CAAP Quarterly Report

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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: *January 10, 2015*

<u>Business and Activity Section</u>

(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

Kick-off meeting:

The kick off meeting was held on November 12, 2015 at Michigan State University led by the PIs: Dr. Yiming Deng, Dr. Prem Chahal, Dr. Lalita Udpa and Dr. Dan Connors. From the USDOT side, the project will be led by the project manager, Mr. Artie Buff and overseen by CAAP program manager Dr. James Merritt. Industry partners, Layne Tucker and James Anspach also participated the meeting through teleconferencing. The proposed technical tasks and educational components were well revisited and better planned for the next three years. The project overview was summarized in the Fig. 1 below.

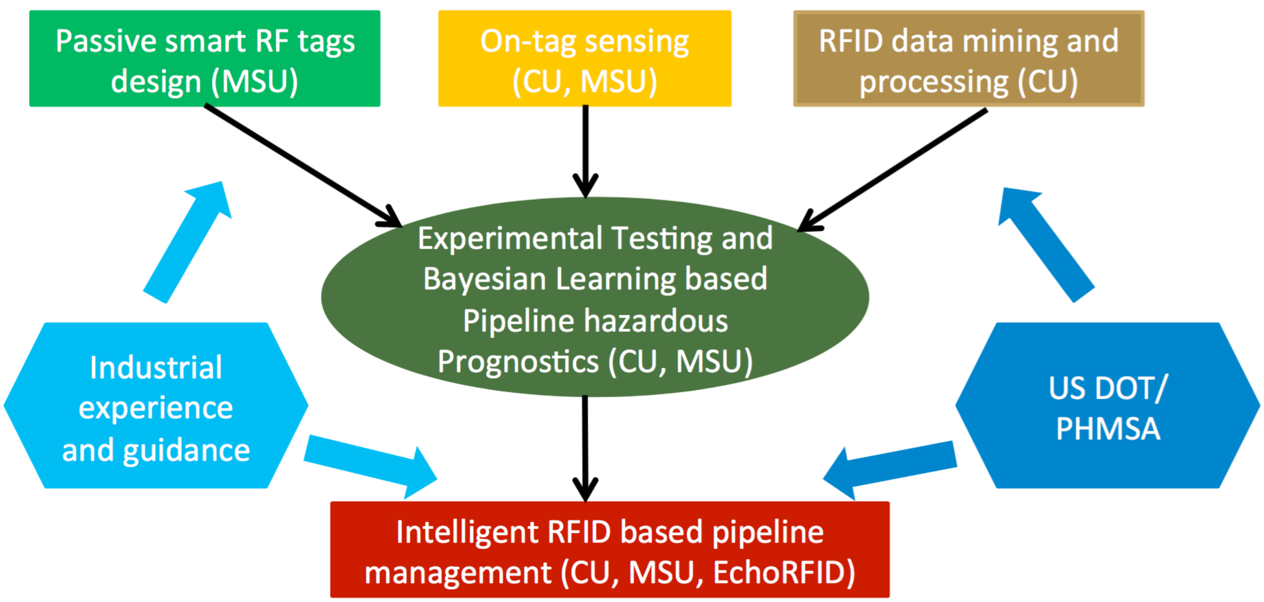


Fig. 1. Project Overview Schematic

Task 1- Design and development of passive harmonic radar based smart RF tags

Harmonic frequency doubler sensor concept is an extension of the simple dipole antenna. The key advantage of this harmonic sensor is the elimination of filters and reducing clutter. The first harmonic design at MSU consists of a diode integrated with two bow tie antennas. The receiver antenna is designed for fundamental frequency (2.5 GHz) and the transmitter antenna for the first harmonic (5 GHz). The system receives the signal at fundamental frequency and reradiates back to the receiver at the first harmonic. The analysis of signal at first harmonic helps identify the tagged infrastructure. Through time gating it can also allow for precise location in depth.

For the first experiments a simple bow tie antenna was designed and simulated using High Frequency Structural Simulator (HFSS) operating at 2.5GHz and 5GHz. They were coupled together using a zero bias diode for frequency doubling. For the measurement two Vivaldi antennas were used to interrogate the harmonic tag. One antenna acts as the transmitter and the other as the receiver.

