[1]An Observation of Very Low Frequency (VLF) Electromagnetic Waves Generated by Lightning Strikes via RockSat-X

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Abstract
In an attempt to observe how very low frequency (VLF) signals from lightning discharges vary as a function of altitude, a sounding rocket payload was built and launched via the Colorado Space Grant Consortium's RockSat-X program. The main components of the payload consisted of three magnetic field antennas, two pairs of electric field plate antennas, an amplification and filtration circuit board, and two microSD cards interfaced with high performance multi-core microcontrollers for data storage. Despite a flight anomaly preventing the retrieval of the stored data, low resolution telemetry data from flight shows the expected presence power line interference.

Background

Lightning discharges occur upwards of 50 times per second globally. As a lightning discharge occurs, very low frequency (VLF) electromagnetic waves are emitted into the atmosphere. Once in the atmosphere, the VLF waves propagate via the Earth-ionosphere waveguide (Wait and Spies 2-1), a process by which the waves reflect upwards from the surface of the Earth and downwards from the ionosphere. The ionosphere is a region in the Earth's upper atmosphere dominated by charged particles. At different times of the day and year, the charge structures vary. Theoretically, waves of lower frequency should not be able to penetrate the upper layers of the ionosphere. However, VLF waves that have escaped the ionosphere have been detected. These escaped waves enter a region above the ionosphere known as the magnetosphere. Effectively, these waves propagate into the magnetosphere, and follow the Earth's magnetic fields back to Earth, where the signals sound like whistling noises ("Introduction to VLF") when converted into audio, and are suitably called "whistlers."

By determining how VLF wave signals change as a function of altitude, the process by which VLF energy escapes into the magnetosphere can be examined as it happens. Ground based receivers for VLF waves have been around for many years, as have satellite receivers, but investigations by sounding rocket have not been carried out in earnest.

This project sought to collect data on VLF signal behavior from a sounding rocket through participation in the RockSat-X program. It was hypothesized that the VLF signals would be strongest in the region below 50 km in altitude. Above 50 km, the signals were expected to weaken

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due to the lower regions of the ionosphere acting as a deflection medium preventing the signals from reaching higher altitudes.

The RockSat-X program is a collaborative effort between NASA and the Colorado Space Grant Consortium to give smaller institutions of higher education access to the space environment. The program is designed to be low cost, yet comprehensive. Selected collegiate teams participate by designing and building a unique payload that utilizes exposure to the space environment. RockSat-X launches a sounding rocket (for this investigation, a Terrier Improved Malemute) from Wallops Island, Virginia, via NASA's Wallops Flight Facility. The rocket ascends to 150 km in altitude, and completes its flight in a total of around 15 minutes with a splashdown landing in the Atlantic Ocean. Early into the flight, a "clam shell" covering the payload section of the rocket ejects, exposing the section to space.

Procedure

Design Summary: The payload consisted of the following three main subsystems: mechanical design, analog electronics, and digital electronics. The mechanical design portion of the payload dealt with all structures relating to the rigidity, safety, and compliance of the payload. The analog electronics subsystem was responsible for data acquisition and preparation. And finally, the digital electronics subsystem was responsible for data storage.

Mechanical Constraint Description: The mechanical engineering challenges faced were: 25 g-forces experienced by the payload during launch, exposure to the vacuum of space, the heat of reentry, and submersion in seawater on splashdown. We also had to work within spatial limits, as the base plate was 12 inches in diameter and we were allowed only a construction height of 5 inches. To address these challenges, all electrical systems were contained in a hermetically sealed container that also protected the electronics from re-entry heat, Teflon- coated wire was used, and custom aluminum support structures were needed to adequately support the antennas.

Antenna Design: The different ways in which electric fields and magnetic fields induce moving charges dictates the type of antenna necessary. Since the frequencies of interest here are very low, the fields to be detected are almost static. As such, the decision was made to use loop antennas to detect the magnetic field component of the VLF signals. The design of the loop antennas was based on Faraday's law of induction, where the electromotive force generated by a given signal is proportional to the rate of change of its magnetic field, the cross-sectional area of the antenna, and the number of turns in the antenna. As a result of the height constraints, each antenna had a maximum of area of only 20.25 square inches (4.5 inches x 4.5 inches). Therefore, in order to induce a measurable electromotive force from the expected signals, a larger number of turns was required (> 5000 turns). In total, three loop antennas were constructed and arranged on the payload so that the magnetic field on all three Cartesian axes were measured.

