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Real Time Bridge Scour Monitoring with Magneto-Inductive Field Coupling

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Real time bridge scour monitoring with magneto-inductive field coupling

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ABSTRACT

Scour was responsible for most of the U.S. bridges that collapsed during the past 40 years. The maximum scour depth is the most critical parameter in bridge design and maintenance. Due to scouring and refilling of river-bed deposits, existing technologies face a challenge in measuring the maximum scour depth during a strong flood. In this study, a new methodology is proposed for real time scour monitoring of bridges. Smart Rocks with embedded electronics are deployed around the foundation of a bridge as field agents. With wireless communications, these sensors can send their position change information to a nearby mobile station. This paper is focused on the design, characterization, and performance validation of active sensors. The active sensors use 3-axis accelerometers/ magnetometers with a magneto-inductive communication system. In addition, each sensor includes an ID, a timer, and a battery level indicator. A Smart Rock system enables the monitoring of the most critical scour condition and time by logging and analyzing sliding, rolling, tilting, and heading of the spatially distributed sensors.

Keywords: Scour monitoring, Smart Rock, active sensors, underwater communication

1. INTRODUCTION

Scour is a process in which a fluid erodes material supporting a structure. When scour occurs near a bridge, the associated erosion can cause that bridge to collapse [1]. Bridge collapses could occur in hours or days. To prevent them, scour must be monitored and its mitigation strategy must be developed in real time. Several methods were developed for bridge scour monitoring, which include magnetic sliding collars, sonar systems, remotely controlled boats, buried probes, fathometers and optical sensors [2-7]. Unfortunately, due to harsh environment conditions, mud, rocks, ice and debris in a river flow; these sensors have limited application area and short life span. Moreover, for timely response to compromising bridge stability / integrity the scour needs to be monitored in real-time. This demands development of automated methods for ground erosion detection, which will be highly effective, safe and easy to use. In this project the electronic embodiments with sensors - a Smart Rock system - is designed to tackle the grand challenge of scour monitoring in real time. Figure 1 shows proposed concept of embedding an artificial rocks into bridge supporting structure base, which are capable to collect own orientation/tilt information and transmit the data wirelessly to a base station control unit.
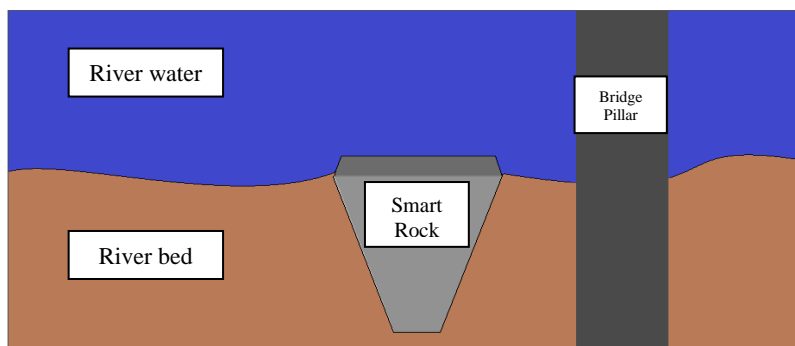

Figure 1. Concrete Smart Rock installation scheme

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Inside the Smart Rocks electronics, batteries, and a receiving/transmitting low-frequency coil antenna are embedded. With time interval or by external request the Smart Rock captures and stores on-board sensors readings, and transmits signature data to the base-station receiver module operated/monitored by a user at the bridge, boat or river bank. Based on RSSI (Received Signal Strength Indication) distance to the rock and its location can be estimated. However, obtained RSSI depends on the receiving/transmitting coils mutual orientation, so processing of RSSI readings only cannot lead to unique determination of the transmitting coil/sensor location. Pitch, roll and heading information obtained directly at the Smart Rock located at the river floor can be used to improve Smart Rock location estimation. An accelerometer, magnetic and pressure sensors embedded in Smart Rock are used to gather this data. Transfer from the rock to the receiver station is performed through water by using inductive-resonant coupling between highly-tuned coil-antennas operating at low radio frequency of 125 KHz [8]. Although the methodology behind Smart Rock data acquisition and communication is pretty simple, the overall system concept is considerably complex and provides possibilities for scaling and further methodology extension. Several concurrent technologies are needed to be evaluated in communication channel implementation as are for example RF and acoustics solutions; Smart Rocks can be considered as independent sensors or could be arranged in more sophisticated network structure with data interchange between the rocks and aggregated data transmission to the base station. Due to required years of on-battery operation low-power consumption has one of the highest priorities in Smart Rock design. Smart Rock movements and low power also could lead to low-level and possibly noisy signals received at the base station, so for data recovery powerful digital signal processing routines are required to be implemented at the system base-station terminal.

The on-board sensors provide the Smart Rock capability to sense the scour related conditions such as depth, location, and orientation of the rock. In order to transmit the sensed data to the base station, all the active components of the Smart Rock are mounted on a printed circuit board (PCB) in addition to the required wireless modules such as a transmitter/receiver antenna, battery, real-time clock and calendar module, sleep/wake-up module, on-board receiver and transmitter circuit, and an inter-IC bridge. The comprehensive embodiments enable the active Smart Rock to be recognized, commanded, and communicated wirelessly and specifically, regarding the ID, battery status, orientation, acceleration, pressure, and/or other scour related data. In addition, with the on-board timer, a Smart Rock is normally in low power consumption sleep mode and can be woken up with specified interval or by external request to arrange communication between the Smart Rock and the base station (for example, every / specific hour, day, month, or year).

In application, the Smart Rock PCB is enclosed into a water-proof (sealed) shell for the purpose of underwater protection. An example of embodiment inside a 2.5 in. diameter spherical shell was used in various small-scale laboratory tests to demonstrate the active sensor concept. For practical application of bridge scour monitoring, the protected or sealed Smart Rock PCB is further embedded into artificial rocks to integrate with the scour mitigation. The on-bridge base station includes large antenna, power amplifier, controller board, and a computer with Matlab graphical user interface (GUI).

2. SMART ROCK DESIGN

2.1 Base Station Transmitter Interface

By default, a Smart Rock is in low power consumption sleep mode and can be woken up by timer or by an external request signal. A Smart Rock uses several modules placed close to each other. To avoid data collision and effectively process the data transmitted by the Smart Rock, it is important that one active module operates at any time. Therefore, a control needs to be provided to the Smart Rock system operator such that the single Smart Rock module can be selected, woken up and read out. The data-exchange channel needs to be established between the base station and the selected Smart Rock module. Figure 2 shows a block-scheme of the corresponding interface involving Control Board, Power Amplifier and a transmitting antenna.