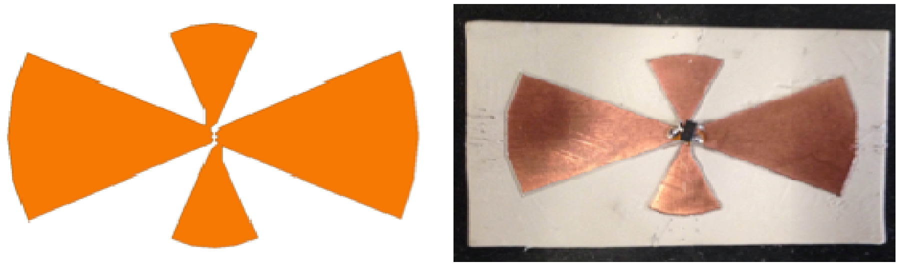


Fig. 2. First tag design consists of two bow-tie antennas coupled to a non-linear device.

The distance/power relationship and power/frequency relationship between the transmitter, receiver and sensor were studied and analyzed for the above tag design. In the first set of experiments, distance between the Tx/Rx and sensor was fixed as 7 inches and power radiated from the harmonic doubler was detected using spectrum analyzer. In the second set of experiments, the frequency was fixed and the performance of the system was studied by varying the distance between the transmitter/receiver unit and the harmonic tag. These first results show that the tag can be designed for desired operating frequency and can be used in clutter environment. This tag will be used a reference to compare future results from new tag designs and interrogation setup.

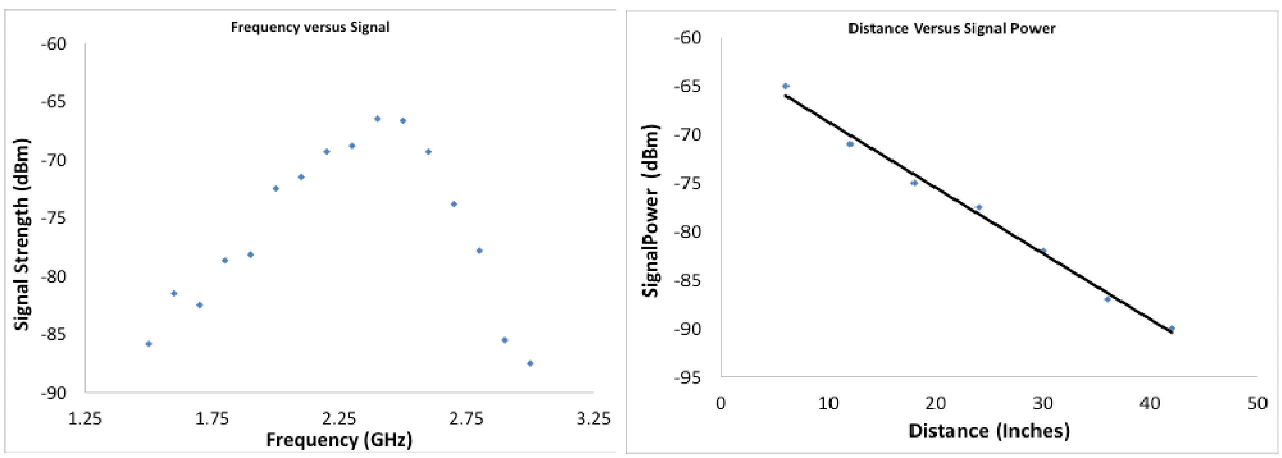


Fig. 3. Left: Measured frequency response of the tag, Right: Measured returned signal as a function of distance between the interrogator and the tag

<u>Task 2-Experimental testing, intelligent data mining and processing and prognostics framework</u>

During the 1st Quarter, research team at CU-Denver started the study of different soil types and their electromagnetic properties, worked on experimental setup inside and outside lab environment and survey data analytics for sensor networks. Soil is the mixture of different minerals, organic matter, liquids and many more different things, whose concentration continuously changes with change in location on earth depending upon the weather conditions, human involvement and many more different reasons. The change of these factors categorizes the soil into different types and leads to change in the conductivity, permittivity, permeability or the electromagnetic properties. Wireless Underground Sensor Network (WUSN) always has this challenge in terms of data acquisition and communication until we understand the electromagnetic properties of soil and changes the protocol accordingly.