Fabrication of the loop antennas was performed in three steps: construction of the frames/supports, winding of the coils, and application of epoxy to the coils for protection. Each frame consisted of four aluminum u-channels insulated using electrical tape attached via four aluminum L-brackets with three bolts triangularly arranged in each branch of the L. This arrangement can be seen in (Fig. 1).

The winding of the coils was done using a drill. A shaft was connected to a square section of polystyrene foam of equal size to the interior of each loop antenna. This polystyrene section was fit snuggly into the interior of the antenna, and the end of the shaft was inserted into the drill. A 36 AWG magnet wire was attached to the frame and the rotational motion of the drill was used to wind the wire around the frame. On both ends of the magnet wire, a section of Teflon wire was soldered and used to establish a connection between the antenna and the electronics via a sealed connector. This process was repeated for each antenna.

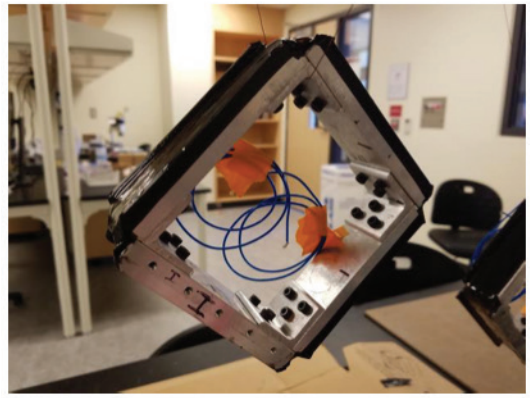


Fig. 1: Image of completed magnetic field antenna

In addition to the loop antennas, a method was needed to acquire data from the electric field component of the VLF signals. The electric fields of an EM wave can cause currents to flow in metallic conductors. Keeping in mind the structural and electrical constraints of the mission, it was decided that plate antennas (quite literally metal plates, wired in pairs) would be used. The rectangular geometry and flat plate construction allows a large surface area to provide an amount of charge measurable by the electronics.

One of the most important components of the RockSat-X program, and vital to the use of the plate antennas, is that the payload section of the rocket is exposed. If the payload section remained closed throughout the duration of the flight, the plate antennas would be ineffective due to the effect of the Faraday cage (general name for an enclosure that prevents penetration of electric fields internally). When the aluminum sides of the rocket come off and the experiment becomes exposed to space, and the antennas become "deshielded" and therefore able to build up charge due to the propagating fields.

Analog Electronic Design: The task of the analog preamplifier circuits was to take changing voltages built up on both types of antennas and process them to an adequate level for the analog to digital converter (ADC). Prior to design, the analog electronics team had to familiarize themselves with concepts surrounding operational amplifiers, feedback, and signal filtration. The preamplifier circuits were designed first using LT Spice circuit simulation software. Following the simulations, different iterations of the circuit were tested via a breadboard, signal generator, power supply, and oscilloscope. Once the basic principles such as feedback, input impedance matching, and biasing were satisfied, the circuit went through many rounds of testing. The goal was to increase the gain so that 60Hz powerline interference would saturate the amplifier. The circuit chosen to accomplish this goal was an instrumentation amplifier. This is a differential amplifier using two op-amps as input buffers removing the need for precise input impedance matching. This helps tremendously by keeping the output bias voltage from drifting when the gain is increased too far. All amplifiers have a maximum gain, and in order to amplify signals expected to be small, another non-inverting gain stage was added. Because 60Hz interference is very prominent near the earth's surface, high pass filters were included using resistor-capacitor combinations. The cutoff frequency for the high-pass filters was set to 3kHz, the lower bound of the VLF band. Also, before the signal is passed on to the ADC, it went through an active low-pass filter whose cutoff frequency was 30kHz, the upper bound of the VLF band. This low-pass filter is mainly implemented to prevent signal aliasing in the ADC. In (Fig. 2) below, the final design is shown.