At the base station, power consumption is not an issue. As such, high power amplifiers and large scale (high efficient) antennas can be applied to produce necessary field strength of the transmitted wake-up signal at considerably large distances and complex environmental conditions. The software PC control core is implemented in Matlab and currently is under revision and GUI design stage. The Velleman K4004B 200W amplifier kit is used. The base station transmitter design is independent of the Smart Rock modules used and can be applied for any revision of the Smart Rock system. Developed software is flexible for modifications in case further adjustments are needed.
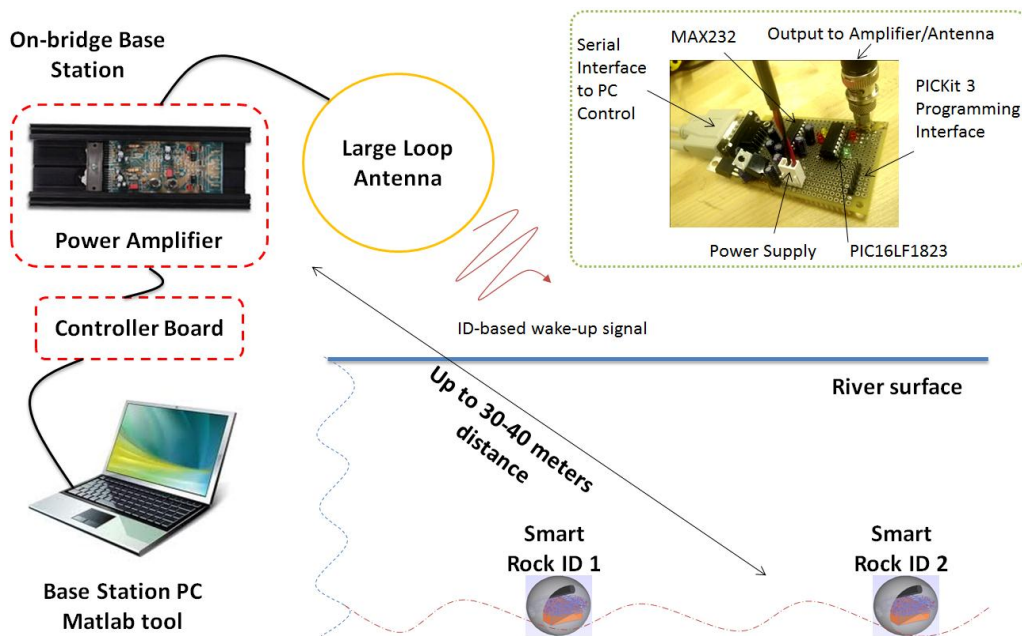
Figure 2. Smart Rock wake-up on demand control interface

Figure 2 top right side depicts the interface controller board photo labeling all of the key components. It is designed based on PIC16LF1823 microcontroller and features MAX232 IC for processing of the data sent from the base station PC through the serial interface (COM port, RS 232). The embedded software translates commands received from the operator PC into the specific wake-up signal pattern required by the Smart Rock on-board receiver module with corresponding ID integration and it does not require to pre-program particular ID signatures (no need to reprogram the board if a new Smart Rock unit becomes available and used for scour monitoring).

2.2 Base Station Receiver Interface

The Base Station receiver interface consists of multiple antennas, band-pass filter/preamplifier module, signal strength log-detector and analog (or digital) demodulator / signal decoder. Figure 3 shows general view of the base station receiver operation configuration.
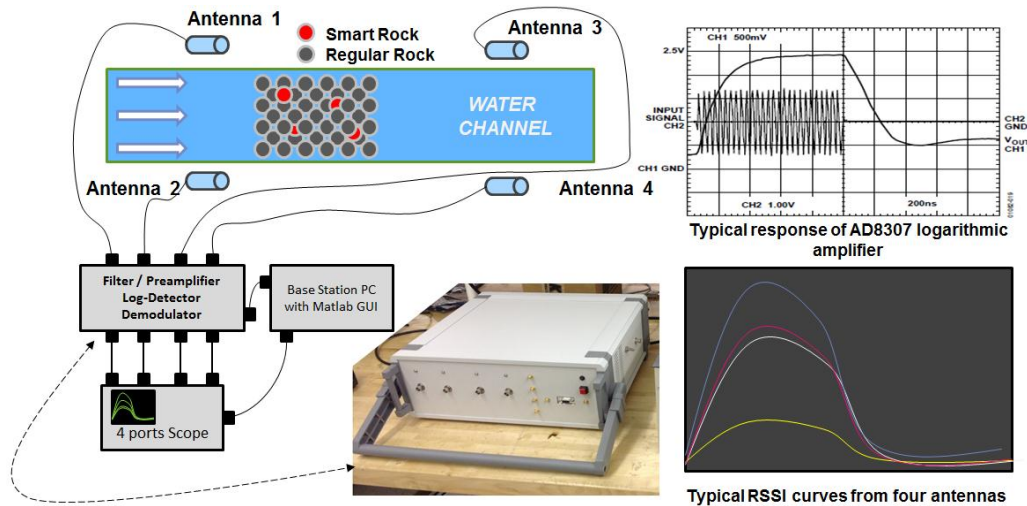

Figure 3. Smart Rock base station receiver operation scheme

2.3 Unit Level Design

The Smart Rock sensor provides the following features:
- 3-axis accelerometer / 3-axis magnetometer
- timer / calendar module for scheduled wake up
- on-board receiver for external wake up on demand with received signal strength indication (RSSI)
- history log of sensors data
- battery voltage monitoring
- adjustable antenna tuning / adjustable baud rate
- ultra-low power consumption

These features are implemented in electronic design utilizing PIC16LF1829 microcontroller, AS3930 low-frequency receiver IC, PCF8523 calendar / timer IC, LSM303DLHC Accelerometer/Magnetometer, L3G4200D Gyroscope. Figure 4 shows photo of the Smart Rock electronic board with major components notes.
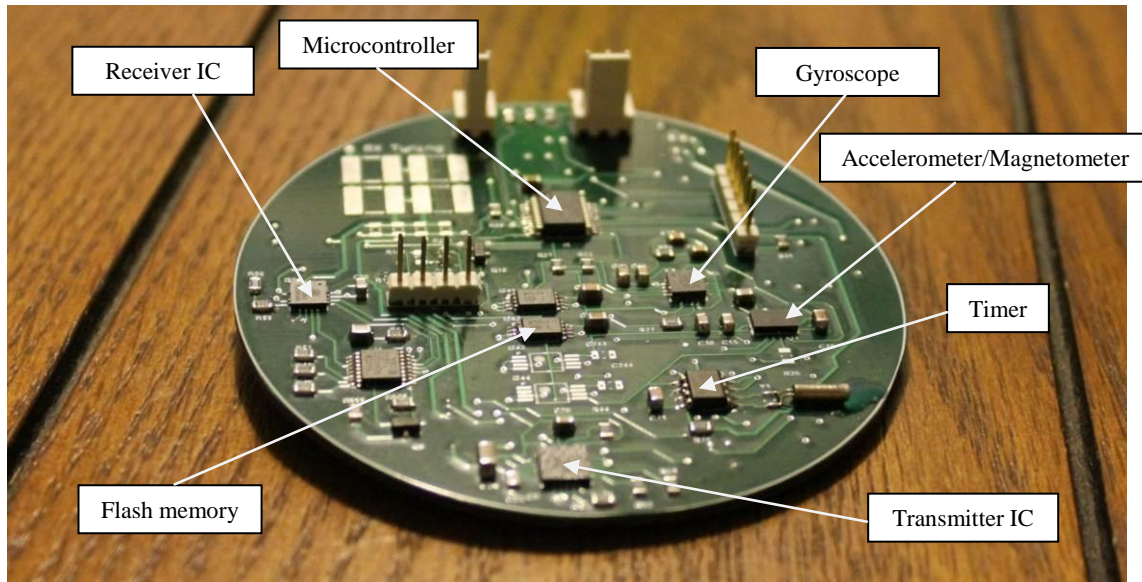
Figure 4. Smart Rock electronics board

