Inexpensive Underwater Data Communication

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Abstract

A system for inexpensive underwater data communication is established enabling more widespread participation in the refinement of this important advancement. Utilizing home audio tweeter piezoelectric elements and an 8bit microcontroller data was encoded into an acoustic wave which was transmitted through water and detected by another microcontroller using an identical piezoelectric element as a microphone. Quantized frequency modulation was used to send decimal digital values on 11 adjacent but discernibly different frequencies. Quantization of frequencies based on anticipated inaccuracies allowed this to be done without any filtering or advanced signal processing. Low frequencies were used due to the inherent limitations in the equipment and to minimize self generated interference from reflected signals. The environment of this test transmission was also selected to minimize any interference. This data transmission was successfully achieved while still keeping the cost of the components involved to less than $60.

Keywords: Arduino, Acoustic, Remote, Control

1. OBJECTIVE

Underwater data communication is essential to our continued development of the underwater environment. In 2004, the US Commission on Ocean Policy directly stated, "Advanced communication capabilities are also required for scientists to remotely operate ocean exploration vehicles, similar to the highly successful use of space probes (USCOP, 2004)." Due to the extremely hostile environment which one interacts with while underwater, it is often much safer to make use of remotely controlled vehicles to perform manual tasks. Although our ability to make these vehicles self guiding and autonomous is increasing, often the task is too undefined and sensor information must be relayed to a person who can make a decision. The decision must then be communicated back to the vehicle to be implemented. Much more research and development of these communication methods needs to be done to provide acceptable options to the system designer. This can be facilitated by delivering a successful methodology that can be implemented by hobbyists, business and academics. Each of these sectors can make immediate use of this type of ability to streamline research and increase public interaction with the underwater environment.

The previous technology used to address this need was the use of a cable which extended from the vehicles pilot to the vehicle. The first tethered ROV was used in 1953 (Christ and Wernli, 2007). It was immediately apparent that the tremendous problems involved with signal degradation and the lateral drag when such a device is deployed in even a slowly moving current necessitated a better solution than a cumbersome cable. This greatly limits the capabilities of the vehicle at the end of this tether cable and much of the design of a successful remote vehicle in the past depended on designing around the tether restrictions. Although such vehicles will be in use for years to come, they will inevitably be replaced by vehicles with the increased maneuverability and depth capabilities that can be realized by using acoustic digital data communication to replace the venerable tether.

In order to stimulate growth in the research, development and usage of acoustic digital data communications, it will be necessary to bring the price down to the point where it is casually attainable. Due to recent maturation of the microcontroller market, it is now more feasible than ever to begin to develop this basic methodology. Further contributing is the relative abundance of inexpensive piezoelectric elements capable of being used as transducers which originated in the home entertainment sector. It should be possible to assemble these factors to send digital information wirelessly through water, and to then decode it back into an accurate representation of that data that can be acted on at the remote location.

1.1 BACKGROUND

When looking into what products are available that use acoustic underwater communication, the only common place it's found in use is diving equipment (Ocean Reef, 2009). The equipment is mostly focused on voice communication between diver and from diver to surface. This use lends itself to frequency shifting the audible sounds into the inaudible ultrasonic range and shifting them back after they have been transmitted so that they might be amplified and directly delivered as sound. This is not really that applicable to data communication because minor irregularities in the received signal are not a significant impediment to voice communications. There are currently manufacturers for underwater acoustic modems which are rated to normal speeds of around 9kbps, although the high prices of these units have kept them relegated to the academic research, oil drilling and military markets. Perhaps the most well known of these is LinkQuest who show a transmission speed of 9600bits per second for their faster modem products, which are all over $8000 to purchase (LinkQuest, 2006).

1.2 APPLIED PRINCIPLES AND TECHNOLOGIES

Sound transmission and reception in water is commonly done through the use of transducers which rely on the piezoelectric effect. This effect is the result of a direct relationship between mechanical stress of certain solids and an electrical potential across their volume. The effect was first discovered in 1880 by Jacques and Pierre Curie (Curie J, Curie P., 1880). The technology found its first notable application in sonar transducers decades later. When a voltage is applied to the crystal or ceramic material, it will deform in direct response to the level of voltage, and conversely will produce voltage across its volume when deformed (Trolier-McKinstry, 2008). Although the deformation is very slight, they are well suited for sound transmission in water, in air the limited movement does not produce adequate amplitude at lower frequencies to be useful.

