Satellite-Based Monitoring System for Ionospheric Disturbances

Anastasia A. Ierides*

University of New Mexico, Albuquerque, NM, 87106

Steve Suddarth, PhD†and Craig Kief†

COSMIAC, Albuquerque, New Mexico, 87106

Rosemary R. Burns‡and Mario Ortega †

University of New Mexico, Albuquerque, New Mexico, 87106

The University of New Mexico (UNM) has started the development of a new, low-cost means of characterizing Total Electron Content in the Ionosphere using a CubeSat System. Developed by a team predominantly composed of undergraduate students funded through the National Science Foundation (NSF) REU program. Configurable Space Microsystems Innovations & Applications Center (COSMIAC) at the UNM is developing a Lightning Spectrometer that will be comprised of spaceborne sensors as well as ground-based detectors. The system works by measuring distortion of lightning impulses as they are bent by Ionospheric diffraction. Students have become familiar with lightning propagation and ionospheric occurrences through analysis and research which revealed that lightning acts as an electric dipole antenna emitting radio wave propagation that affects the ionosphere. Understanding the relevant physics is key to measuring dispersion and Total Electron Content. Using Uman's Model as a basis of gauging lightning, we can calculate the electric potential emitted by each signal. Radio wave propagation modeling and Chapman's functions help represent how the ionosphere reacts to natural occurrences. We detect the lightning intensity using the dipole antenna that transmits these signals to an Analog-to-Digital Converter wherein the information is captured and transformed into Fourier space. The signal path is determined by locating the lightning using time of flight to both the spacecraft and inexpensive ground stations. This specialized monitoring system involves a transformation of an alternating signal to a direct signal at which point the data is efficiently buffered and time stamped for convenient downlink. This will allow for a client to download the data and perform their own analysis of the ionosphere or for the engineered satellite-based monitoring system to perform detailed trending. The eventual goal of this project is to provide a nano-satellite package for low earth orbit with the capabilities described previously.

I. Introduction

The plasmas contained within the ionosphere vary in density based upon many factors such as solar heating, geomagnetic storms, and solar wind effects including solar mass ejections (SMEs). Ionospheric composition is important for many reasons on earth, and particularly affects the propagation of radio frequency signals such as those emitted by lightning events. In particular, the accuracy of GPS can be affected significantly by the bending of RF waves from satellites, therefore affecting timing measurements which are the very basis for GPS operation.

*Research Assistant, Department of Physics and Astronomy, 1919 Lomas Blvd NE, University of New Mexico, Albuquerque, New Mexico, 87131

†Director and Deputy Director, Configurable Space Microsystems Innovations and Applications Center, 2350 Alamo Avenue SE, Suite 100

‡Research Assistant and Undergraduate Researcher, School of Engineering, UNM MSC01-1100 1UNM, University of New Mexico, Aluquerque, NM 87106

There are several ways of measuring the density fluctuations in the Ionosphere however many of these approaches are limited in terms of the area of the Ionosphere that they encompass. A very successful approach to measuring plasma density, or Total Electron Content (TEC), is to fly a spacecraft through or above the Ionosphere while measuring the distortion of RF signals emanating from Earth by counting the ingested charged particles. Two successful missions from Los Alamos National Laboratory (LANL), FORTE and Cibola Flight Experiment (CFE), demonstrated the value of such measurements by measuring distortion in natural lightning signals in the form of spectral chirps. During FORTEs and CFEs missions, acquiring accurate geographical location data on lightning sources was not feasible. Presently both systems are inactive and hence much of the subsequent modeling was incomplete.

The University of New Mexico "Lightning" Team has undertaken an effort to research the Ionosphere through the creation of a Nano-Satellite Sensor Package (NaSSP) that will both continue the mission begun by FORTE and CFE, as well as enhance the data collected by correlating it with earth-based lightning sources. The basis of the system is a low-power, low-cost set of electronics for detecting and timing the arrival of lightning signals, as well as a space-borne spectrometer for characterizing the chirp properties of signals that have propagated through the Ionosphere.

II. Basic Architecture

The NaSSP system requires the use of a spacecraft because the measurement in question must involve a signal traversing the Ionosphere. Signals are generated on Earth through natural lightning. Since lightning is a near-ideal impulse it contains a broad spectrum of frequencies. Each of those frequencies is bent by a different amount upon reaching the Ionosphere. The resulting spectral smear can only be measured by a spacecraft on the other side of the diffracting interface.

Ground stations aid in the collection of timing data that is used to determine the origin of the lightning used as a test pattern. Thus, all key variables are known: location of the lightning, location of the spacecraft, and diffraction effects (smear or chirp) at each relevant frequency. Total electron content can be calculated from these parameters.

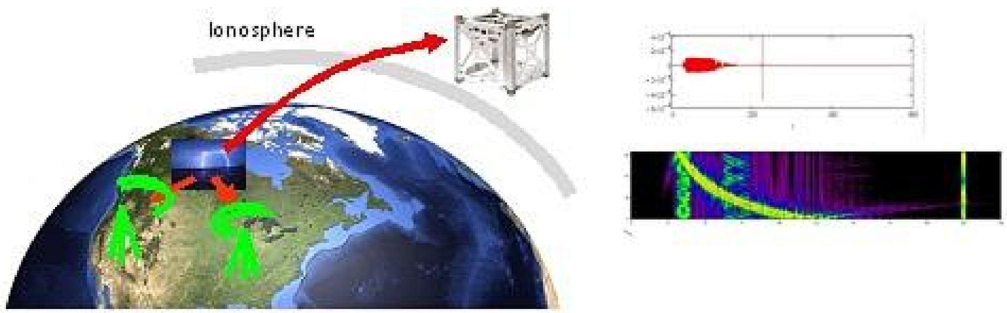


Figure 1. The NaSSP concept involves measuring bending of RF signals generated by lightning as they pass through the Ionosphere. The graphs on the right are from FORTE data and show the time series (red) and Fourier spectrum of a lightning impulse after Ionospheric diffraction. The noticeable *chirp* is related to Total Electron Content and the path taken through the Ionosphere. Ground stations aid in geolocation to determine the path, thus allowing isolation of factors to the properties of the Ionosphere itself.

