Indoor Localization with HF Signals

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Abstract

Localization systems such as GPS fail indoors because the frequencies are too high (> 1 GHz) to penetrate buildings. In this research experiment we will attempt to use low frequency signals in the HF band (< 20 MHz) to allow indoor penetration. Using standard tri-lateration principles, we will attempt localization using three transmitters. We will not need high accuracy clocks, as GPS does, because we will only demonstrate displacement from a known starting reference point, rather than absolute positioning.

1. Introduction

Recent advances in technology have witnessed a lot of research on developing Location Aware Systems that complement the Global Positioning Systems already available. The primary motivation behind these advances is the increasing demand of indoor-localization based applications. Since GPS fails to operate indoors, there are various indoor alternatives coming up: motion sensors, Wi-Fi based, mobility model-based, to name a few. However none of these alternatives demonstrate sufficient levels of accuracy. This forms the ground for the proposed system in this research document. It is suggested to exploit low frequency wireless signals to implement localization. The proposed frequencies to work with fall below 15MHz. With that range of frequencies, the wavelength of the signal is long enough to be able to penetrate through walls making indoor measurements easy.

2. Related Work

With the advent of devices and applications that use location awareness, researchers all over the world are devising ways to determine a user's location by either various signals of opportunity like Television, Radio, GSM and Wi-Fi [5] or by systems based upon Bluetooth [9], RFID [13], Ultrasound [11] or Infrared [12].

2A. Related Work – Approach

Most of the work that has already been done fails in terms of accuracy over large distances. Primarily because the propagation models employed are based upon signal strength and with varying strength, it becomes a challenge to get enough samples for the model to accurately decipher user's location. The most accurate of the systems mentioned above is WiFi with an average error of 2 meters over 3000 meters over an area with decent signal strength.

2B. Related Work – Ideology

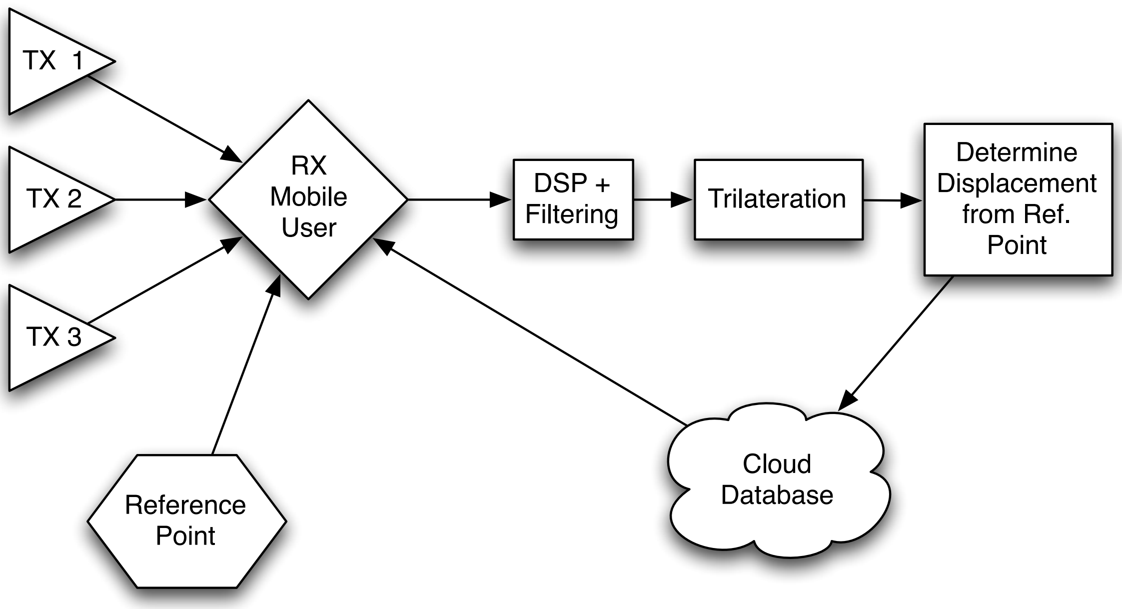
The primary concern with WiFi is the cost of deployment and maintenance. Also, signal strength is not the same in sub-urban and rural areas where perhaps location-based awareness is needed the most. Thus came the ideology of using radio signals. Few suggestions have been made on FM systems based upon spontaneous recalibration [7], fingerprinting architecture [6] or RSSI measurement techniques. However, the biggest challenge in audio signals is maintaining synchronization since mostly the transmitters and receivers for FM radio signals are unsynchronized. Thus additional software/hardware needs to be deployed to make the system trust-worthy which pulls up the cost of deployment.

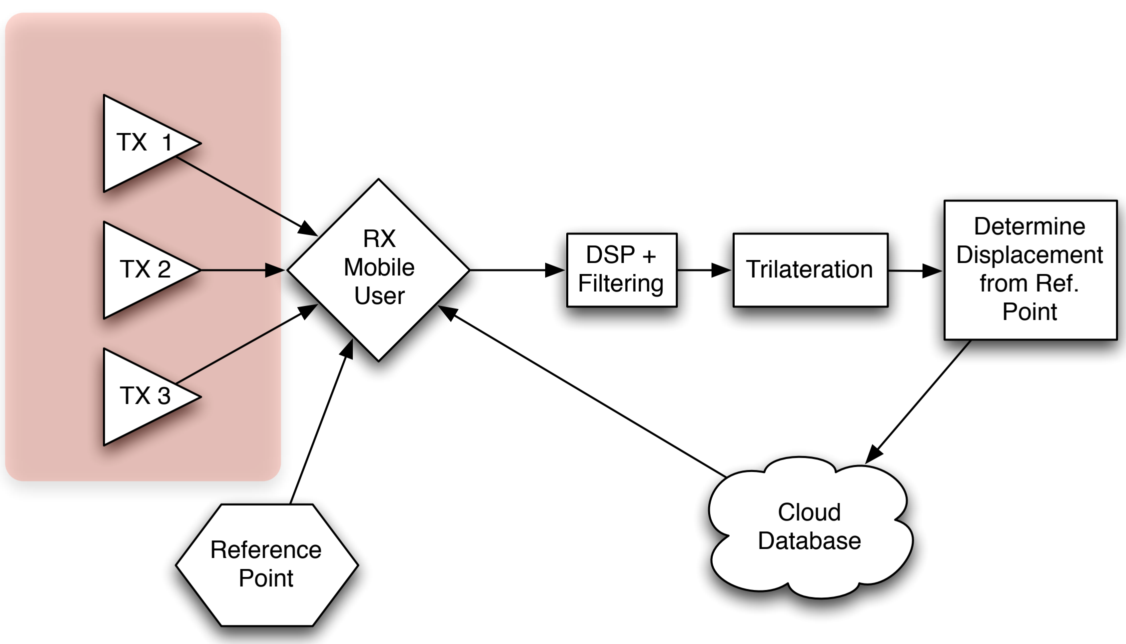
3A. Design – Objective Requirements

Achieve localization in office environment:

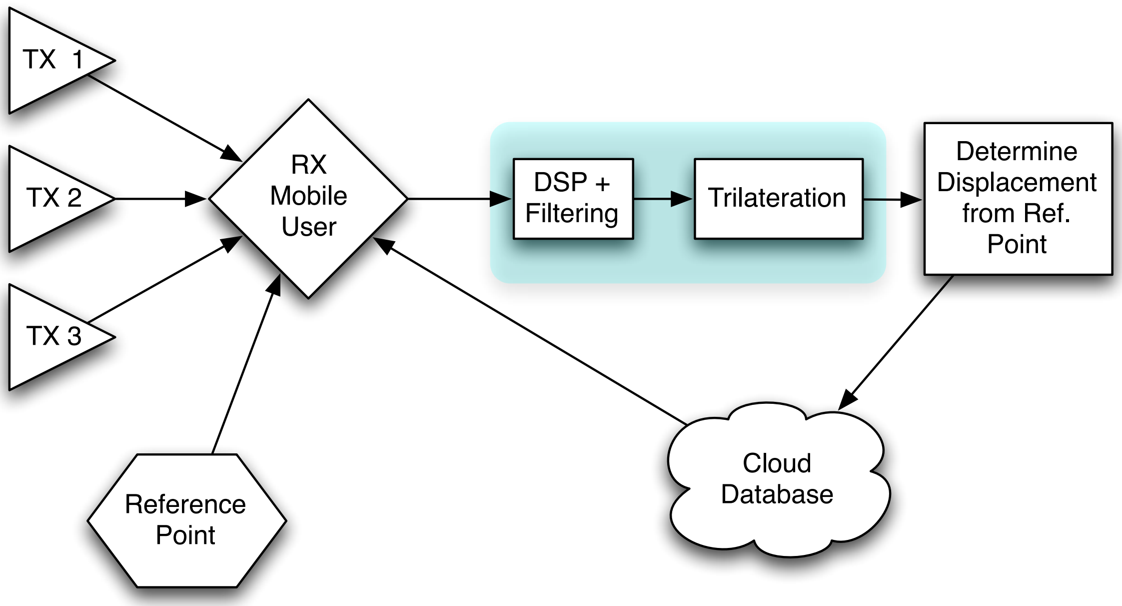
- **"Localization" means a vector from a reference point e.g. entrance to the office.**
- **System is feasible for mobile device implementation within 10 years**
- **Resolution < 10 meters**

3B. Design – Block Level Diagram

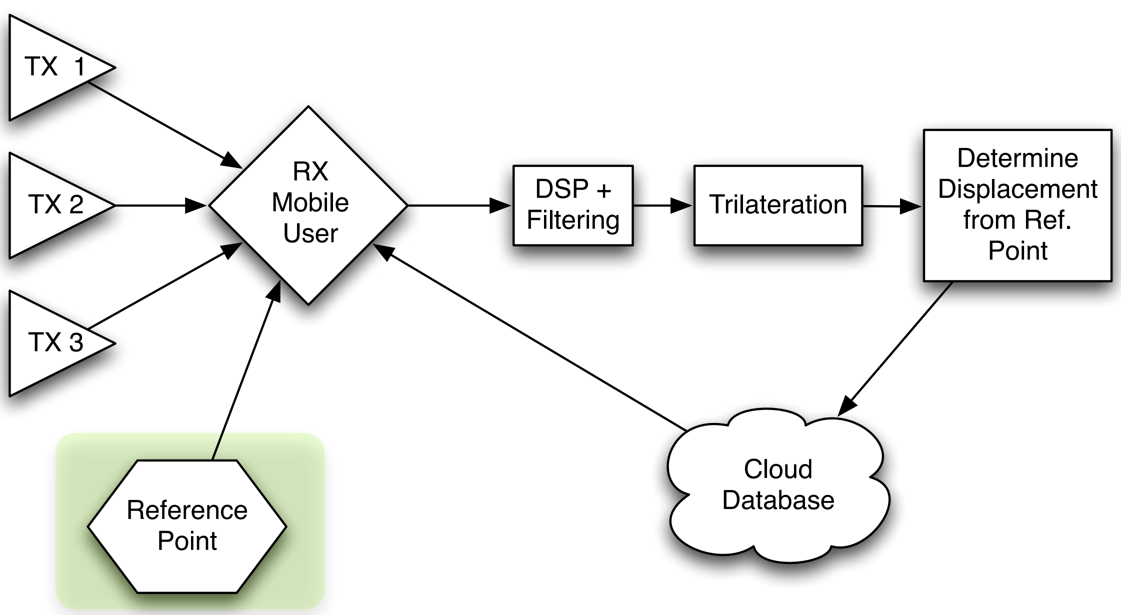




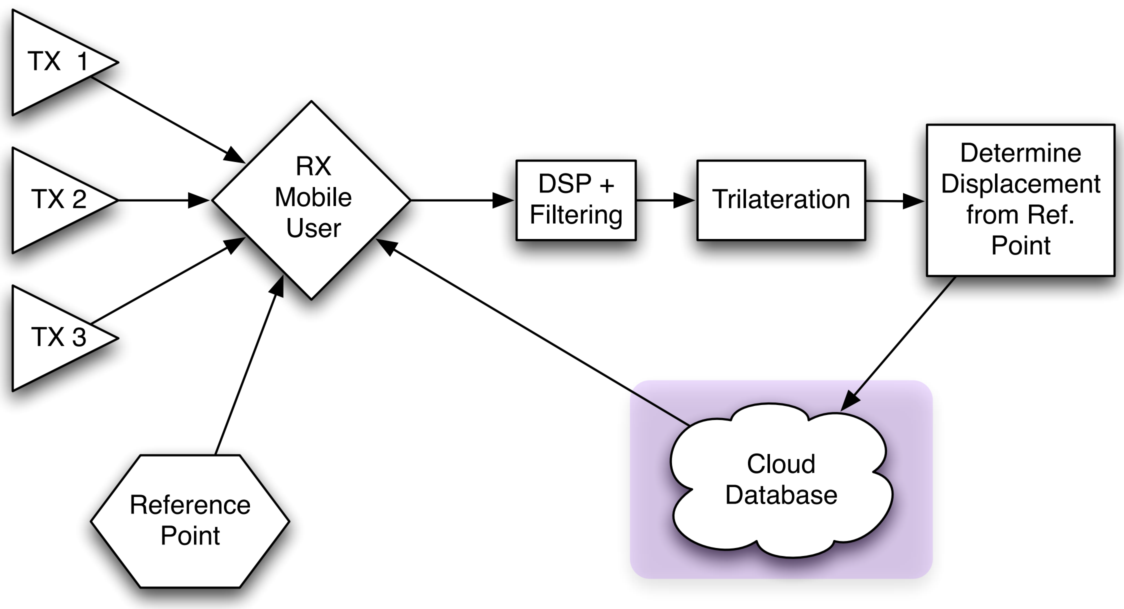
Transmitters surround the building that the user is in. Ideally, in an equilateral triangle, but this is not necessary.



Basic process: Discrete Fourier transform + apply notch filter around TX frequency + inverse discrete Fourier transform + apply matched filter to time-domain signal to recover perfect original signal + determine displacement via phase shift + apply trilateration