By creating voltage outputs which fluctuate as a relationship with the sine function and applying them to the piezoelectric transducer, areas of alternating high and low pressure water are created. When the pressure waves reach the receiver transducer, the high pressure creates a proportional increase in potential across the transducer contacts. Once the high pressure subsides the potential returns to zero. Low pressure waves stretch the material and cause it to create a potential which is the negative of that produced by the high pressure. As this process continues to cycle, it generates a voltage fluctuation that should match that which was applied to the transmitter.

A microcontroller will need to see these as a series of quantized digital values in order to process what shapes the signals contain. Analog to Digital converters accomplish this by a process called sampling. At more or less evenly spaced time periods, the microcontroller will check what the voltage input level is and assign that level a digital numeric value. Due to the imprecise nature of the sampling timing it is also necessary to record the elapsed time parallel to each of these values so they can be better analyzed by the microcontroller. The microcontroller can now be programmed to find the peaks and troughs and with that information calculate the incoming frequencies and from them it can determine the values of the data which was sent. The encoding of the data will be a simple system of Quantized Frequency Modulation where a value of 0 to 9 will be sent by a set of five sine waves of a specific frequency chosen from 11 frequencies that are spaced apart far enough to be discernibly unique.. Despite an in depth treatment of the topic, Stojanovic did not cover this method in his review of current advancements and methods in underwater data communications (Stojanovic, (1996).

1.3 OVERVIEW

This report covers the initial testing necessary to determine the parameters used in the final test as well as the final test and results. The proposed method of data communication involves several factors that contribute to the decision of what frequencies to use for the reference marker frequency and the frequencies used to represent the data to be transmitted. In order to present this information with clarity but full explanation, these initial tests are covered in their own subsections throughout the paper. The analysis of this initial data was used to propose the parameters of the main experiment.

The proposed experiment is to prepare a carefully constructed oscillation of voltage which represents hypothetical data which will be applied to one piezoelectric transducer. This transducer will cause corresponding pressure waves to travel through the water. A second piezoelectric transducer will be vibrated by these pressure waves causing it to generate an oscillation of voltage which will be read into a microcontroller using periodic sampling for analog to digital conversion. The resulting digital values will be decoded into the same hypothetical data at this receiving end. To control as many of the variables as possible, the two transducers will be held in close proximity in a small flexibly contained volume of water.

2. METHODOLOGY

2.1 INITIAL TESTING

A function generator was used to create a stable sine wave oscillation of voltage which was attached directly to a piezoelectric transducer. The transducer was placed in a large acrylic test tank of approximately .8m x 7m x .25m depth and was positioned at half depth about 1m from one end and in the center in the .8m dimension and was placed with the sound projecting face aimed down the tank toward the other end. It was held in place by being suspended only by the shielded wire that connected it to the function generator. The function generators port for 1kΩ and 10Vp-p output was used. The Oscilloscope was connected to the second transducer which was positioned in a similar fashion as the first but about four meters away along the long dimension of the tank. Its projecting face was aimed toward the first transducer.

The function generator was turned on and set to approximately 1 kHz sine wave output with maximum amplitude. The Oscilloscope was then turned on and adjusted so that it displayed a stable image of the wave detected. The Function generator was then turned off and the oscilloscope indicated that the signal was no longer being received. The function generator was then powered back on and the previous signal was seen again on its display. The function generators output frequency setting was adjusted and the received frequency was monitored and set as close as possible to the desired values. The actual frequency displayed on the oscilloscope and the amplitude voltage of the received signal was recorded in the same chart.

After additional consideration it became necessary to also determine the usability of lower frequencies so this entire test was set up again on a different day. The function generator was this time connected to the 50Ω output by mistake, which was not noticed until after data had been collected and recorded.

2.2 MAIN EXPERIMENT

Two tweeters from a home stereo speaker system were disassembled to obtain the piezoelectric transducers for this experiment. They were unlabeled so their model number and brand could not be determined but they are representative of the normal inexpensive piezoelectric type tweeters commonly available in the audio market. These types of speaker are available for around $20 at the retail level. The plastic housings were discarded and everything was removed from their surfaces except the thin disc of crystal and their two bonded metallic surface contacts. The elements are 23mm diameter with a brass contact sheet on the bottom, a piezoelectric material disc in the center and on the other surface of the disc, a very thin metallic coating which could be soldered directly to a wire, as could the brass contact. A thin coaxial wire was attached to each with the shielding being soldered to the brass contact and the center conductor soldered to the other contact. These transducers were used due to their common availability and affordability.