The propagation constant for a plane wave traveling within a media with parameters ε (permittivity), μ (permeability), ω (angular frequency) and σ (conductivity) can be described in real and imaginary parts:

$$\gamma = \alpha + j\beta \qquad (2.1)$$

Where the Real part, α (attenuation constant)

$$\alpha = \frac{\omega\sqrt{\varepsilon\mu}}{\sqrt{2}}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]^{1/2} \tag{2.2}$$

Imaginary part, β (phase constant)

$$\beta = \frac{\omega\sqrt{\varepsilon\mu}}{\sqrt{2}}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right]^{1/2} \tag{2.3}$$

The dielectric loss tangent or dissipation factor for a wave traveling within a media is defined

$\tan\delta = \frac{\sigma}{\omega\varepsilon}$

The loss tangent of the material of which it is traveling through quantifies dissipation of the electromagnetic wave. Electromagnetic waves propagating in a soil medium are dictated by the soil characteristics. Relative permittivity, relative permeability, and conductivity can vary due to different soil types and different water content level within the soil. Propagation of the wave also depends on the operating frequency as the soil characteristics have frequency dependent behavior.

Soil volumetric water content can significantly affect RF signal traveling within the soil and should be considered when developing the RF communication network. High water content in the soil typically has a much more significant effect then low water content.

Soil types from different locations, of different densities, mineral composition, and porosity can have effects on the propagation characteristics of the soil. For specific applications, it may be valuable to measure these properties, as the soil can be a composition of various types of soil composing of various minerals, or include different layers of various soil types. The table found in Arthur R. von Hippel, ed.: "Dielectric Materials and Applications", M.I.T. Press, Cambridge, MA, 1954 provides relative permittivity and dielectric loss tangent over a range of frequencies and soil types. Using the information from the tables, the following plots from Fig. 4 to Fig. 6 describe the relative permittivity and dielectric dissipation factor of generic soil types, such as sandy, loamy, and clay, over a range of frequencies with various volumetric water content levels.