3. LABORATORY TESTING

3.1 General description of the tests

The laboratory tests were performed in the Turner-Fairbank Highway Research Center Hydraulic Lab during summer 2012 (photo in the Figure 6). The Smart Rock boards were enclosed into plastic spheres of 2.5 inch diameter. Assembled module included: PCB with electronics circuit, receiving/transmitting coil antenna, two CR123A batteries in parallel and set of small size (~3.5 mm diameter) brass balls to add weight necessary for assembled units to sink (more than 160 grams). The brass balls were painted to avoid electric conductive contact within the set; the balls then were glued inside the plastic spheres using hot glue gun or super-glue application. The coil antennas integrated into the assembly were placed perpendicularly to the Smart Rock electronic board to decrease possible detuning of the antenna by metal parts of the board. To assure waterproof properties the spheres were sealed using silicone adhesive and tight wrapping by electric tape. Figure 5 demonstrates details of the tested units assembly.
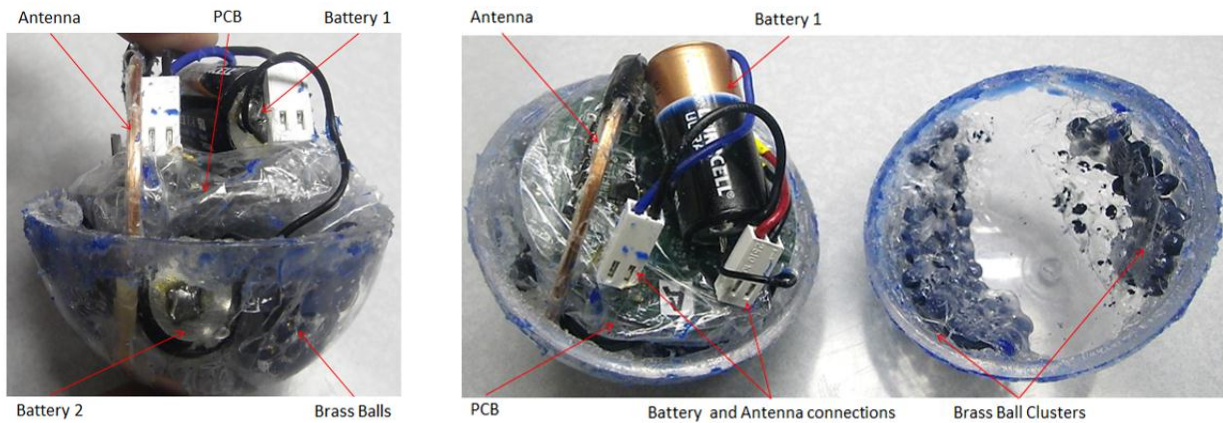
Figure 5. Scaled-down Smart Rock sensor

During the tests four Smart Rock units were used. Two of them were programmed for continuous sensors data acquisition and transmission with predefined timer delay; other two were programmed to respond on external wake-up signal interrupt. Data transmission and processing were performed using analog signal processing procedures; transmission was arranged in RS232 protocol, ASCII code, without data encoding/compression and error recovery.
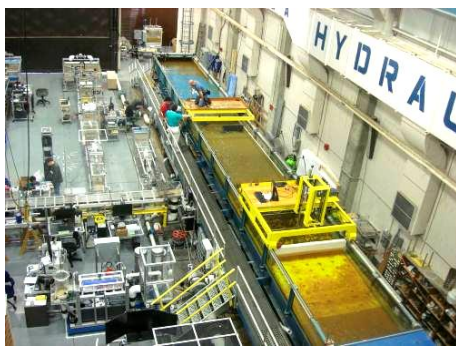

Figure 6. General view of the hydraulic lab
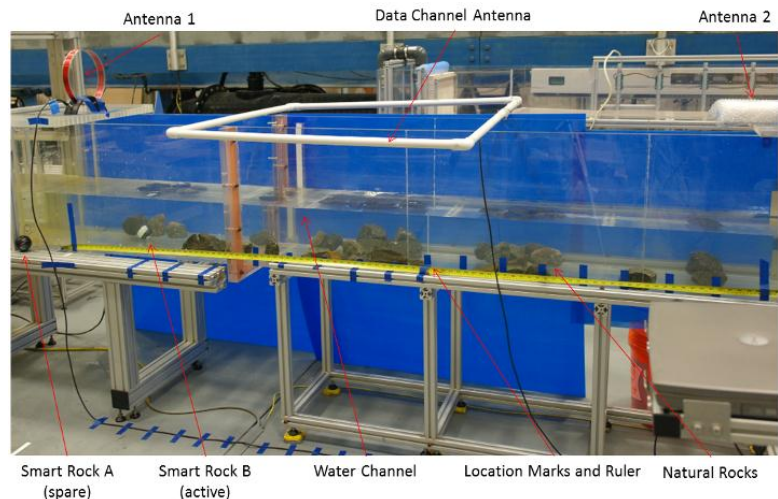
Figure 7. General view of the test flume with Smart Rock sensors

Tests were performed by following scenario: a Smart Rock module was placed into the water channel at very left position as it is shown in photo at Figure 7 (Smart Rock B), by water flow the module was then moved to the termination position at the right side. Time needed for a module to complete the path varied from 10 second up to a couple of minutes depending on water flow strength and arrangement of the natural rock groups. The natural rock groups' placement gave possibility to arrange areas along the path in which active rock was accelerating or opposite – areas which took longer time to pass.

3.2 Calibration

To adjust localization routines to particular laboratory environment antenna reading vs. test Smart Rock module calibration was performed. It should be noted that presence of external electronics, power supplies, chargers, high-speed cameras, pump controllers and motors make hydraulic laboratory environment very noisy from electromagnetic point of view. In noisy environment Smart Rock signal-to-noise ratio degrades, which could lead to potential issues with data decoding and wake up signal processing. Before tests and calibration the lab was inspected and several significant noise sources were determined and eliminated.