The microcontroller selected for this experiment was the Arduino Uno version 3 due to its ability to be programmed in the ANSI C programming language, low cost and common availability. The Uno board can be purchased for around $20 and from a large variety of sources around the world. The Arduino family of microcontrollers is by default configured to only support 9600 samples per second due to a slowing of the sampling clocking which is controlled by a parameter called prescale. By reducing the prescale setting to 16 from its default setting, the microcontroller can achieve around 58,000 samples per second. This provides a much more accurate determination of the incoming signal's frequency than would be possible with the default setting.

The signal to be sent was generated in Matlab version 2010a due to the precise nature of its geometry. Representative values were selected to be the hypothetical data that would be transmitted and the resulting sound data was converted into the .WAV sound format and saved as a file. This file was then transferred to a laptop computer with basic sound capabilities and the sound file was loaded into Microsoft Media Player for use. The sending transducer was then attached to a 1/8" Phone plug and inserted in the laptops headphone signal output jack. The volume on the laptop was set to maximum which should result in a 5 V peak to peak output.

The Arduino was connected to a USB port connection from a second computer. The 5 volt output from the Arduino was put through two resistors of 1kΩ each in series and then into ground to act as a voltage divider. The shielding contact of the transducer connection wire was connected to the junction between these two resistors and then to the brass contact of the second transducer. The other contact was connected to the A0 pin of the microcontroller which inputs voltages to the Analog to Digital Converter of the microcontroller. This was done to bias the analog input by adding 2.5 volts to it so that the ADC, which can only read positive voltages, could collect the full waveform.

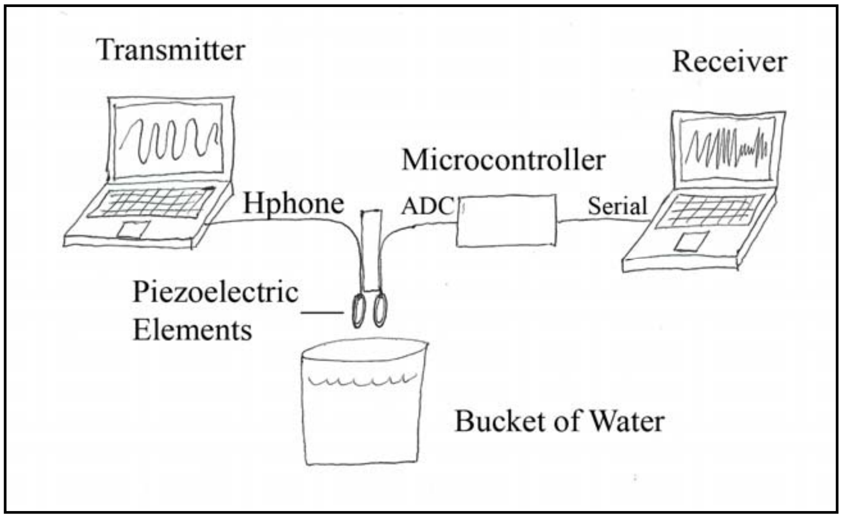


Figure 1: Main Experiment setup

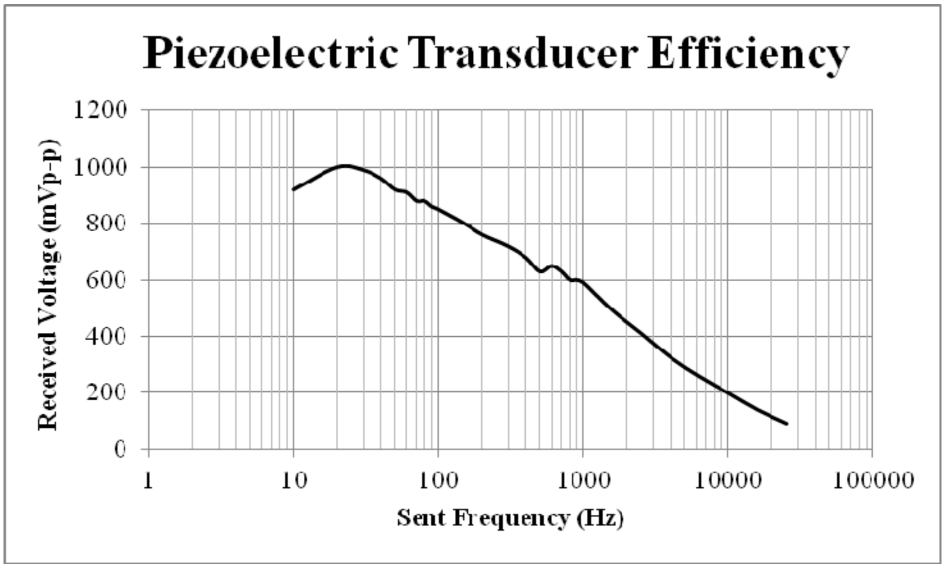
A serial monitor was opened on the second computer using the Arduino software so that it could act as the receiver. The Arduino was allowed to run until it was displaying "Listening" on the serial monitor. The .WAV file was then played from the laptop and the program executed and displayed the results. The results were then copied into Microsoft Excel for graphing and analysis.