These circuits were fabricated using an in-house printed circuit board (PCB) mill called the Othermill. The signal processing circuits, along with power regulating circuitry, were translated into PCB with the software KiCad. (Fig. 3) is a view of the PCB in KiCad's layout software called PCBnew. Gerber files were exported from PCBnew and imported to Otherplan, the path mapping software for the Othermill. Once the circuits were done cutting on the double sided circuit board, all components were soldered on and the board was tested and integrated. The end result is shown in (Fig. 4).

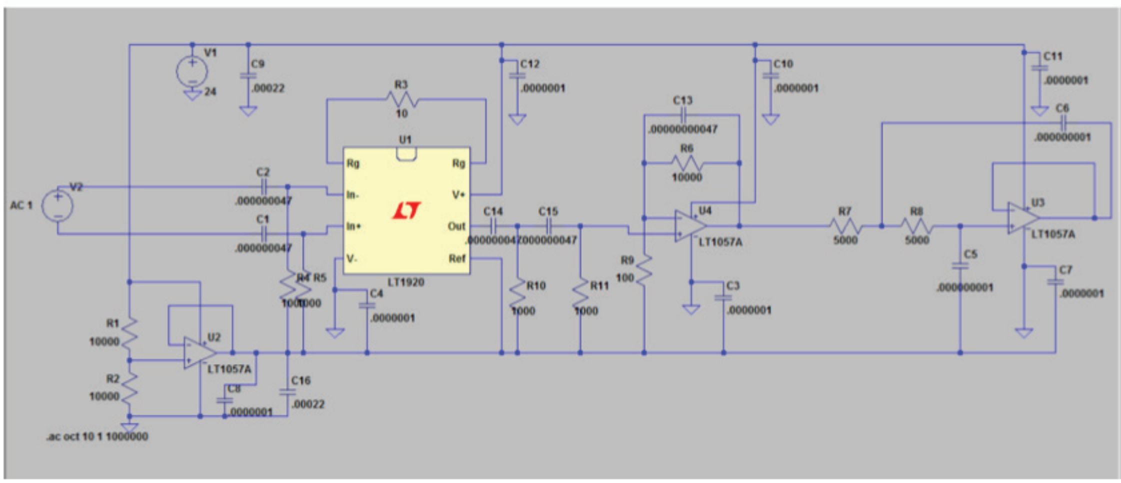
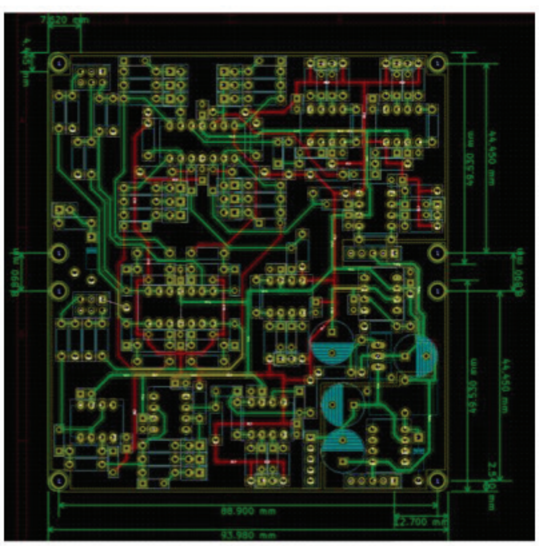


Fig. 2 (above): This is the final draft of the signal processing circuit in LTSpice. Specific values may be arbitrary. The skeleton is the design.



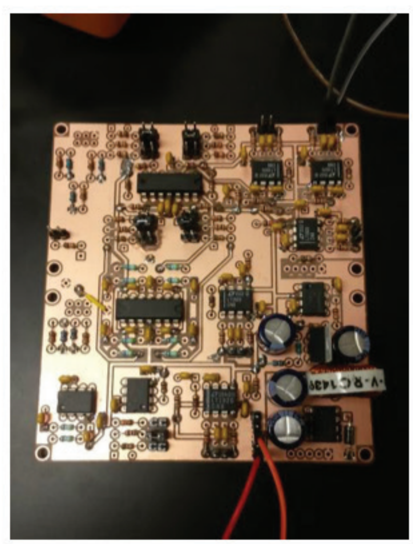


Fig. 3 (left): This shows the power and signal processing circuitry in PCB design software.
Fig. 4 (right): This image shows the final PCB milled and soldered

Digital Electronics: The analog signals must be converted into digital signals. The data- acquisition system is then responsible for correctly storing this data on to some sort of disk.