General scheme of performed calibration procedure is shown in Figure 8. A sample Smart Rock was manually moved along the path with fixed (~10 cm) distance step. At each position RSSI readings from localization antennas were stored. The procedure was repeated three times for three orientations of the Smart Rock integrated antenna and 15 locations along the channel.
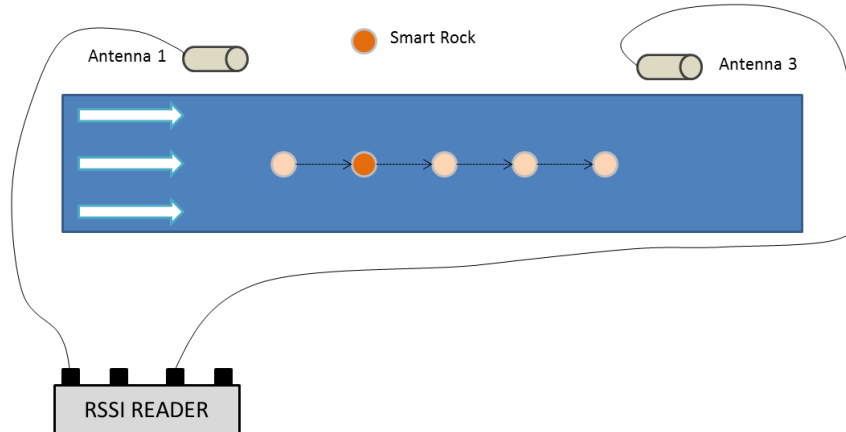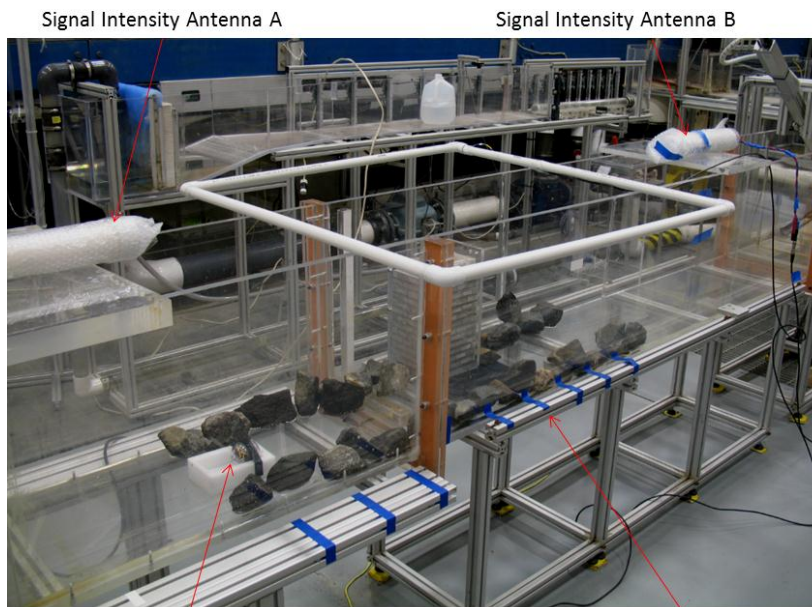

Figure 8. Calibration procedure scheme

Water flow direction is considered to be X-orientation, perpendicular to X in horizontal plane to be Y-direction, and perpendicular in vertical plane to be Z direction. Figure 9 shows photo of the calibration setup. Calibration was performed without water in the channel, using a Smart Rock module fixed on a styrofoam holder in specified position.

Figure 9. Calibration procedure photo

Figure 10-Figure 13 show average relative RSSI antenna reading for each orientation. Figure 12 shows curve of overall average of Antenna A to Antenna B RSSI reading ratio vs. test module location. X-axis in these figures represents the calibration-step / position number. This data was further interpolated in linear range from position 3 to position 15 and used as reference data for location estimation for arbitrary oriented Smart Rock module.
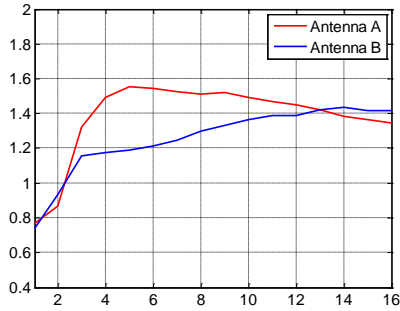
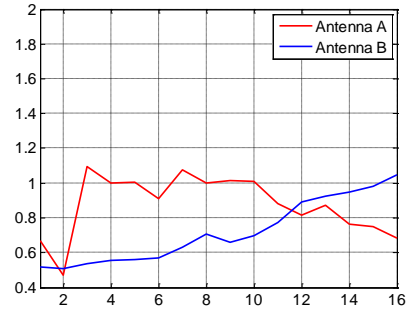Figure 10. X-orientation calibration
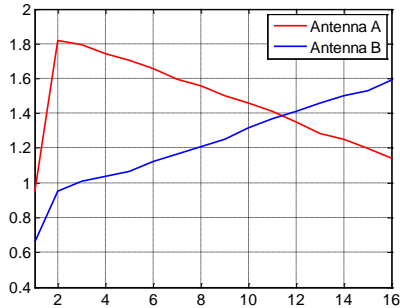

Figure 11. Y-orientation calibration

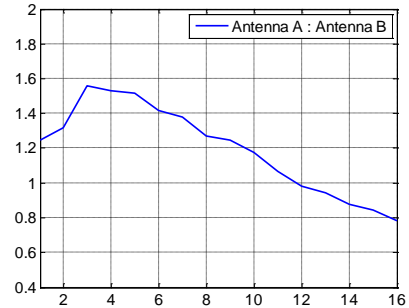Figure 12. Z-orientation calibration

Figure 13. Average RSSI ratio vs. Smart Rock position

It should be noted that such kind of calibration is only applicable in a laboratory environment, while for the field tests numerical modeling of the environment might be more efficient, since it could be impossible to perform manual experimental calibration at the river floor.

3.3 Test results

Two active Smart Rock modules with external wake-up signal processing were moved manually within the water channel with 30-40 cm distance step. Movement was performed in steps one after another and at each position data from each Smart Rock module was collected. Figure 14 shows screenshot from Base Station control GUI with RSSI data, pitch, roll, heading and estimated location values.

On the graphs data from rock 'A' is shown in red color, while data from rock 'B' is shown in blue color. Top left graph shows RSSI reading from antenna 1 in solid curve and from antenna 2 in dashed line. Top right graph shows pitch in solid curve and roll in dashed line for both Smart Rock modules. The interface supports simultaneous visualization of data from four different Smart Rock modules.