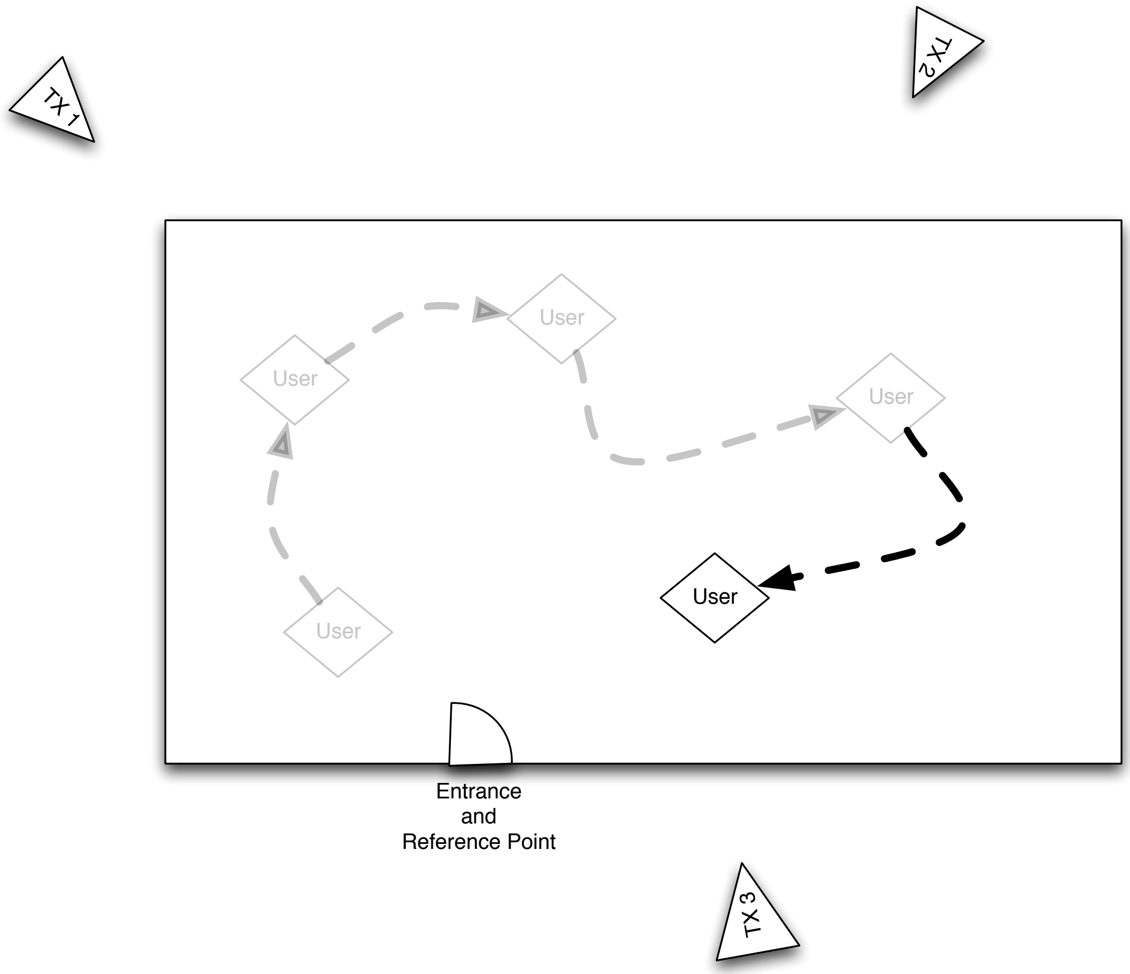


Reference point is e.g. entrance to a building. **Mobile user begins localization at the reference point.** Reference point can send metadata via Internet to mobile user e.g. transmission frequencies.



Cloud database is a way for mobile user to offload localization results in a way that other users can benefit from. E.g. common areas of building can be ascertained such as hallways, meeting rooms, and localization results can be compared against stored values for common areas or paths. A user might find that the localization results indicate, according to the cloud database, he is traveling down a hallway toward a meeting room. This may help resolution.

3C. Design – Bird's Eye View



The user should enter a building at one of the defined "reference points", such as an entranceway. A reference point is simply a location that is already known. The user then begins calculating his location using our proposed system, and the result is a displacement vector from the starting reference point. The indoor structure is surrounded by 3 or more transmitters operating on different frequencies.

3D. Design – Considerations

- Lower frequencies penetrate buildings better than higher frequencies.
- Most commercially available antennas are designed for >20MHz.
- For our system, we want to use frequencies <20MHz, so commercially available antennas are not available.

We can try:

- Building our own transmitters and antennas
- Using existing AM radio signals (~ 1MHz signals)

3E. Design – Details

We will use the USRP and USRP-N210 software radios to generate transmissions and receive signals.
These will allow us to record 25 mega-samples per second. That's about **170 MB/s** of data!

The real basis of our idea is that the phase of the signals we're capturing should change as we move the receiver closer or away from the transmitter.

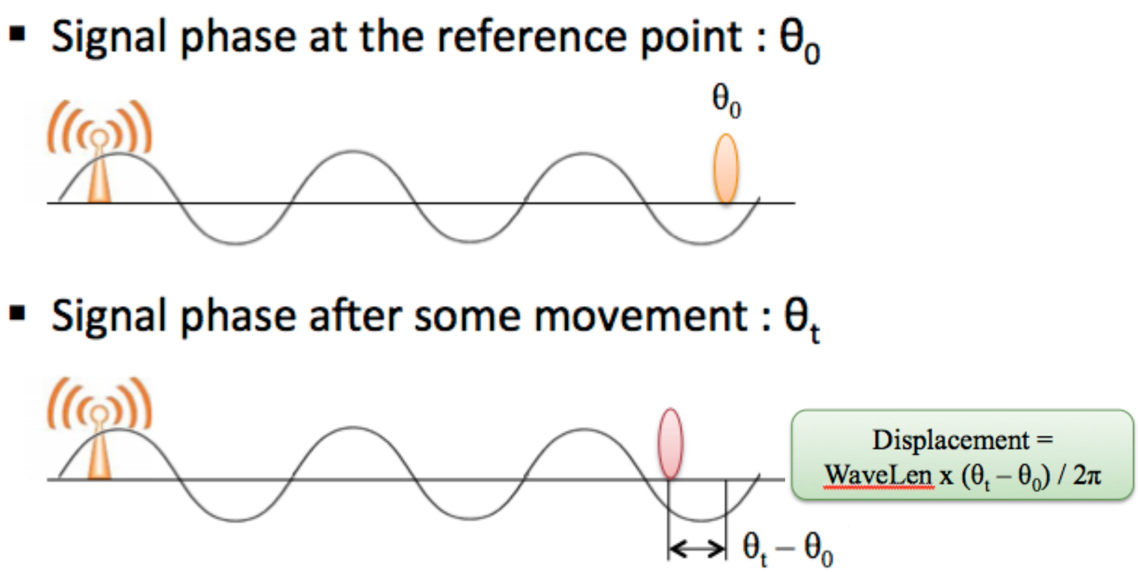


Image courtesy K. Lee / S.Yoon

We employ 2D trilateration for the localization component of our system.
The coordinates of three transmitters w.r.t to the Reference Point are known.
The unknown coordinates can be found by using a system of three equations with two unknowns. Once the location of a point is determined, we could store the location so that now this point acts as a reference point, in addition to the three transmitters. This way, we can build a fingerprinting database.

3F. Design – Details – Why No Clock?

GPS needs very precise and accurate clocks. Why don't we? Simply: because it is too hard to obtain them! Atomic clocks are huge and expensive.

We avoid clocks altogether by instead measuring displacement from a known reference point. The reference point can be determined with e.g. GPS, of course.

3G. Design – Details – Supplemental Information

We plan to supplement our design by letting users upload their localization results to an Internet database. (We assume localization is implemented in an Internet-capable device and that access is available). The database will allow the design to be augmented by previous users' localization results. For example, it may be observed that people tend to move in certain areas of an office, but not others. Some localization coordinates would be lower probability than others, and the database can provide these probabilities as they accumulate. This can help when a result is not certain. The higher probability choices are preferable.

```xml
<?xml version="1.0" encoding="ISO-8859-1"?>
<CSC773_Localization_Metadata_From_Cloud_To_User>
  <uniq_identifer>00014827</uniq_identifer>
  <transmitter_info>
    <TX1>
      <freq>5000000</freq>
      <coordinates>+40.689060 -74.044636</coordinates>
    </TX1>
    <TX2>
      <freq>7500000</freq>
      <coordinates>+40.679260 -74.045821</coordinates>
    </TX2>
    <TX3>
      <freq>10000000</freq>
      <coordinates>+40.689938 -74.048832</coordinates>
    </TX3>
  </transmitter_info>
</CSC773_Localization_Metadata_From_Cloud_To_User>
```


Example XML packet from Cloud Database to mobile user.
Assume that this transfer takes place at the reference point initially.
It tells the user where the transmitters are (coordinates and frequency) and the user has a way to respond to the Cloud Database now with results.

4A. Prototype and Experiment: Iteration 1

Our first experiment was to set up 2 USRP software radios and capture data in plain sight. Then, we'd try capturing through walls to determine if various materials introduced a phase shift in the received signal. For the receiving antenna we used a Terk Advantage.

We quickly ran into problems. The laptop we used for reception was not powerful enough or fast enough to handle the max sampling rate that the USRP was capable of putting out. The signals were stronger now, but we began to think that another approach might lend better results: use 3 existing AM radio stations as sources, and a full desktop computer on a mobile platform.

Mobile receiver, version 1.
This laptop could not handle the max sampling rate of the USRP N210.