3. RESULTS

3.1 INITIAL TESTING

The data in Graph 1 has been corrected to normalize the difference created erroneously by using two different outputs on the function generator as mentioned in the methodology. A logarithmic scale is used to more accurately portray the frequency data. Although parts of this experiment were repeated with different distances between the two receivers, their results were not significantly different from the results represented in the graph, so they have been omitted.

Graph 1- Frequency Response of Transducers



This experiment was well controlled as there was only one piece of information that was being collected. The geometry of the test tank will certainly have had an impact on the transmission of these test frequencies and its reflective properties for the frequencies is mostly unknown, but in this case was of little concern. Any effect that it may have had can be looked upon as the type of factor that the tested system will need to handle in eventual usage and is therefore not completely undesirable. The relevant variables as they are currently understood have been compiled in Table 1 and should give a feel for what has been considered to influence the results. The water was freshwater although not especially clean, and stayed at a recorded temperate of 72ºF. When attempting to adjust the function generator any higher than about 29 kHz, the signal became scrambled to the point that voltage readings could not be gathered.

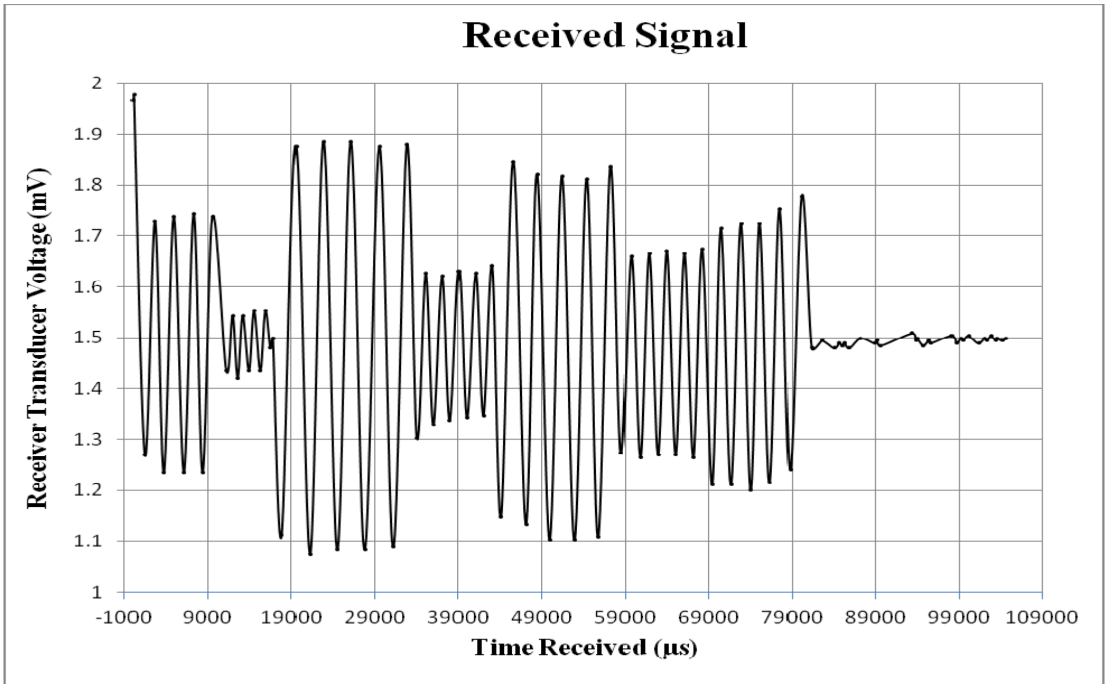
Table 1- Initial Testing Variables and Parameters