Thus rocks were moved manually, there is not much change in pitch, roll and heading information; main objective of this test was to estimate Smart Rock modules location. Position information for each rock is shown in bottom right sub-graph on this figure. After four steps along the path the rocks were returned to initial start position (sample reading #6). Position estimation demonstrated accurate trend; accuracy of the location distance was observed to be about ±15 cm.
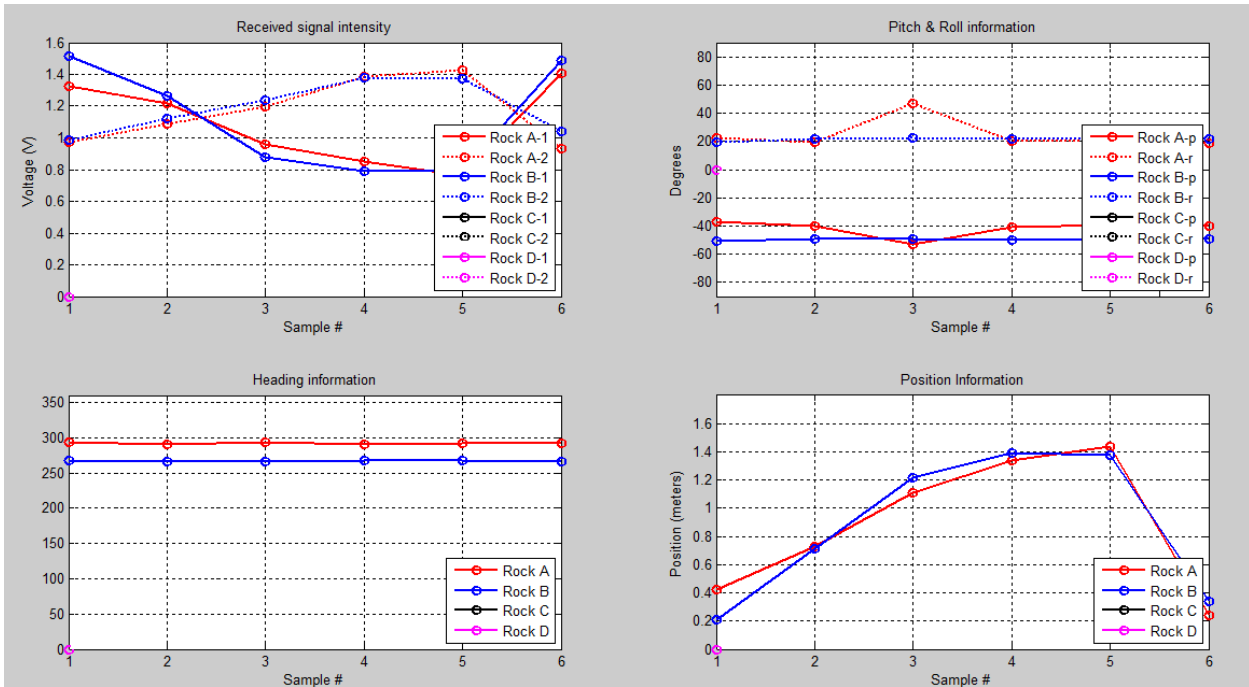
Figure 14. Data from two active Smart Rocks moved manually along the route

Figure 15 demonstrates results from regular test, when a Smart Rock module was moved along the channel by water flow.
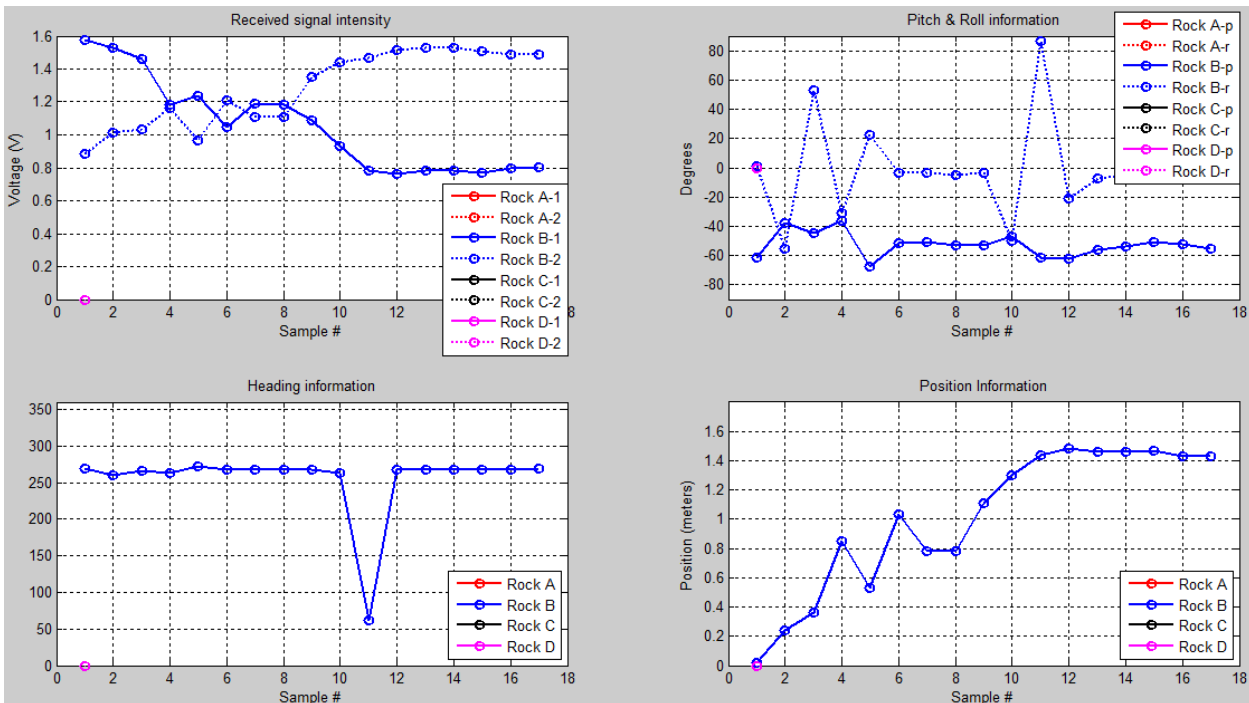

Figure 15. Data from two active Smart Rocks moved manually along the route

While a Smart Rock module was actually moving only in the forward direction with the water flow, position estimation results show some peaks. These peaks were occurring during rock's shaking / rotation at steady position along the path, for example samples 5, 6 and 7 were obtained at almost the same position. However, as it can be seen from pitch and roll information, orientation of the rock was changing, so as a result RSSI (top left sub-graph) ratio between antennas also changed, which led to corresponding inaccuracies in location estimation.