- Off the shelf tunable AM loop antenna
  - Terk brand, Model “Advantage”

4B. Prototype and Experiment – Iteration 2

We chose to record AM 1240 to begin with. The transmitter is located approximately 5 miles east of NCSU campus. Knowing the precise transmission location, we planned to record the station while moving towards it for 100 feet.
We used a USRP N210 to receive the data at the maximum sample rate possible: **25,000,000 samples per second**. Such a data rate results in about 170MB/s, and this causes a problem. No computer can write data to disk that quickly, even with a solid state hard drive. We used a 'ramdrive' partition on the receiving computer so that we could dump data directly to RAM. That meant we were limited in the size of the dump we could capture -- about **18 seconds, or 4GB**.
We captured many dumps, but were beset by technical glitches.
Eventually, we were able to analyze dumps taken outdoors on the top of a parking deck. We also had a dump taken indoors on the top floor of an office building.
We learned quite a lot.

AM radio gets a lot of interference from electrical power lines and electronic devices. It is hard to get clear reception from AM radio stations. It is also much harder in the daytime to receive AM signals due to atmospheric conditions. The FCC has this to say about the situation (http://www.fcc.gov/mb/audio/bickel/daytime.html) "Because of the way in which the relatively long wavelengths of AM radio signals interact with the ionized layers of the ionosphere several miles above the earth's surface, the propagation of AM radio waves changes drastically from daytime to nighttime. This change in AM radio propagation occurs at sunset:

"...due to radical shifts in the ionospheric layers, which persist throughout the night. During daytime hours when ionospheric reflection does not occur to any great degree, AM signals travel principally by conduction over the surface of the earth. This is known as "groundwave" propagation. Useful daytime AM service is generally limited to a radius of no more than about 100 miles (162 km), even for the most powerful stations. However, during nighttime hours the AM signals can travel over hundreds of miles by reflection from the ionosphere, a phenomenon called 'skywave' propagation."

It turned out that AM signals were very weak, and of course by definition they were modulated with audio. Our goal was to extract clean sinusoid carrier signals by using matching filters on the signals. However, it turned out the matching filters were having a hard time with so much noise and attenuation. We were not sure this method was going to work out, though we had hope for writing some algorithm to clean the signals up. After some thought about the deadlines, we decided we should abandon this avenue of exploration and try building our own antennas and transmitters.

4C. Prototype and Experiment: 3

We decided to build our own antennas because we knew that an efficient antenna is preferable to strong amplification through an inefficient antenna. Amplification increases noise, whereas an efficient antenna raises the signal to noise ratio.
We decided to choose transmission frequencies to tune the antennas to that were within the US Amateur Radio Band. That way there would be a body of knowledge about suitable antennas available from hobbyist websites. We know that you can't buy low frequency antennas under 20 MHz right off the shelf.

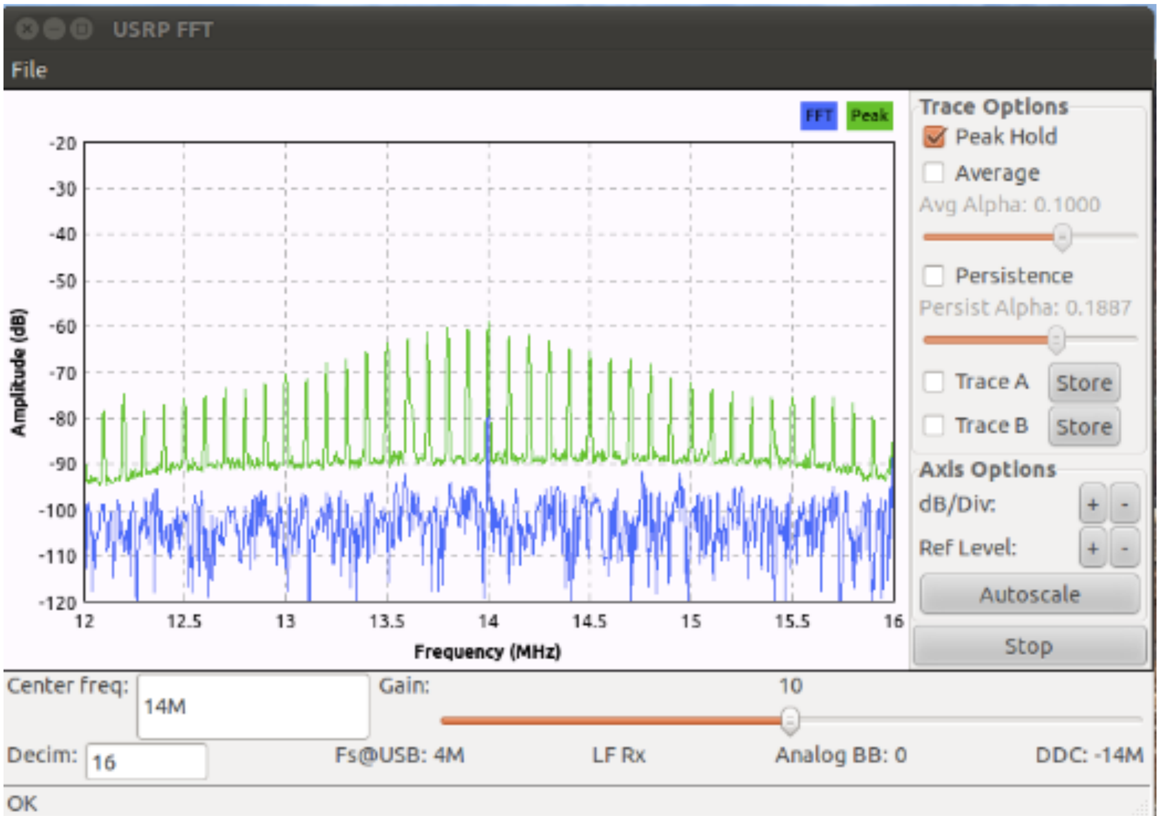
We focused on a frequency around 14 MHz. Referencing this website (http://www.n2mh.net/helix.htm) we built 4 identical antennas of a 'loading coil' design. We used PVC for the core of the antenna, and wrapped 12 gauge solid copper wire around them. The basic idea is that you use 1/4 wavelength of wire and just coil it up to save space. You attach a connector to the bottom end of the antenna, and secure everything in place.

Here is one of our antennas.
You can see the PVC pipe, the green insulated copper wire, and the base connector.
It is a very simple antenna. But as you will see, it is VERY efficient.

1/4 Wave Helical Coil Antenna
Small form factor due to coil.
Simple parts: PVC pipe, copper wire.