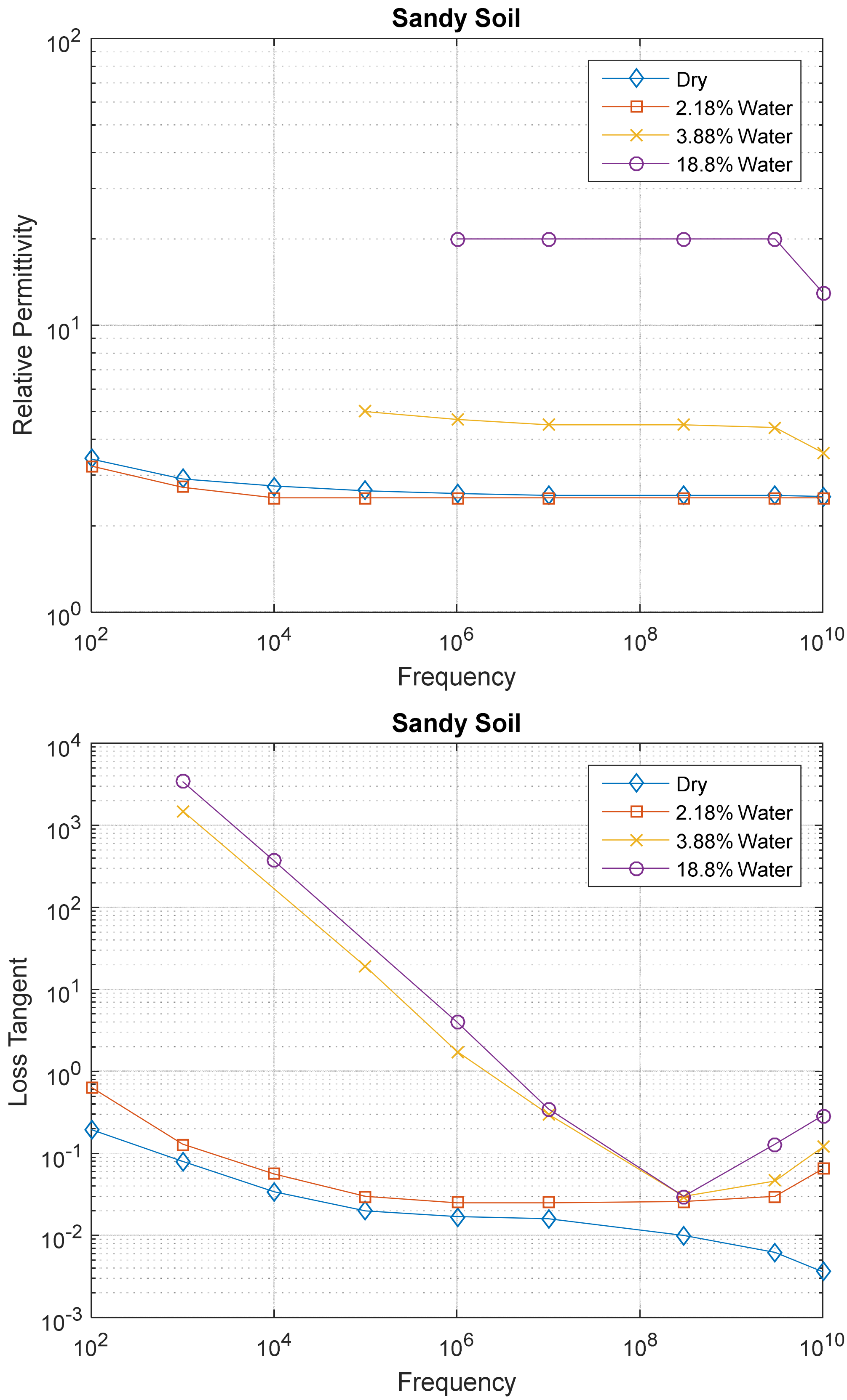
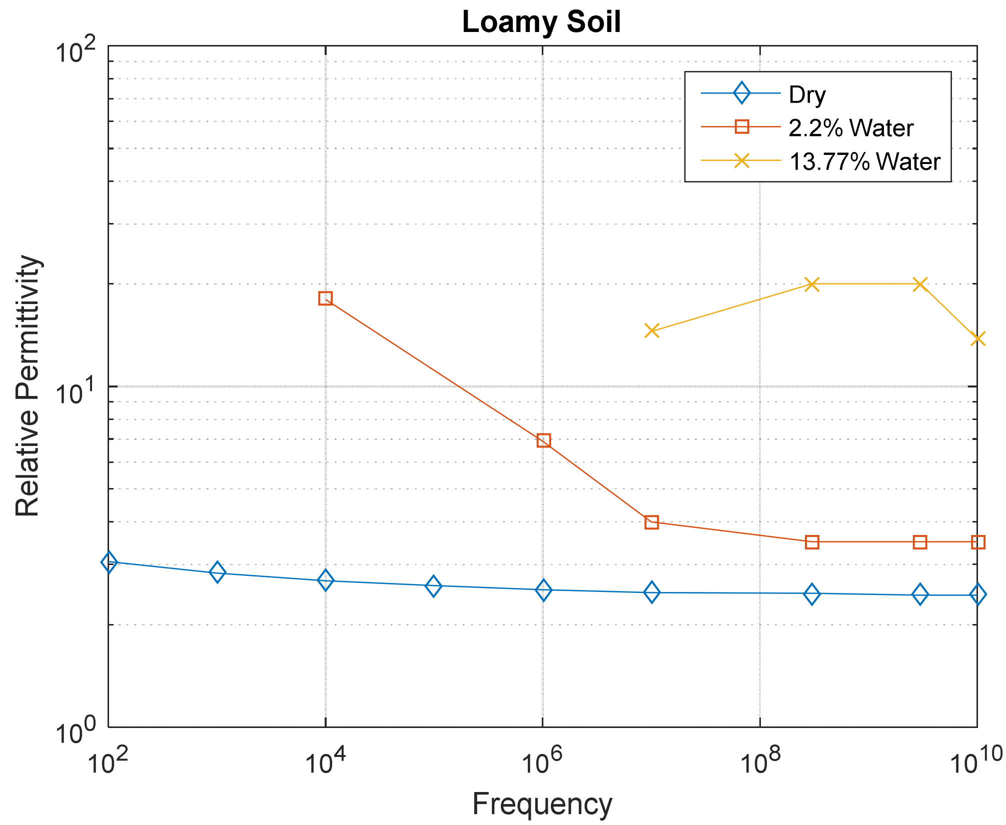