With lighting interactions occurring within less than a few microseconds, the experiment must have a fast-sampling data acquisition system to capture the details of the signal in its recordings. To quantify how fast the data-acquisition system needs to be, one can turn to the Nyquist Theorem, which states that the sampling frequency shall be at minimum twice that of the highest frequency of interest, in the case of VLF, 3-30 kHz. Thus, in order for the experiment to accurately record the VLF EM signals, the data acquisition system must have a sampling frequency of at least 60 kHz for lossless digitization. However, having a higher sampling frequency provides better data. Eventually, the data acquisition system was able to reach 170 kHz per channel with the help of the XMOS StartKit microcontroller.

Offering a multicore system, the XMOS StartKit can simultaneously read and write data at the same time, providing continuous recording. The graphs below show the difference between a single core vs. a multicore system. The spike in the left graph shows a gap in the signal; this is caused by a delay in the microcontroller's processor when data is being written to the MicroSD cards. However, if more cores are allocated to the specific task of writing to the MicroSD cards, then it is possible to get seamless data collection as seen on the right. (The little spikes near the peaks and crests of the right graph are effects of electronic noise in the surrounding area).

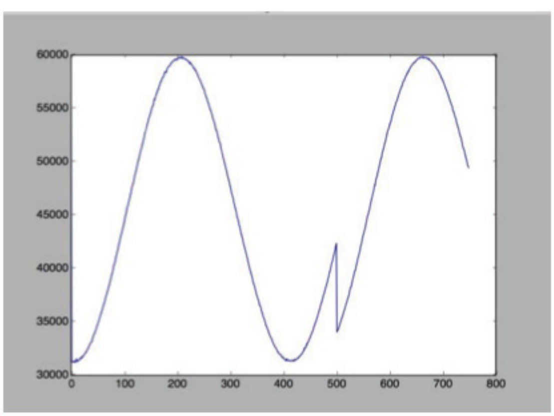


Fig. 5: Single core data-acquisition with spike in data.

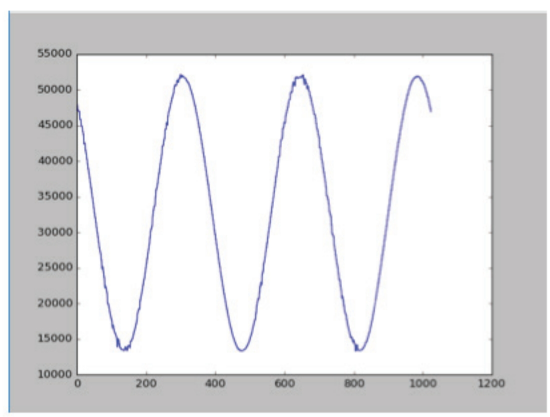


Fig. 6: Multi-core dta-acquisition with no gaps in data

The completed the payload can be seen in (Fig. 7). All electronics subsystems are contained within the box.

Launch Anomaly

All payloads went through a series of integration processes and tests before mounting to the rocket. Once all tests were completed, the rocket was taken to and set up on the launch pad. The rocket successfully launched on August 16, 2016. Unfortunately, during re-entry, a flight anomaly occurred. This anomaly led to the loss of the payload. Under normal circumstances, a collaborative effort by both an oversight aircraft and a boat would lead to a successful location and retrieval of the rocket. In this instance, neither the boat, nor the two supporting aircraft were able to locate the rocket, leading to the conclusion that the rocket had submerged and was irretrievable. The causes of this flight anomaly are currently under investigation by NASA.