Quantity	Description
Stimulated voltage at receiver	Independent Variable
Frequency of transmitted signal	Controlled Variable
Signal reflection from tank walls	Controlled Variable
Amplitude of transmitted signal	Parameter
Water Salinity	Parameter
Water temperature	Parameter

3.2 MAIN EXPERIMENT

Although it was possible to cause the microcontroller to take 55000+ samples per second of the analog signal, there is insufficient memory to store this raw data for an entire packet worth of samples. Since the only data of concern is the timing separations of the points of highest and lowest amplitude, that is all that is recorded. This is accomplished by averaging the current sample with the last nine in both amplitude and time stamp. Whether the signal voltage is currently increasing or decreasing is then also recorded and when a new sample yields an average which fails to continue the previous increase or decrease, the current average amplitude and time stamp are recorded. The microcontroller was programmed to transmit this data once it had recorded a preset number of points, which can be seen in Graph 2 as a series of those points of high and low amplitude plotted against their time of acquisition.

Graph 2- Recorded Signal Peaks



Most likely due to the high amplitude that was necessary to start the recording of data, the first group of five waves does not have reasonable data for 9 points however, there are still seven peak to peak transitions which can be considered. For each change from one frequency to the next, the time should be the sum of one quarter period from each of the two frequencies. Since each quantized frequency represents a separate unrelated data value, it must be evaluated separately which is not possible to do where the two separate frequencies each contribute a quarter to make up the one transitional half wave, so they will be ignored.

This test focused on greatly limiting the possible variables to reduce the complexity of the signal processing that would need to be performed on the data so that processing can happen as the analog information is read without slowing the microcontroller to the point that it can no longer collect sufficient information. Variables in

Table 2 reflect what has been considered and what has been controlled or parameterized.

Table 2- Main Experiment Variables and Parameters

Quantity	Description
Received Frequencies	Independent Variable
Transmitted Frequencies	Controlled Variable
Transmission Distance	Parameter
Reflection of Boundaries	Parameter
Water Temperature Distribution	Parameter
Ambient Acoustic Sound	Parameter
Water Chemistry and Density	Parameter

4. DISCUSSION

4.1 INITIAL TESTING

The low frequency efficiency is very surprising when it is taken into account that these types of piezoelectric elements are rated to be efficient in air for around 4 kHz - 25 kHz. The difference seems to be attributable to the dramatically higher efficiency of sending the compression waves through the uncompressible water as opposed to the compressible air. This result allowed the possibility of much lower frequency transmissions than had previously been considered.

The question most at issue for the initial testing is how much separation is needed between transmitted frequencies in order to be able to able to determine one quantization from another after the signal is received. The factors involved that have been identified are the error based on the resolution of timestamp recorded when each sample is taken, the time offset from the highest amplitude sample taken to the actual peak of the signal, which is based directly on the samples per second. These can both be considered to contribute to a combined factor of the peak to peak timing error;

$$\text{Timing error} = (1/\text{samples/s})+(0.000004\text{ s}) = (1/50000)+0.000004 = .000024\text{ s}$$

Where the time resolution of the Arduino is 4µs and a maximum of 50000 samples per second is expected. The measurement of any peak (or trough) could be off by up to .000024 s which means for each measured half wave it is possible to be off the actual frequency by;

$$\text{Frequency range} = 1/(2*(\text{half wave period} \pm (0.000024 * 2)))$$

By measuring time from peak to trough and the vice versa, half waves are being measured and at each end there is a possible error of 0.000024 s which accounts for 0.000048s per cycle in Cycles per second instead of half cycles. By selecting a quantization of frequencies, as seen in Table 3 – Quantized Frequencies, that have high and low ranges that do not overlap, it will be possible to send data values that can be recovered at the receiving end.

Other factors which could affect the ability to determine the received wave's frequency are possible distortion caused in the amplification and output of the sending device and interference with the apparent shape of the signal wave caused by either outside sources, or buy reflected versions of the signal itself. which can be used to determine a high and low frequency that could represent the reception of the actual transmitted frequency. It is the intention of this lab to account for these other factors with test environment control, rather that additional signal processing. Seven values will be sent with five full waves of each values frequency as a representative data transmission. A two gallon plastic bucket with flexible sides will have the sending and receiving transducers held 20 mm apart and facing each other at its center. This should eliminate the considerations of signal attenuation over distance and reflected interference.