Fig. 4. Sandy Soil Relative Permittivity (above) and Loss Tangent (below)



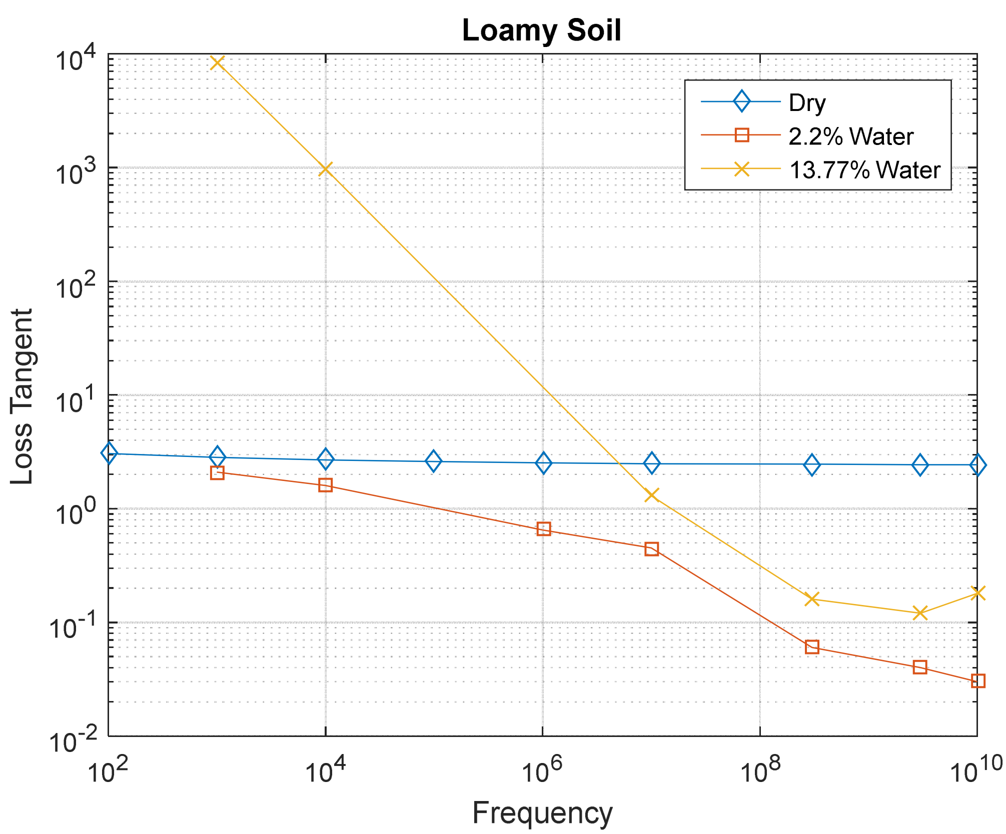


Fig. 5. Loamy Soil Relative Permittivity (above) and Loss Tangent (below)