Figure 16 shows results of a test, in which two Smart Rock modules were placed in the water channel simultaneously. The rock 'A' reached end of the channel earlier than rock 'B', it took 5 reading steps for rock 'A' and 11 steps for the rock 'B' to travel through the channel.
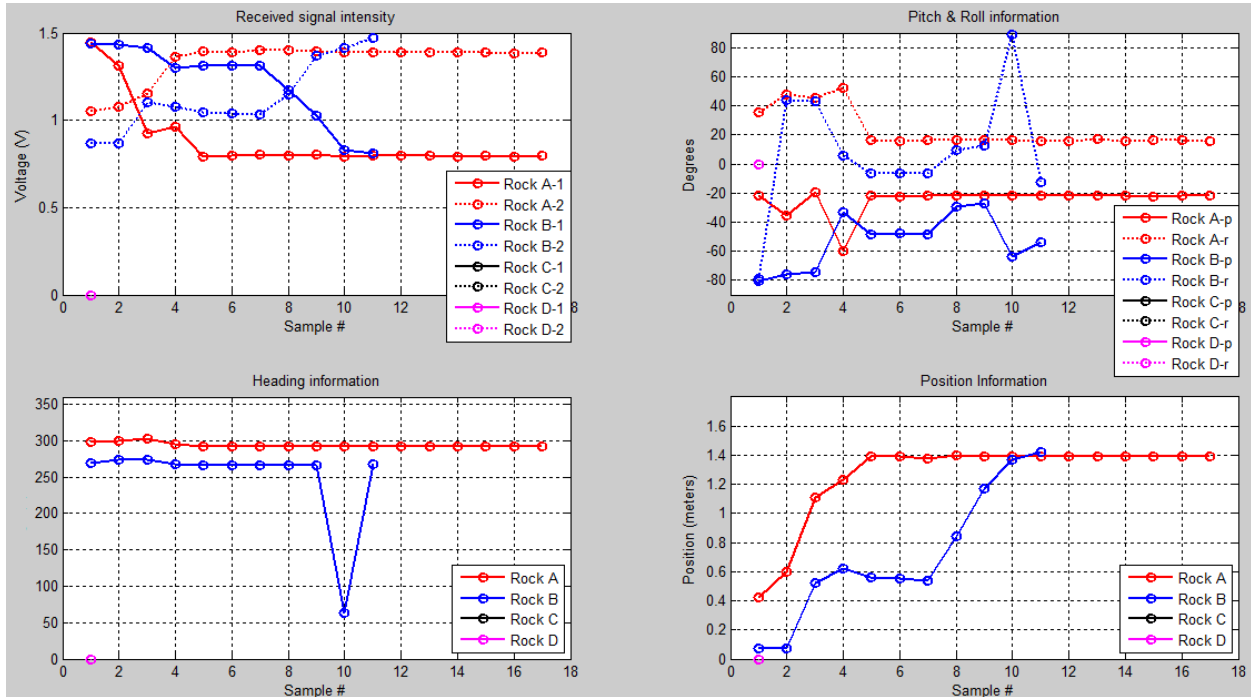

Figure 16. Data from two active Smart Rocks moved manually along the route

After 5th step rock 'A' was stuck at the channel terminal, so readings from this rock are very stable – there is no orientation/location change observed. Rock 'B' stayed in the middle of the channel for some time, when reading 4-7 were obtained. It can be seen that during this arbitrary movement of the rocks overall localization / position tracking was performed successfully.

4. FIELD TESTING

4.1 Design updates

Initial filed tests of the Smart Rock system were performed at two bridge sites in Missouri: U.S. Highway 63 – Gasconade River Bridge, Maries County, MO, and Interstate 44 – Roubidoux River Bridge, Pulaski County, MO. The field tests were completed during September 24 – October 3, 2012. Specifically, the Smart Rocks were placed in the rivers and tested for their responsiveness, signal strength, and background noise in bridge application environments with the use of wireless transmission systems.

For field tests the Smart Rock embodiments design had to be updated. As compared to described above laboratory tests following changes were necessary to be performed:
- Active Smart Rock concrete shell was designed and casted
- Antenna was replaced by larger scale (~9 inch) antenna
- Transmitting and Receiving parts of the Smart Rock boards were re-tuned to the new antenna
- Special high capacity / long term batteries were integrated

The Smart Rock boards, antennas and batteries were enclosed into plastic bucket containers, which further were plugged into large and heavy concrete shells. To ensure waterproof characteristics of the containers very tight lids with insulation gasket were used with the buckets. After closing the lid the area at bucket/lid interface was additionally heavily covered with waterproof silicone.

Figure 17 – Figure 19 demonstrate details of the active Smart Rock concrete assembly. The interior of the waterproof bucket was filled with constriction foam to prevent any accidental moves of the battery pack/ board or antenna during the tests.

Figure 17. Active Smart Rock concrete shells – base and lid

Figure 18. Smart Rock 2.4 electronic assembly

Figure 19. Closed concrete shell

The Printed Circuit Board (as well as on-board accelerometer module) was co-oriented with the antenna plane. The Kaito/ Grundig AN-200 antennas are used for the rocks. Nominal frequency range of the AN-200 antennas is 520 KHz-1510 KHz, which is off the 125 KHz frequency of active Smart Rock communication link. The antennas resonance was accurately tuned to using low-loss Mica capacitors. Measured Inductance of the AN=200 loops is 345 uH, which requires 4.7 nF capacitors for 125 KHz resonance. With precise tuning of the antenna transmission / receiver stages operate most effectively, however during transmission the antenna becomes capable to drain very high currents (more than 1.5 A), which is not desirable. To avoid too high current consumption during transmission the Tx stage of the antenna connection circuit was slightly detuned from ideal 125 KHz resonance to reach maximum current levels during transmission to be not more than 1 A.

The integrated power supply for the Active Smart Rock is based on very low self-discharge rate batteries – Tadiran TL5930/T, which can last in charged / operational conditions for more than 10 years. Each battery can supply pulse current up to 500 mA, however datasheet recommended continuous current should not exceed 230 mA. To assure stable power supply for the active Smart Rocks the packs of four TL5930/T batteries were used for each rock module. Additionally, a super cap of 5F capacity was applied to the battery pack to improve dynamic response of the batteries. The batteries voltage is 3.6 V, single battery capacity 19 Ah.

4.2 Test results

The two bridge test-sites are significantly different by physical structure and river flow. At each of the bridges two active Smart Rock modules were deployed in October 2012 – the rocks were placed in near proximity to the bridge pillar and communication was attempted from the river bank and from the bridge deck as well. The bridge height over the water is about 55-58 feet, distance to the rocks placed under water is about 65 feet.

Figure 20 and Figure 21 show antennas placement during communication session arranged from the bridge deck. Here Stormwise C14T-100K-220K-BC 125 KHz ferrite-core antennas are used.

Operation of each of the deployed rocks was successfully tested. In both locations sensors placed under water were accurately responding to the wake-up signals sent, providing data about current orientation of the rock module (accelerometer / magnetometer / pitch / roll data).