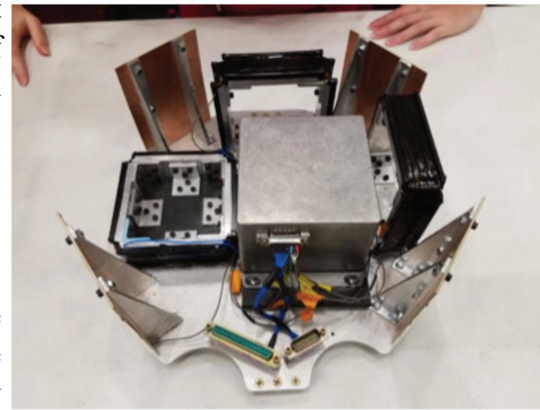


Fig. 7: Image of completed payload prior to integration on the rocket

Data Analysis

Given that our data was set to be stored on micro SD cards on-board the rocket, the only data we could retrieve was low resolution telemetry data transmitted from the payload during flight. Unfortunately, the telemetry system NASA provides sampled at a frequency of 1 kHz, whereas our on board microcontrollers could sample at a frequency of 170 kHz. This difference in sampling frequency led to a significant decrease in both the quantity and quality of the data provided through the telemetry system. An analysis of the telemetry data follows.

There are many different approaches to analyzing signals such as these, but one of the more common ways of examining these types of signals is done by using Fast Fourier Transforms, or FFTs. An FFT converts a function of time into a function of frequency, such that signals of various frequencies can be identified. By applying the FFT to short-duration segments of the data, we can create a spectrogram showing how signals of various frequencies evolve with time. Shown in the diagrams below, each value on the y-axis in Figures 8 and 9 represent a frequency that has been recorded through our experiment, the x axis represents time, and the color scale represents the intensity of the signal.

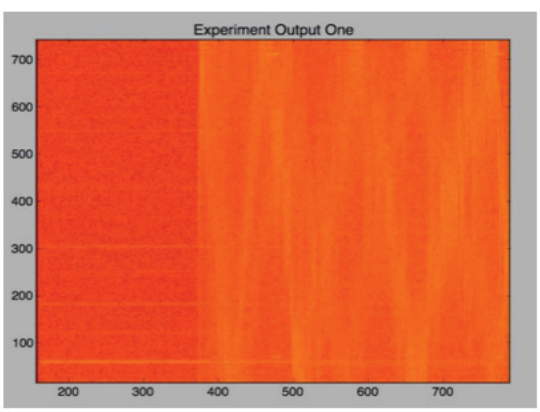


Fig. 8: Spectogram showing domain frequencies

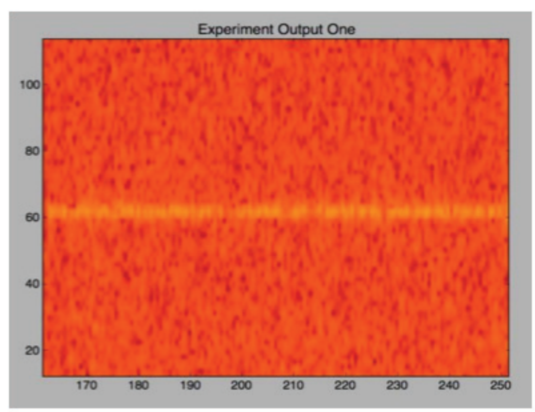


Fig. 9: Isolated 60-Hz frequency dominant in signal

It was evident that 60 Hz signal was clearly present, as seen in (Fig. 9). This phenomenon can also be seen in Figure 8, where the horizontal lighter orange lines on the left side of the figure represent 60 Hz interference, as it can be noticed that each line occurs at a multiple of 60 Hz. Because the interference is not a pure sine wave, the signals also contain 120 Hz, 180 Hz, etc.. This was something we had expected going into the project, as power lines generate intense electromagnetic interference making it nearly impossible to filter out of our signal. It seems to slowly roll off as time goes on, however it is still a strong signal even when the rocket nears the edge of the atmosphere.

Conclusion

While some information can be gathered from the telemetry data, for the purposes of this investigation, there is nothing to conclude about how VLF signals act as a function of altitude. Minimally, it can be concluded that the hypothesis about 60 Hz interference from power lines was correct, as the telemetry data did indeed show 60 Hz interference, but the low resolution of the telemetry data prevents productive analysis.

In future investigations, the hope is to improve antenna, amplification, and overall payload design. Although the current payload was functional, there was concern about the sensitivity of the antennas and proper gain tuning of the amplification and filtering circuits. The payload also had components that were swiftly fabricated, and therefore not of the

highest quality. Without having retrieved the payload, it is also difficult to make any conclusions about which aspects of the payload were constructed to meet the design criteria.

Aside from the inconclusiveness of the investigation itself, the RockSat-X program was a very involved, comprehensive, and educational program for all participants on this team.

References

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