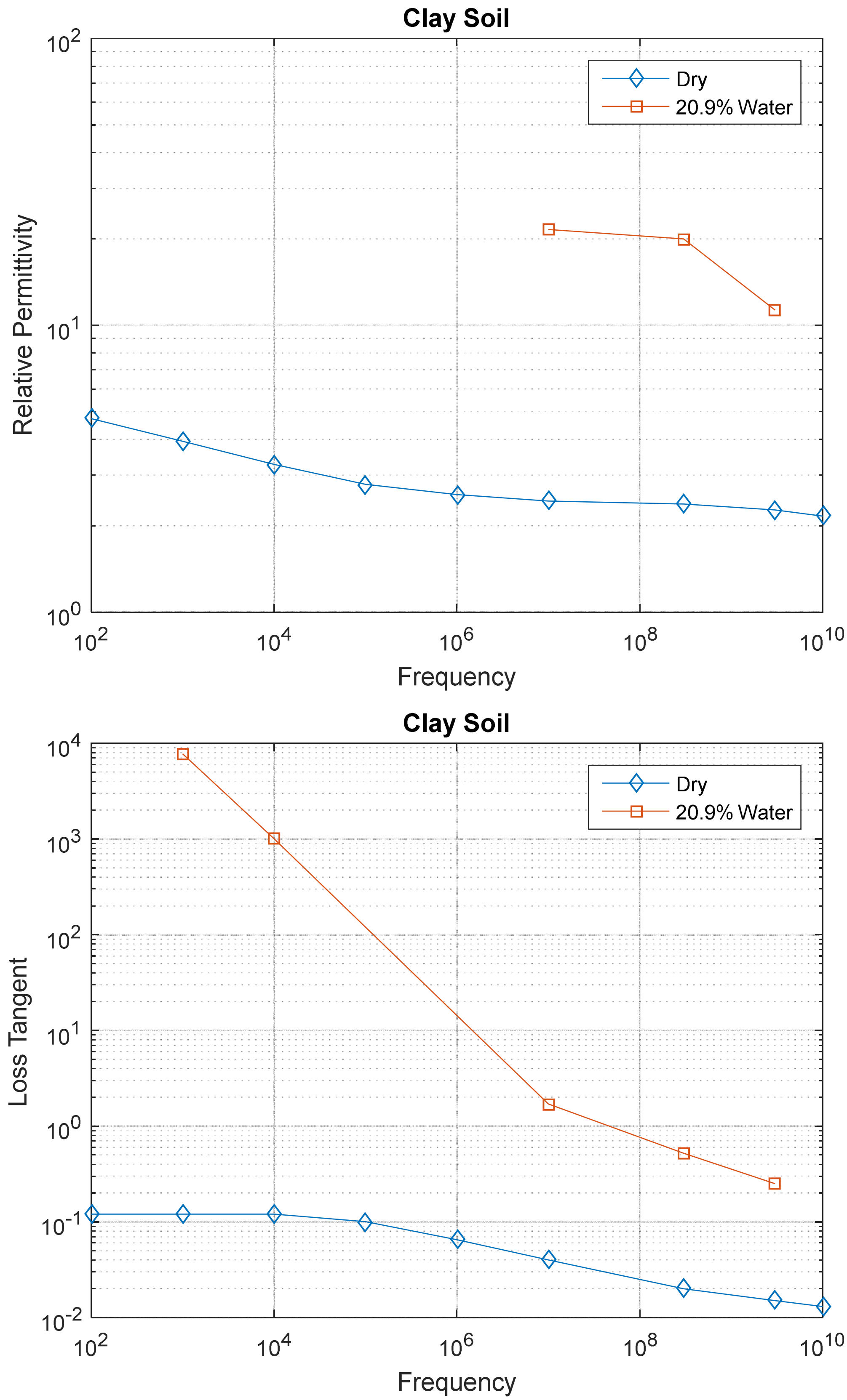


Fig. 6. Clay Soil Relative Permittivity (above) and Loss Tangent (below)

Experiments will be performed both inside and outside lab environment for reliability of the system. Experiment setup inside lab will have four different containers each having different kind and mixture of soil. All sides of containers will be layered with RF absorbing material for achieving real site environment. Size of all containers is same: 2'x2'x5'. The tags can be inserted inside from sides with reader in top of the soil containers. The soil mixture for initial experiments will be homogeneous and dry, complexities will be get added with time.

Setup outside lab is a real site, it's a space borrowed from Civil Engineering Department at CU, for having different depth of holes in ground to put transponders. The field experiment with different depth is to observe the signal and information extraction in more complex environment and frequency shift due to change in local stress level. The illustrations of experimental testing facilities at CU LEAP group are shown in Fig. 7 with geometry information in Fig. 8. The setup is expected to be completed in the 2nd Quarter.