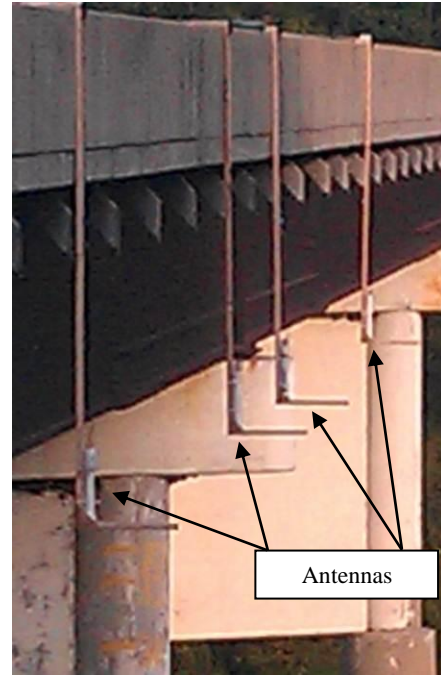Figure 20. US 63 road bridge

Figure 21. Four antenna holders attached to the bridge deck

Figure 22 and Figure 23 show general overlook on the Analog Base Station setup at both test locations.

Figure 22. US 63 road bridge – river bank base-station location

Figure 23. US 63 road bridge – bridge deck base-station location

Figure 24 and Figure 25 show data signals patterns received from each of the rocks in response to the corresponding wake-up signal transmission.

During the tests the communication link between base-station and underwater Smart Rock was validated.
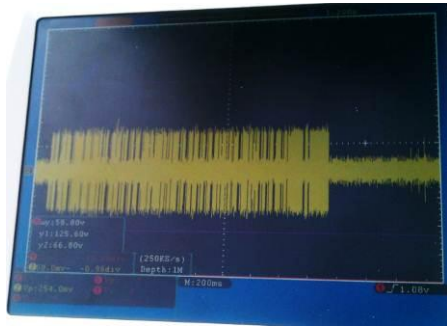
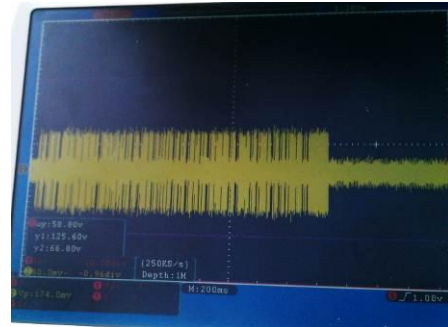Figure 24. Signal response from the Rock A

Figure 25. Signal response from the Rock B

Observed noise pk-pk levels are ≈ 50 mV, signal pk-pk ≈ 150 mV. For initial tests at large distance from the rocks (about 60 feet) observed signal quality should be considered to be good. In this case the preamplifiers gain was set to be about 500.

EM radiation response levels from the underwater placed Smart Rock were high enough for data processing; wake-up interface demonstrated robust operation.

Maximum communication distance depends on co-orientation of the Smart Rock antenna and the receiving antenna bundles. For river bank base station location communication distance exceeded 30 feet, for bridge deck base station location the communication distance exceeded 60 feet.

Waterproof casing of the Smart Rock electronic components was also validated. Initial pitch and roll parameters of the placed Smart Rocks were stored.

Stability of the power source batteries is validated. Batteries pack is continuously able to supply required current amount for Smart Rock effective operation.

The U.S. Highway 63 – Gasconade river bridge-site was revisited in November 30th, 2012 (after 10 weeks since initial sensors activation). Communication with sensors was successfully performed from the bridge deck, at about 65 feet distance. Both sensors flawless responded to the base station wake up signals.

Figure 26 shows test site scene photo, the base station setup at the truck and antennas located in the bridge side. Figure 27 shows the wake up signal sent from the base station followed by response from one of the sensors as observed at the scope screen.

Base Station's wake-up signal

Smart Rock sensor's response

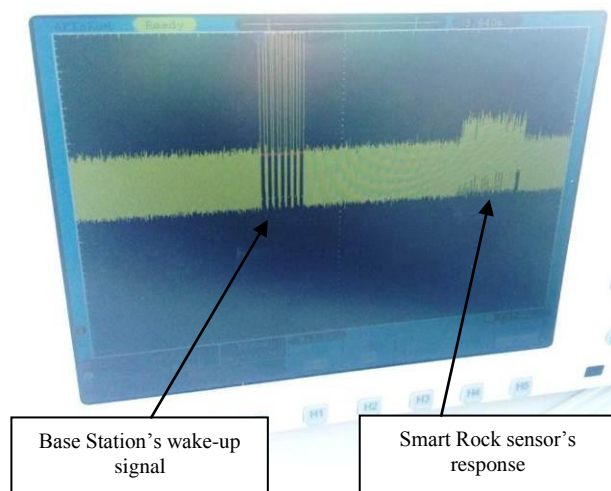Figure 26. US 63 road bridge – Bridge deck location

Figure 27. Scope signal observation

Figure 28 and Figure 29 show recorded communication signals for Rock A and Rock B. It can be observed that response signal from Rock B is significantly stronger, which indicates difference in distance from the base station to the sensor location. Further tests will be performed for localization algorithms development.
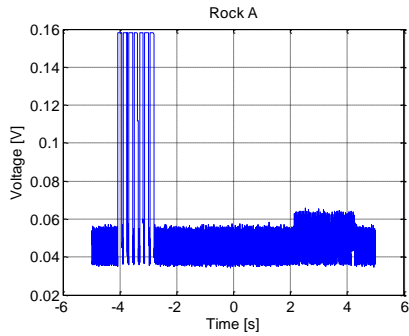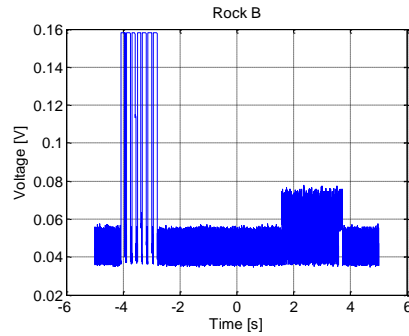
Figure 28. Communication with Rock A

Figure 29. Communication with Rock B

Performed tests validated relatively long-term stability of Smart Rock electronics design and waterproof enclosing design for Smart Rock sensor shell.

5. COMMUNICATION LINK MODELING

For further optimization of communication link / channel to achieve larger communication distances modeling of antennas used in Smart Rock assembly was performed. The Smart Rock deployed at bridge sites are equipped with Grundig AN-200 antennas, shown in Figure 30.

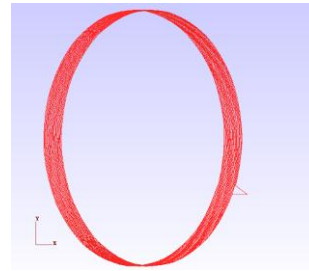

Figure 30. Grundig AN-200 Antenna

Figure 31. 3D Simulation model

The antenna is double-coil antenna containing a couple turns excitation active part and coupled resonant external passive coil. For simplicity of analysis (and tuning) the feeding structure of the antenna was modified – the short 'feed-coil' was disconnected and the outer coil was excited by a source directly. The coils have following geometrical parameters:

Coil wire radius	0.4 mm
Coil radius	11.35 cm
Number of turns	28
Turn-on-Turn Height	2.3 cm

The inductance of the coil was measured using LCR-meter, obtained using analytical expression and using Static 3D modeling in EMCoS EMC Studio [9] (Figure 31). For self-inductance extraction using Static 3D simulation the coil was placed in free space. Overall length of the coil wire is ≈20 m, which was segmented with about 1.2 cm mesh size (resulting in 1662 segments). DC-Resistance of the coil is 0.8 Ohm.