Table 3 – Quantized Frequencies

Data Value	Frequency	Low Freq.	High Freq.
0	300	291.6018663	308.8962109
1	319	309.5212221	329.0776747
2	341	330.1908716	352.5407748
3	366	353.5767281	379.3280711
4	395	380.56883	410.5687677
Ref	428	411.1083789	446.3391844
5	468	447.8777485	490.0154125
6	516	491.6458321	542.8927345
7	573	543.1238436	606.3543395
8	645	607.3903872	687.5746205
9	737	688.301306	793.1144323

4.2 MAIN EXPERIMENT EXPECTATIONS VS. RESULTS

The received signal can be mathematically compared to the known sent data to determine if the sent values can now be determined by the receiving microcontroller. Each line on the graph above has a horizontal component which represents the time which passed from one peak until the next. Table 4 shows the average of the valid nine samples and compares it to the intended frequency.

Table 4 – Received Frequency Error Levels

Data Item	Average Frequency	Expected Frequency	Percent Error
1	472	428	10.28%
2	801	737	8.68%
3	300	300	0%
4	503	516	-2.52%
5	340	341	-0.29%
6	463	468	-1.07%
7	421	428	-1.64%

The first two recorded points clearly had anomalistic values. So much so that if those two points are removed from the calculation, Data Item 1 records an average frequency of 428 and reduces it percent error to zero. We also see that a similar Peak to Peak Timing Error produces much greater ranges of high to low possible values when the frequency that is sent is higher. This contributes significantly to the lack of precision of the higher frequency data items. Adding to this effect was the unexpected severely reduced amplitude that was seen in the higher frequency transmissions which reduced the effective resolution of the ADC for those results.

4.3 PROBLEMS ENCOUNTERED THAT AFFECTED DATA

The piezoelectric transducers were left with bare metal surfaces during this experiment. The one which was used for sending signals corroded significantly and although it never wore away completely from the surface of the piezoelectric crystal, its efficiency likely declined over the course of the experiments. It should be coated with a spray on plasticized coating to protect it from corrosion while being careful not to affect its sound transmission characteristics.

5. CONCLUSION

Using a basic microcontroller with only minimal signal processing and calculation the transmitted data values were able to be distinguished upon reception. With less than $60 worth of material it was possible to send seven pieces of data each with 11 possible values. Despite this being a very controlled environment of testing, the real story here is how much wasn’t required to get this successful result.

It became apparent during the analysis of the received data, that the frequency should be changed from one value to the next at a peak or trough, and not at the zero cross point, as was done in this test. This would allow all of the received data points to be valid for frequency calculations, instead of the nine out of ten that were available with this method. Additionally it should be very possible based on these results to use only 1.5 waves for each value instead of the 5 that were used here since that would still allow accurate determination of the transmitted data value, perhaps by removing the most differing of the three times and averaging the remaining two. It also appears from the received results that the quantized frequencies could be much closer in value, perhaps three times as many in the same bandwidth.

With these new parameters in mind we can see a possibility of values from 0-31 being transmitted 333 times per second around the 500 Hz frequency band which can be thought of as 1665 bits per second. This is too slow for applications like sound or video transmission, but it is more than sufficient for basic telemetry and remote control communications.

5.1 FURTHER DEVELOPMENT

Second order low pass and high pass filters will be needed to focus on the desired frequencies when the method is attempted in less controlled conditions. Ambient sound across the full range which the transducer can record is expected in environments where this methodology would be employed including wave generated noise and, at the very least, vibration from the operation of the controlled vehicle. It may also be possible to dynamically adjust the gain of an amplifier to keep the full resolution of the 10bit analog to digital conversion regardless of the amplitude of the received wave form, while making the gain level available to the microcontroller so that the values of relative amplitude are maintained in the received data.

Using correlation calculations instead of a ten sample moving average and peak only analysis, could drastically improve the accurate determination of the received frequency. Any increase in precision at this level would allow a more narrow total frequency band for the same number of quantized values, resulting in better filtering of interference, and therefore greater reliability, or possibly narrower quantization separations, and therefore higher bits per second rates.

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