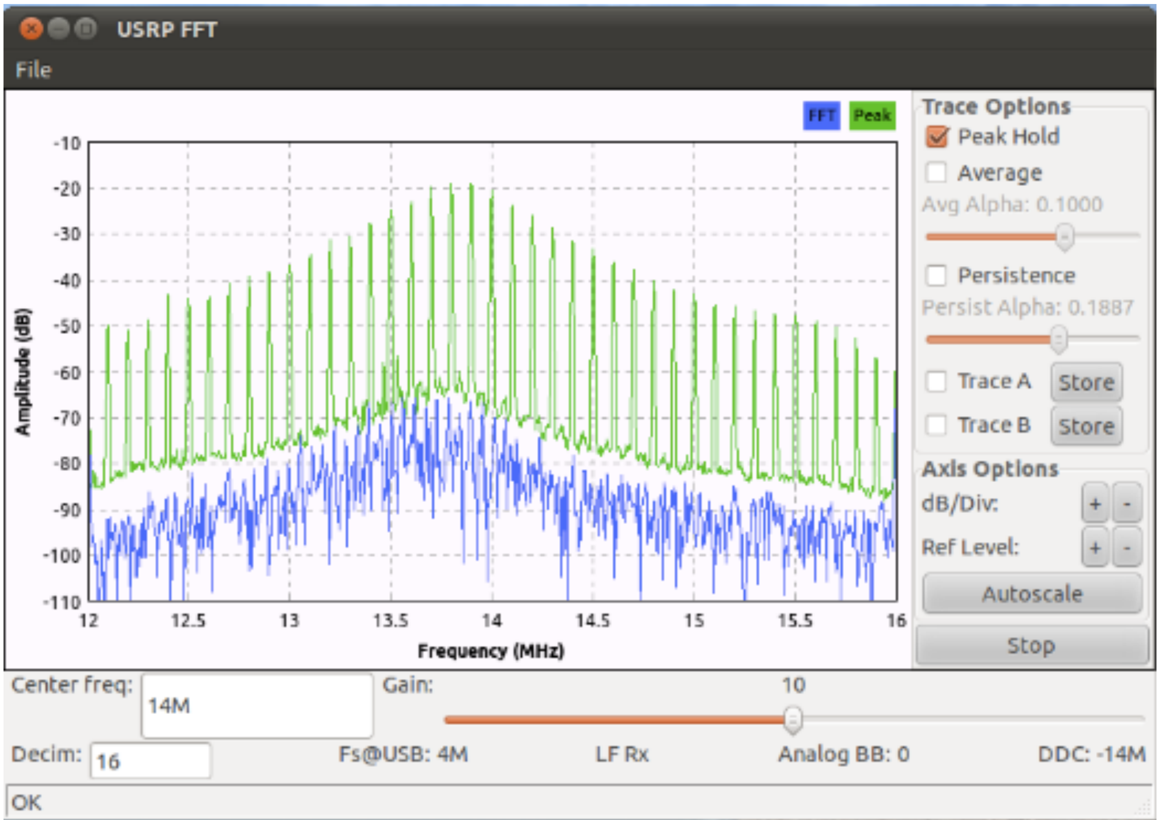
4C1. Prototype and Experiment 3: Antenna Tuning

The helical coil antenna type works on a simple principle. The longer the copper wire, the smaller the optimal transmission frequency. We intentionally built our antennas with too much wire so that we could shorten them and tune them down to the ideal 14 MHz frequency. To accomplish this, we connected the antennas one at a time as transmitters to a USRP running a signal generator. We used a conventional receiving antenna (a "rubber duck") connected to a USRP and a spectrum analyzer. We varied the transmission frequency through our custom antenna and watched the amplitude change on the spectrum analyzer. As you approach the optimal tuned frequency of the transmitter, the received amplitude increases due to more efficiency. The result is a curve that pinpoints the most optimal transmission frequency for the custom antenna. If we decide that frequency is too low, we cut off some wire and run the test again. The new optimal transmission frequency should be higher now. We repeat this process of trimming wire until the antenna is tuned to 14 MHz.



In this graph, the blue represents real-time frequency spectrum analysis. The green represents a recording of previous peak values. As we sweep the transmitter across the spectrum, the green peaks accumulate to show that some transmission frequencies result in stronger received signals than others. In fact, it is a nice curve, with the maximum of the curve indicating the transmission antenna's optimal 'tuned' frequency. This is the natural resonance of the antenna, and it is a factor of the length of the copper wire as well as the internal impedance of the transmission antenna.

The above image is not optimal because a "rubber duck" receiving antenna was used for consistency between experiments. However, that rubber duck antenna was designed for GHz range signals, not low MHz range. We should get much better performance now that all of our custom antennas are tuned if we use a custom antennas on both the transmitting and receiving ends of the system. The chart below shows a huge jump in received signal strength for the same experiment as above. This is a demonstration of how antenna efficiency can have a larger impact than signal amplification. Consider that these gains increase signal to noise ratio, while amplification often does not (because it amplifies the noise, too, in that case).

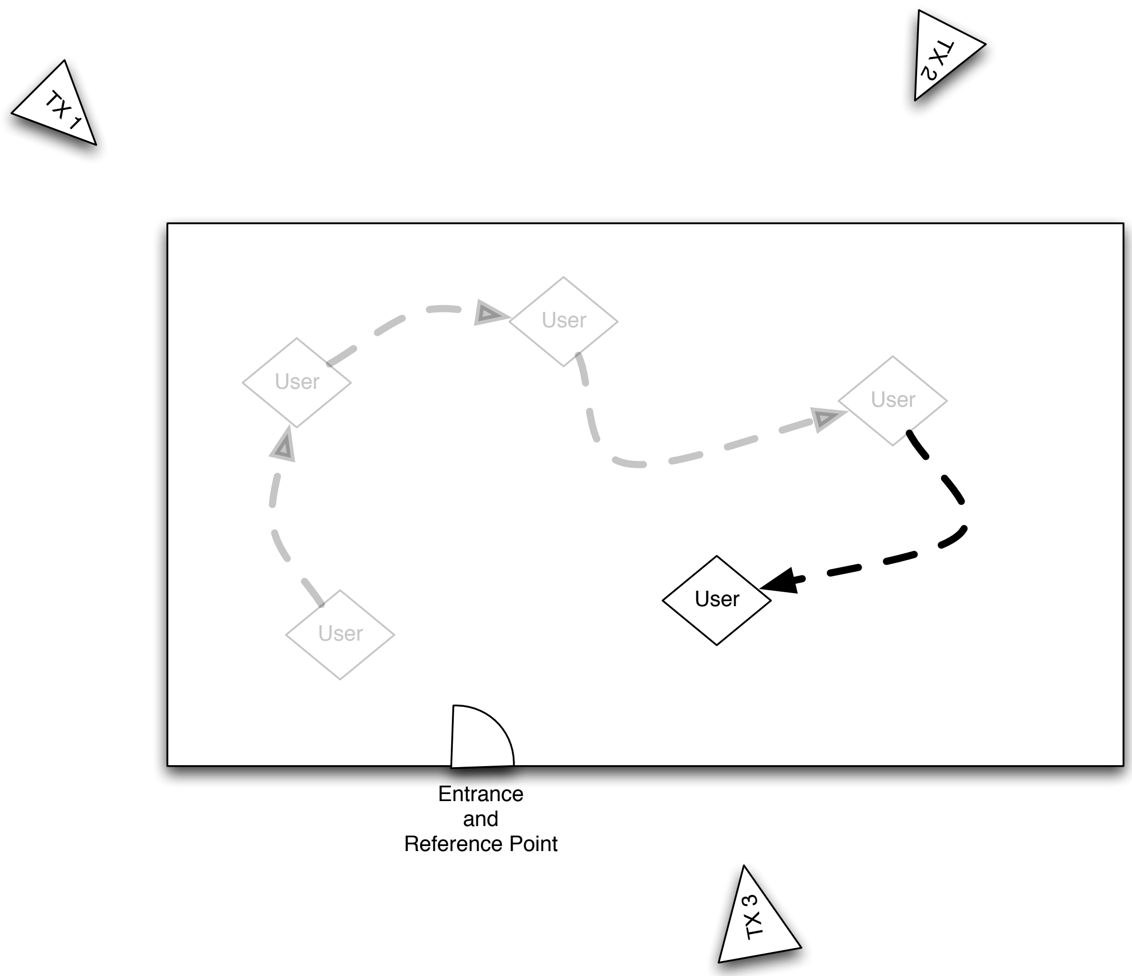


Our peak received signal went from -60dB to -20dB! An increase of 40 dB represents a 2^13 amplification factor. 8,192 times stronger!

