth by approximately 15dB. This shows that the tag can be placed at a significant depth while getting sufficient return signal (good signal to noise of the return signal).

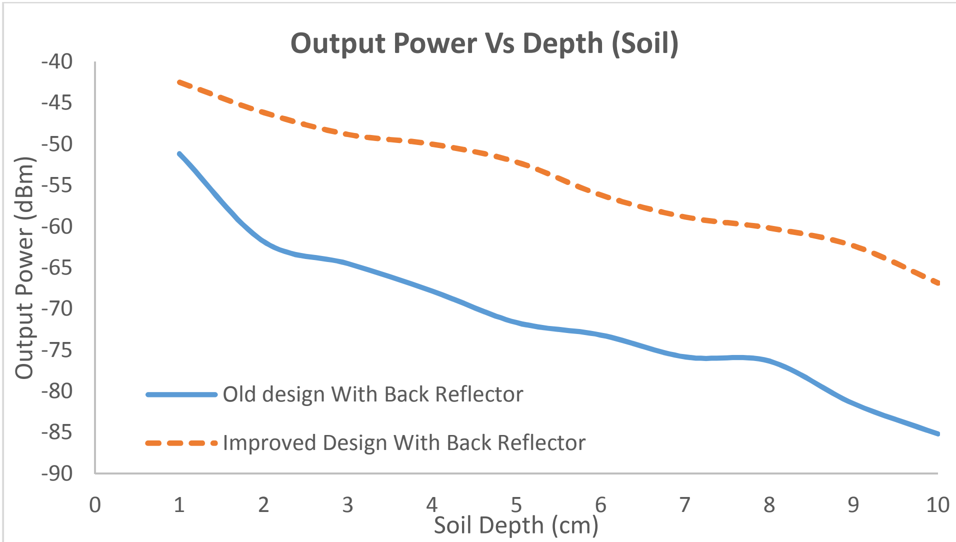


Fig. 16 Output Power versus soil depth for old and improved designs.

<u>Further improvement to the tag design</u>: Under this last report it was shown that the soils absorption is significantly lower at lower frequencies than at higher frequencies. In order to take advantage of this soil property, a new tag design is being investigated. It builds upon the design shown in Figure 1. The simulate return loss of the new tag design in shown in Figure 17. In the next phase, design of this RF tag, 915 MHz (UHF), will be completed and demonstrated for use in buried pipes.

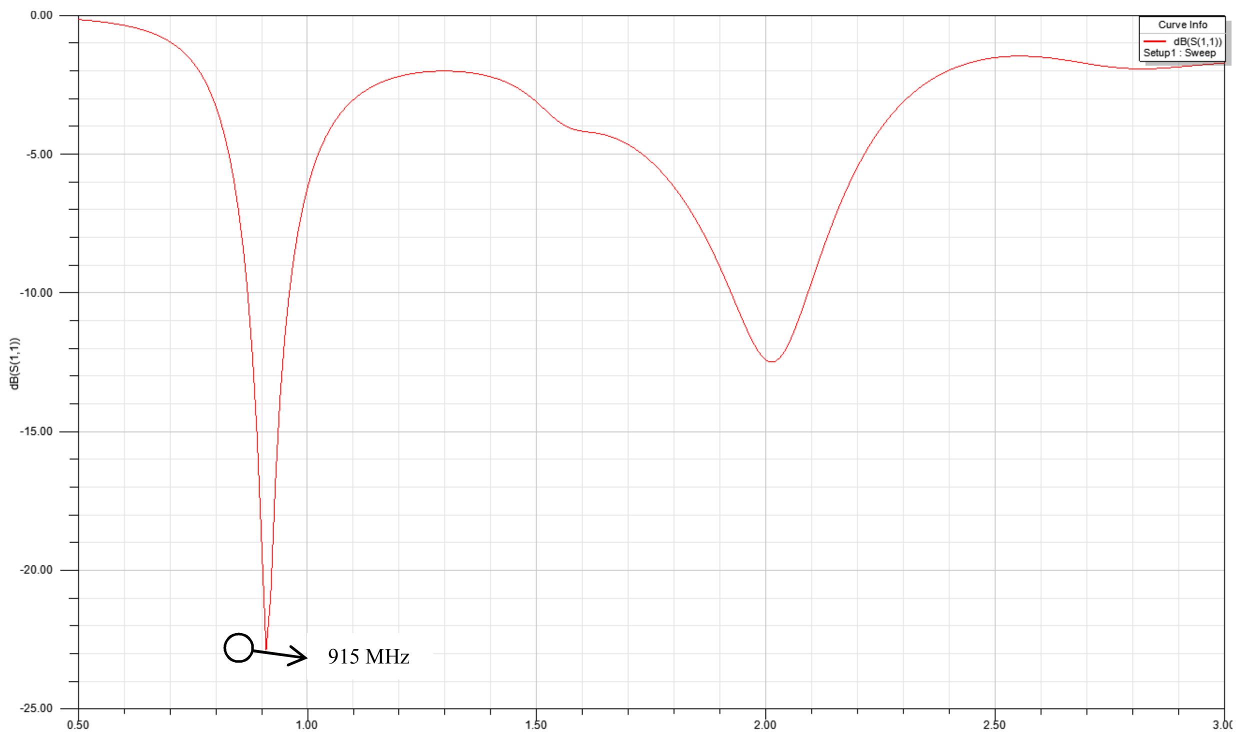


Fig. 17 Simulate return loss of the new tag design for use at 915MHz.

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

- The power profile with the increment in burial depth of tag will be the subject of concentration.
- Experiments will be performed using different soil types and states.
- New container will be tested and improved.
- Check the integrity of system using Bayesian based methodologies.

MSU: NEW PASSIVE RFID TAG DESIGN:

- Complete the design of new 915MHz (UHF) tag.
- Demonstrate integration of tags into plastic pipes
- Power budget analysis of the system setup.
- Designing the tag, which has the capability to be used at multiple frequencies.
- Further improvement to the existing design to achieve detection at longer depths.