The table below summarizes the coil inductance observation results:

Measurement	348 uH
Analytical expression	317 uH
EMC Studio Static 3D simulation	349 uH

For means of Transmission and Receiving in Smart Rock the coil is tuned to 125 KHz resonance frequency using correspondingly series and parallel connection with a capacitance of ≈4.7 nF. In simulation exact C matching 125 KHz resonant frequency was applied to the coil. The C = 4.64 nF. Figure 32 and Figure 33 demonstrate simulated and measured input impedance of tuned coil antenna. Simulation is performed in full-wave EMC Studio Method of Moments and in Agilent Advanced Design System (ADS) as an L-C circuit at the Rx/Tx –antennas part of the system (S-parameters solver).
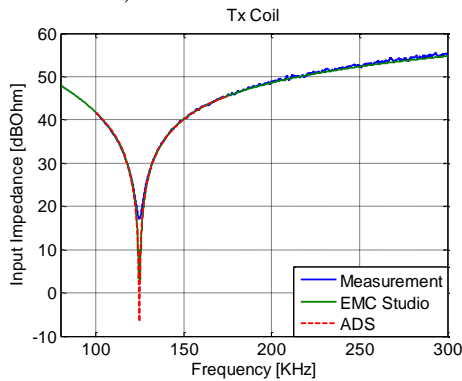
Figure 32. |Z11| TX Coil: C in series

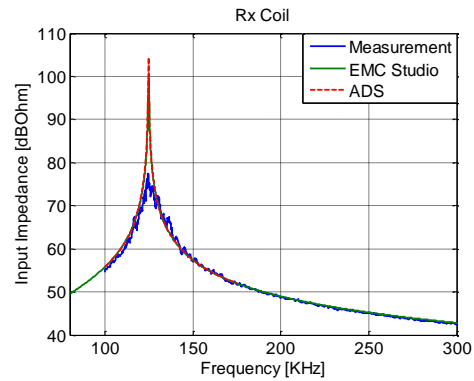
Figure 33. |Z11| RX Coil: C in parallel

Simulation results match very well between each other; also good match with measured data is obtained. Resonant frequency is accurate, however simulation model misses some losses, so demonstrates much higher Q-factor. To improve the model skin effect and resistive losses were introduced in the model.

Next, mutual coupling between two identical antennas was analyzed. To simplify simulation the TX antenna was replaced by impressed current source-equivalent driving 1 A current. The excitation and receiving antennas are co-axle located and the receiver antenna is rotated to estimate polarization loss factor. This configuration is similar to actual Smart Rock application with communication channel established from a bridge deck. Figure 34 shows view of simulation model, d is distance between the coils; α is a tilt angle of the receiver coil as measured from parallel to Tx coil orientation. Figure 35 shows the receiver antenna port model.
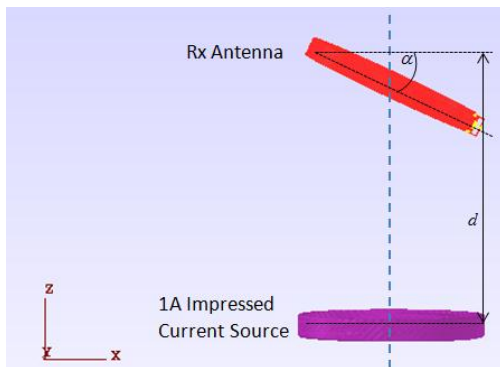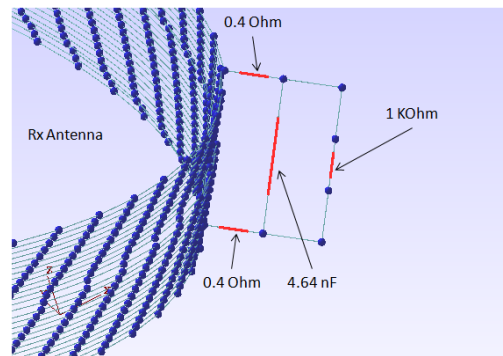

Figure 34. Antenna orientation sweep

Figure 35. Receiver Antenna Port

Pair of 0.4 Ohms in series with the coil represents DC resistance of the coil (in general the coil wire is set as PEC), 4.64 nF is tuning capacitor and 1 KOhm is load, corresponding to the input of pre-amplifier/filter stage of Smart Rock base station hardware unit.

Coupled voltage is observed at the 1 KOhm resistor. Figure 36 - Figure 38 demonstrate change in coupled voltage vs. distance from Tx to Rx antennas, and angle dependence for fixed distances to Rx Antenna.
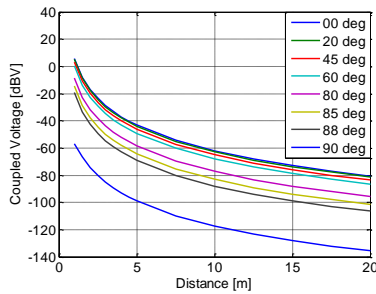
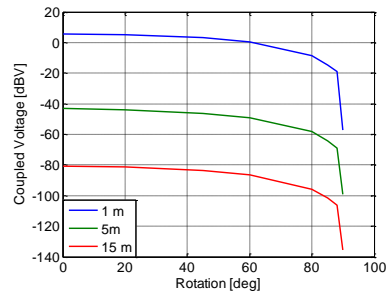Figure 36. Coupled voltage vs. distance

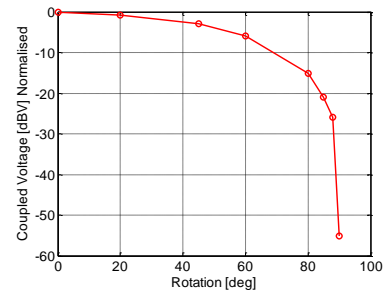Figure 37. Coupled voltage vs. rotation angle

Figure 38. Coupled voltage vs. rotation angle - Normalized

Antenna response has about 20 dB range in 0-85 degree angular miss-alignment case. Below 60 degree miss-alignment antennas polarization loss stays less than 6 dB.

CONCLUSION REMARKS

In this study, a new methodology - active Smart Rock - is proposed for real time monitoring of scour. The sensors use accelerometer, magnetometer and pressure sensors with wireless communication systems to provide data required for the deployed unit localization. The active Smart Rocks have their own IDs for specific requirements such as wake-up / sleep and transmitting scour related signals to the mobile station near a bridge. With the used small antennas and transmitter amplifier / antenna pair in the primarily tests, a maximum wake-up distance of 100 ft. is achieved. The developed scour monitoring system is currently under on-going evaluation in field conditions at bridge sites.

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