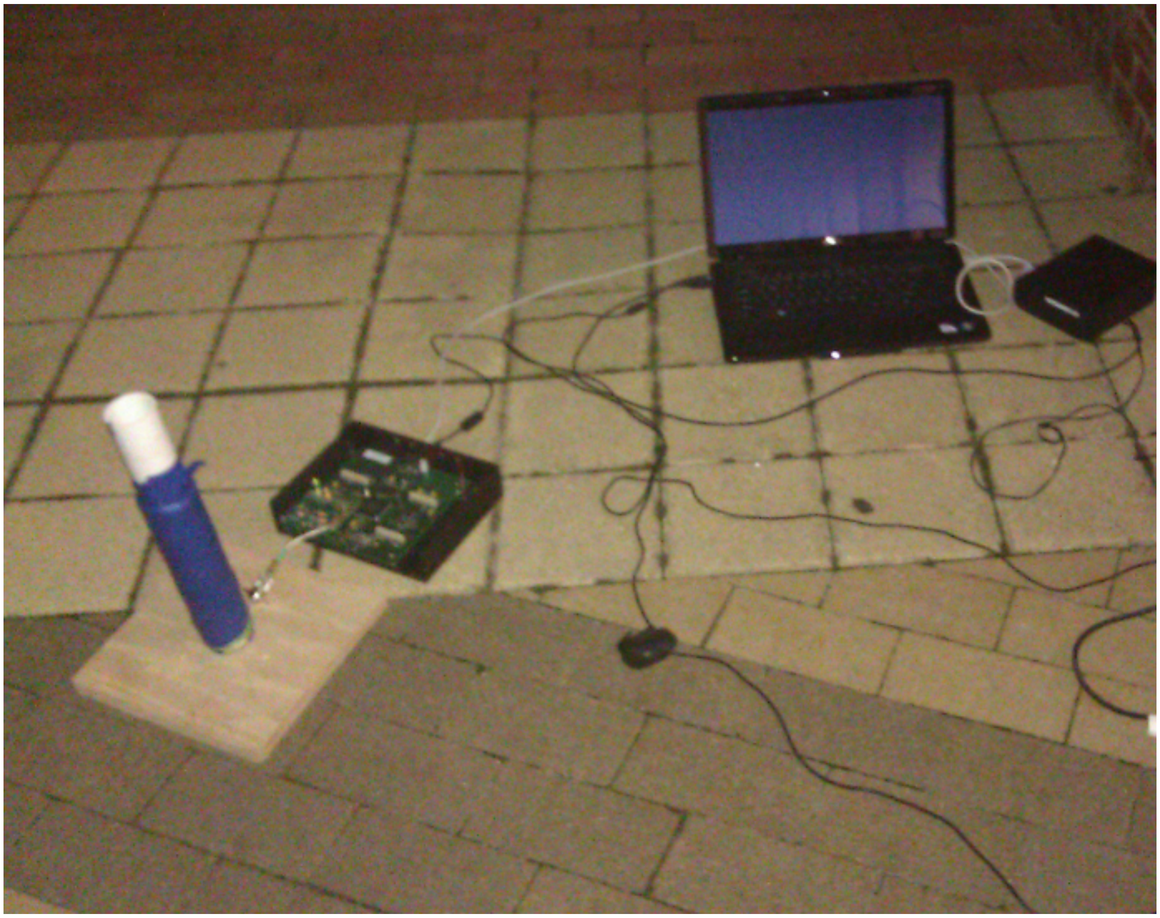
By comparison, our off-the-shelf amplifiers (that we did not need to use) are only rated at 24dB, for an amplification factor of 2^8, 256 times stronger.

Having tuned our antennas, we set up a field experiment in front of the MRC building to gather data from 3 transmitters.

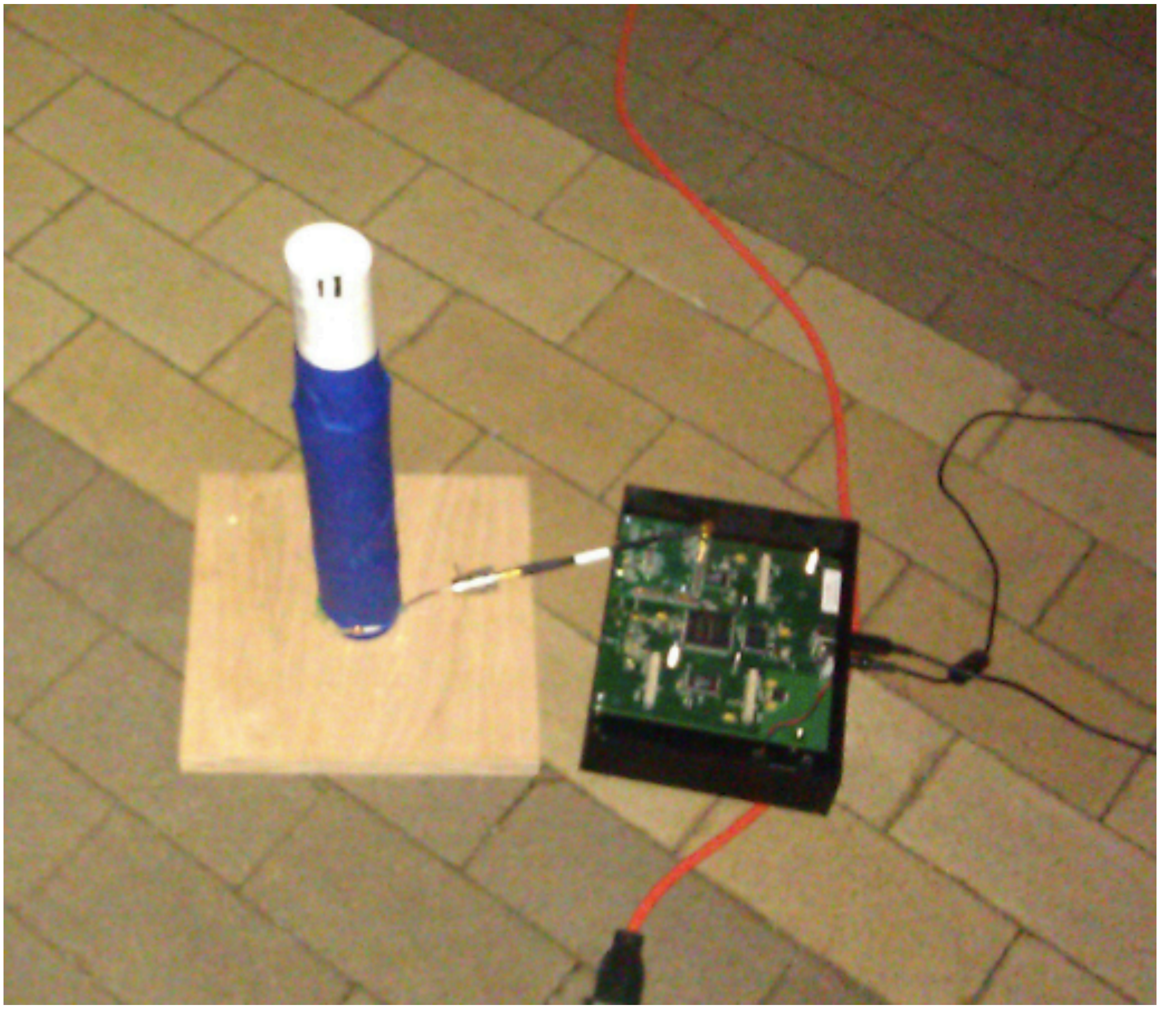
Refer to this concept:



In the field experiment, we began outdoors, with no walls to obstruct the signal. We first chose the grassy area in front of MRC's brickyard because the brick area was in use by other people. Upon setting up our experiment, roughly as indicated above, we noticed that our transmissions were hardly being received at all. Troubleshooting revealed that by placing our antennas on the ground, *even though they were insulated from the ground,* the signals were being absorbed by the earth. In fact, we should have known that groundwave propagation is very common for low frequency signals. AM radio towers are designed around this principle, such that the earth itself is used as an antenna to propagate signals for long distances. We eventually realized that if we lifted the antennas off the ground at least 3 feet, we could get better reception. However, the best case scenario is to place the antennas on the MRC bricks. Eventually, we gained access to the brickyard and set up our experiment there. The bricks were wonderful insulators, and we did not experience any earth absorption.