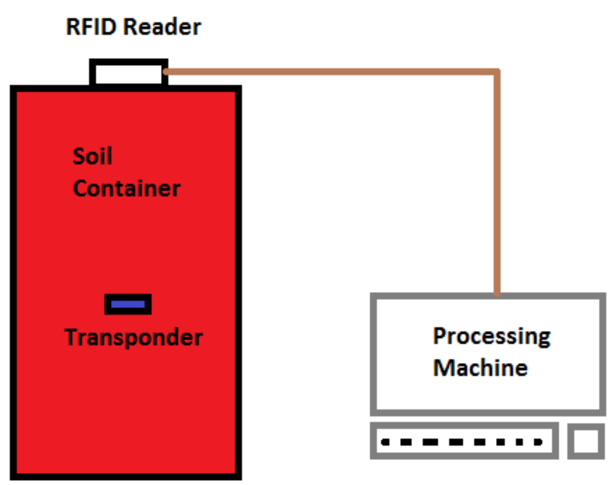


Fig. 7. Preliminary design of RFID experimental testing facilities

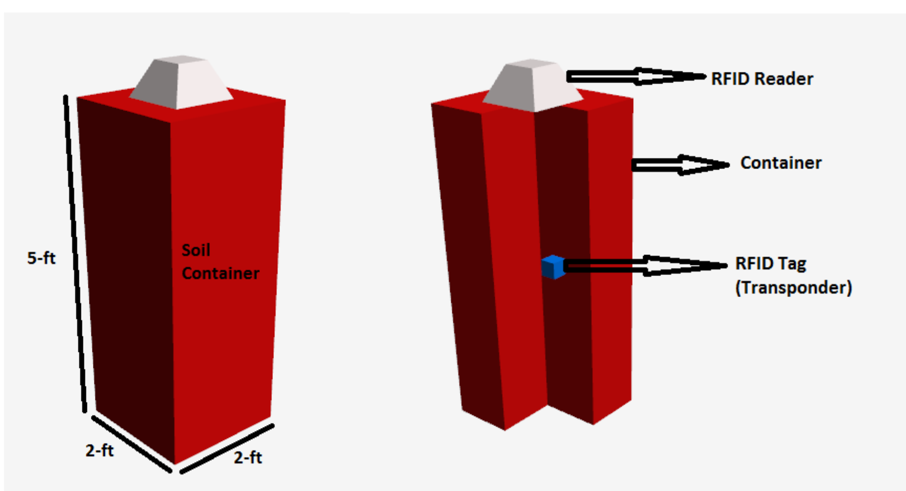


Fig. 8. Geometry of the RFID testing facilities at CU

Hardware technology is advanced to next level, can acquire tremendous amount of data in real time that can be mined for various logical insights. In case of RFID's the volume of data collection is enormous and requires some efficient and real time processing techniques. Although the proposed RFID tag design will improve the signal and noise characteristics, we expect the data will be noisy, contain redundancies, and miss tags. A smoothing technique will be developed based on the data collected, but we also believe that Bayesian Learning techniques making use of user known parameters could provide cleaner data or enhance data cleaned by the smoothing window. Studied techniques for Bayesian inference are described below:

The *StreamClean* method is based on the assumption that the multiple readings in the data are not random. With this assumption of multiple data points can be used to clean the data given Global Integrity Constraints, or user-stated properties that are known to be true about the data. If conflicting data is observed, the probability model will be used to determine which is correct. Redundancies in data will cause inconsistent readings but will also provide useful information about the location of the tag given the background information known about the location of the pipe This method is helpful in this study due to the knowledge we have about where the pipe should be located, and how far apart each tag will be placed on the pipe.

Kernel density based probability-cleaning method, or KLEAP, removes cross reads by determining the most relevant reader in an instance of redundant data. The method will estimate the density of each tag using a kernel based function and use this density to determine clusters of tags. An assumption is made that in instances of redundant readings, the reader with the larger amount of tags in a given position is most relevant, therefore, readings from other readers are cross-reads and less relevant.

(c) Planned Activities for the Next Quarter

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

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.
- Choice of wider bandwidth antennas to be considered.
- Power budget analysis of the system setup.

ON-TAG SENSING, DATA MINING AND PROCESSING SETUP:

- A FDTD model for simulating power transmission and reception in different soil types will be developed.
- Study of more soil types like mixtures will continue.
- All proposed setup (inside and outside) will be at their place.
- Investigate new massive RFID data mining, processing and classification algorithm.
- Check the integrity of system using Bayesian based methodologies.

References:

[1] Arthur R. von Hippel, ed.: "Dielectric Materials and Applications", M.I.T. Press, Cambridge, MA, 1954

[2] Charu C. Aggarwal, ed: "Managing and Mining Sensor Data", ISBN: 978-1-4614-6308-5, 2013