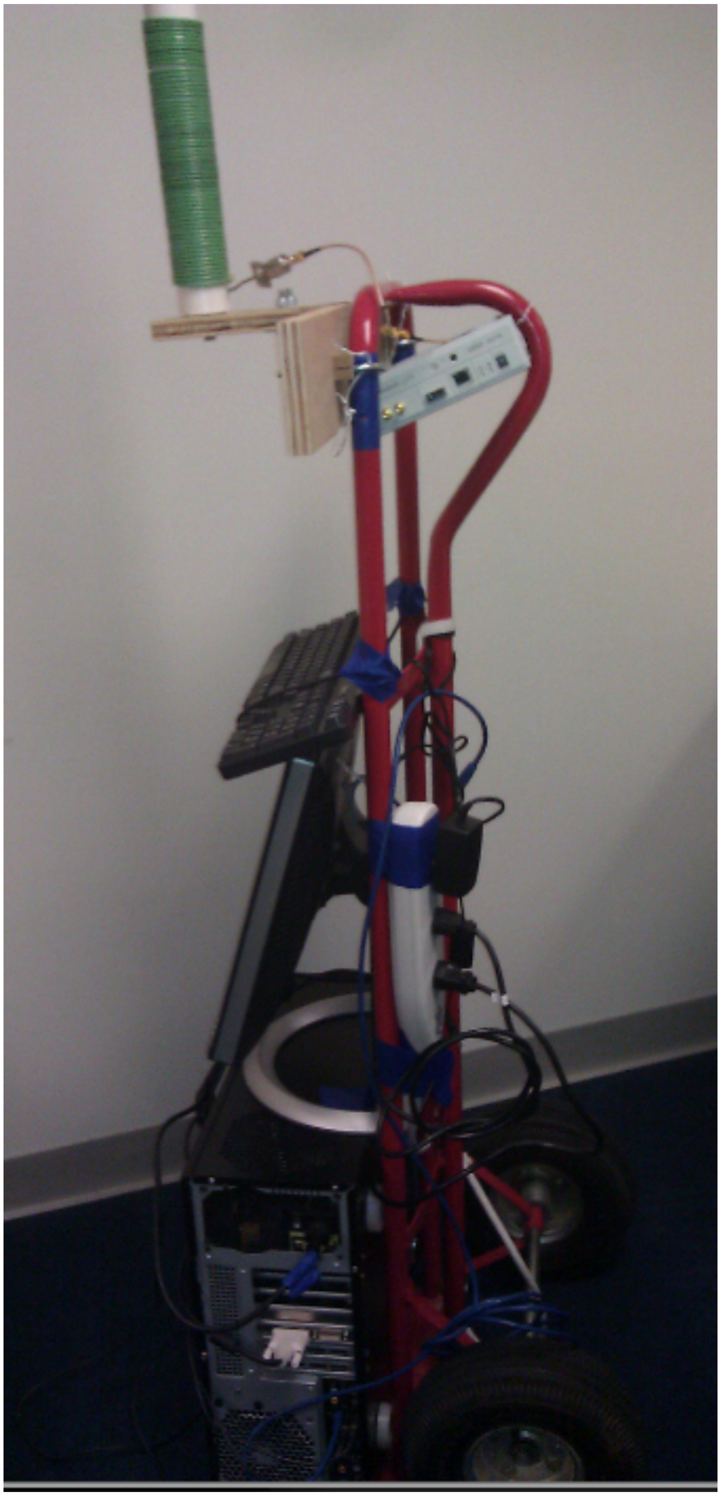


One of our transmitter antennas, along with a USRP and laptop. Note that this is placed on bricks to insulate the transmitter from the absorption effects of the earth.



Our transmitters were arranged in a triangle out on the bricks. We intended to move the receiving antenna and capture system around inside the triangle.

Our receiving system consisted of a hand-truck cart with a computer, monitor, keyboard, USRP-N210, and receiving antenna attached. We connected power with an extension cord, and were able to move the cart quickly between the transmitters during our experiments. Since we were dumping directly to RAM, we only had the capability to record 18 seconds of data at a time. This was just enough time to move in a predetermined pattern between the transmitters.



Our mobile receiver carried a desktop computer, monitor, keyboard, USRP N-210, and transmitter antenna. An extension cord trailed behind.

Our mobile receiver cart in action.

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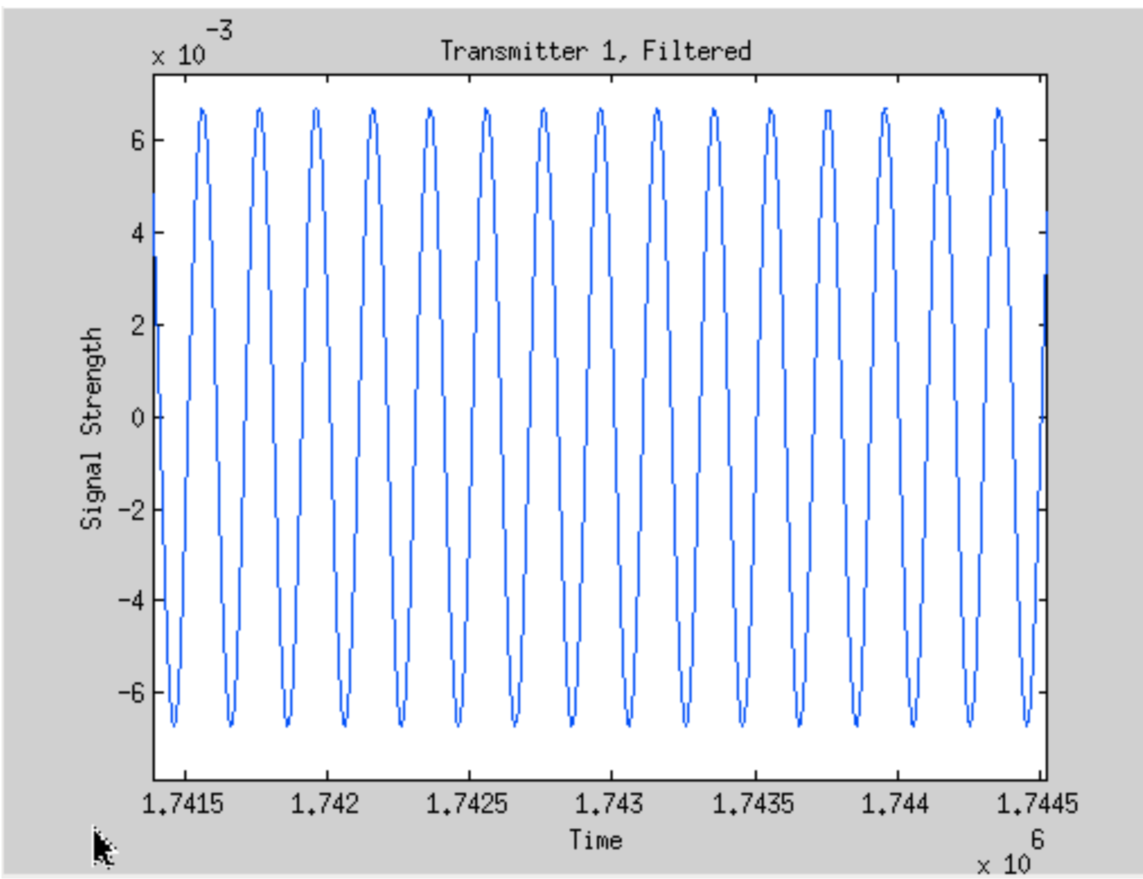
We gathered 20 GB of data in this field experiment. We recorded simple movements, such as directly between one transmitter and another. We also made simple movements such as a circle within the transmitters, and a path in the form of the letter "C".

4D. Prototype and Experiment 3: Analysis

The real question about the data sets is whether the movement of the mobile receiver can be detected from the recorded data. Our initial plan suggested that the information would be locked in phase shifts of the captured signals. To first get to the clean, captured signals, we needed to filter them out of the noise. We discovered we were fortunate to have such a high signal to noise ratio due to our efficient antennas.

You can see here that the recovered time-domain signal is very clear after minimal processing:



We have 3 clear signals captured in the same traces, so the next step is determining how we can extract information that represents the movement of the receiver. We initially stated in the proposal that we were looking for phase shifts:

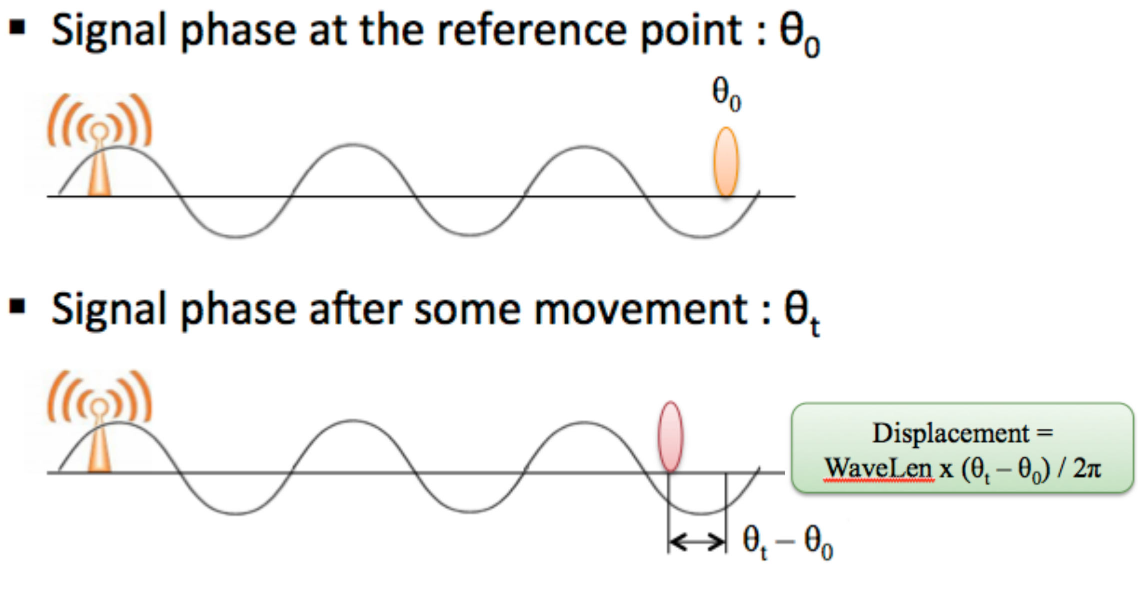


Image courtesy K. Lee / S.Yoon

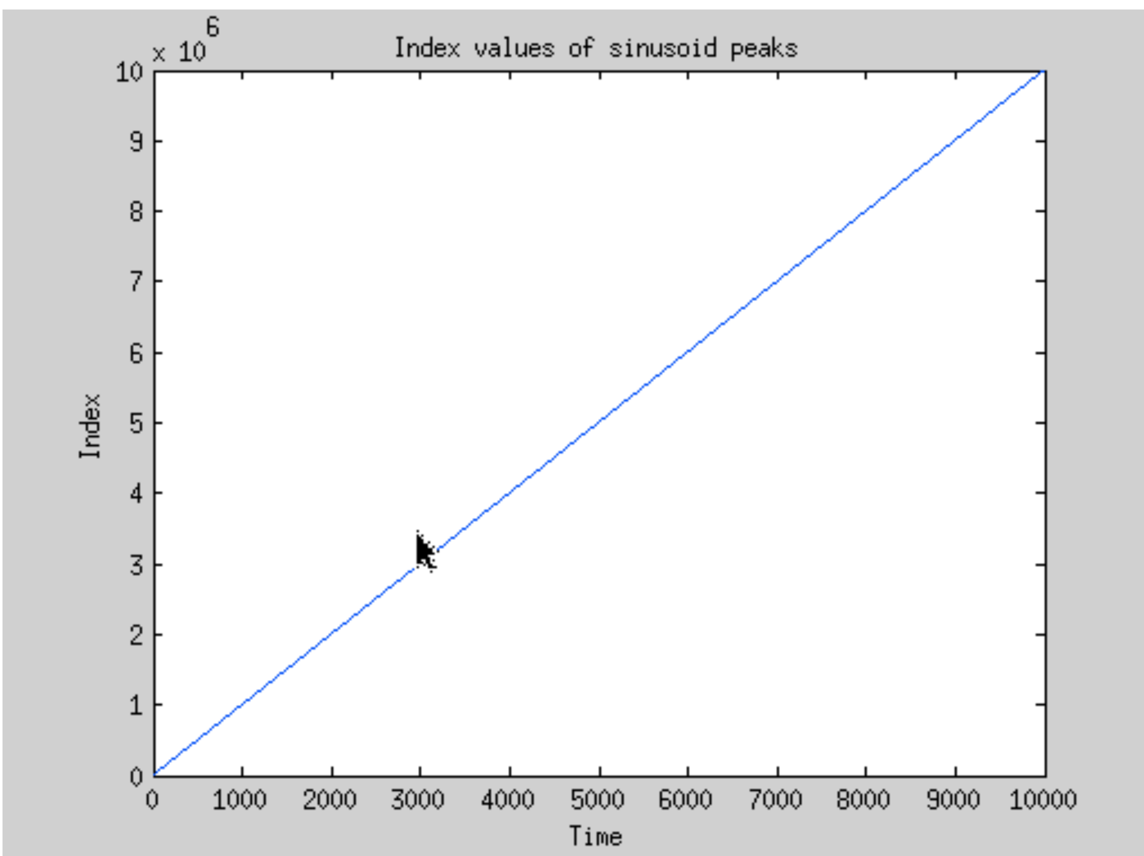
However, extracting this information is not as simple as plotting the phase of our signal over time. The graphic above is perhaps misleading. In order to determine that the phase of the signal has changed relative to an earlier observation, it is necessary to observe if, for a given period of sampling points, more or less cycles of the sinusoid appear. The fact is that we won't see an instantaneous phase shift; we expect to see a transition reminiscent of a Doppler shift.

The methodology we use to detect such a shift is to determine the index of each sampling point at the peak of each sinusoid. Looking at these index values, we will get a sense of how regular the periodicity of the signal is.

An initial look at the index values of the signal peaks shows that there is some drift, which we should expect due to frequency offset of the USRP hardware:

1001
2002
3002
4002
5003
6003
7003
8004
9004
10004
11005

The next question is does this drift in the least significant digit of the index value stay constant (as we would expect of a steady signal) or will we see acceleration as we would expect of movement toward or away from the transmitter. What we find out is that no acceleration appears in our analysis.



This is troubling, as it indicates that we're not able to discern the movement toward or away from the transmitter.

We think, however, that the signal is clean enough, and the sampling rate high enough, that the information we seek is still locked in the data sets. The signal is obviously clean enough by observation, and the high signal to noise ratio we observe in the spectrum analysis of our antennas. The sampling rate, 25,000,000 samples per second, it should be noted, is a complex value sampling rate. At each sample, the USRP captures an In-Phase and a Quadrature value. This means there is more "information" per sample than simply measuring the amplitude of the signal at each sampling point. Additionally, our sampling rate shows approximately 333.3 sampling points per cycle for a 14.3 MHz signal. This ought to be plenty of sampling points to detect subtle shifts in the signals.

For future work, we suggest interpolating the zero-crossings of the sinusoid, and comparing the distance between them in a similar way as we did previously. This time, we should make a histogram of the distances between zero crossings. We should see a uniform histogram at the beginning of the data dumps, because the receiver is still stationary. At the transition where movement of the receiver begins, we should see an imbalance in the histogram indicated that some values of the distance between zero crossings are longer or shorter than others.

Upon achieving success with such analysis, then we would take the experiment indoors and compare the results to see what affect walls and structures have on the system.

5. Conclusion

This experiment has the potential to revolutionize the localization industry if it can be shown that low frequency signals can penetrate buildings and achieve high resolution localization. There are many important uses for this technology, especially in emergency response for cellular phone users who are in large structures. We believe that we have made progress towards this technology's feasibility by setting up the initial platform to explore the technology.

6. References

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