III. Lightning Spectrum Detection and Analysis

Signal emissions from lightning strikes are in a low enough frequency range, i.e. $30-300$ MHz, to be refracted by the Ionospheric plasma layers back to Earth. Although the Ionospheric measurements will mostly rely on cloud-to-cloud and upper atmospheric lightning, cloud-to-ground lightning provides a good model for understanding the mechanics of how lightning works. Most cloud-to-ground lightning follows a pattern described by Uman.[1] Normally the process begins with the creation of a plasma channel also known as a leader. Each leader leaves the cumulonimbus with a small voltage that is comparable to that contained within the base of its source. As it propagates to the ground it exhibits a voltage drop, breaking down the tropospheric molecules in the surrounding environment, specifically a plasma is formed, and the conductive nature of the plasma provides a short to ground. These channels can move through regions of induced electric field of a few thousand V/m and usually take no longer than 50ms to develop.[1] Meanwhile, a streamer (an upward leading plasma channel) forms from a conductive medium on the Earths surface and climbs up to meet the main leader, creating a full channel for the current to pass through (see **Figure 1**). As soon as the channel is complete, the path is clear for a final discharge of the built-up charge in the base of the cumulonimbi. In general, the overall flash lasts for no more than two to three seconds, yet the energy released is immense enough that the power released is detectable by instruments a few hundreds of miles away.

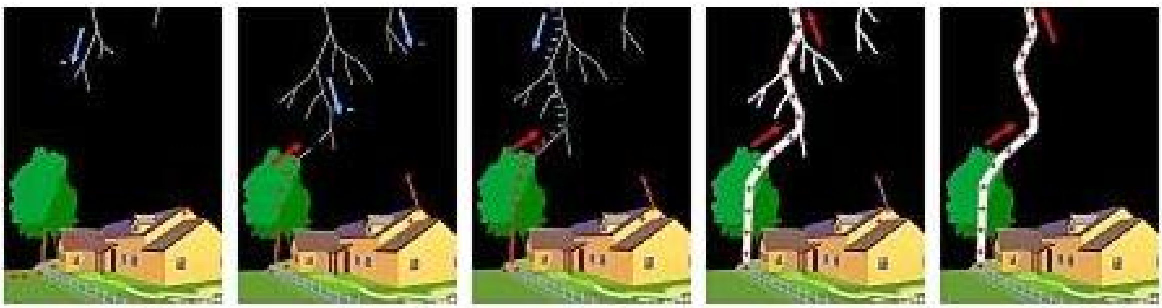
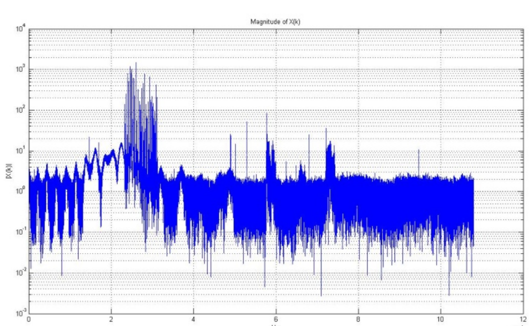


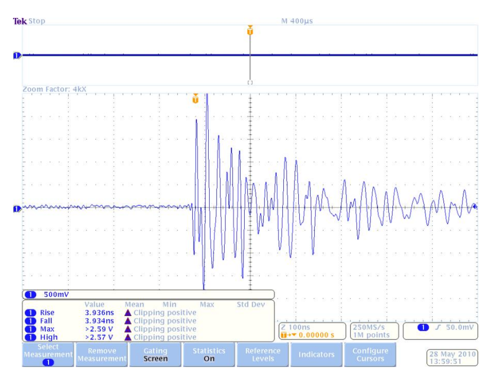
Figure 2. Steps taken by lightning strike in the most basic scenarios. Beginning from the left, the leader begins its descent to the Earth, as it approaches the ground, an ascending streamer forms from the Earth of opposite charge, the leader then connects with the streamer forming a full channel, the electric current moves upward, known as a return stroke. The return stroke is called the final discharge if it is the last flash of current between cloud and ground, otherwise, the process mentioned is repeated until all the charge in the cumulonimbi is released.[2]

A. Lightning Detection Using Biconical Antenna

Lightning discharges are electrical impulses, exhibiting a broadband. The NaSSP team has studied these impulses by receiving them through a Com-Power AB900 Biconical Antenna with a frequency range 30−300 MHz. This antenna has the ability to uniformly detect the electromagnetic field in all directions. The signal is then transmitted to and captured on the screen of a Tektronix MSO4054 Mixed Signal Oscilloscope wherein the lightning data is sampled for a duration of 40ms using 1 million data points. It is then saved and transferred to a computer to be analyzed using the MATLAB software. Analysis is accomplished using a Fast Fourier Transform (FFT) to transform the data from the time-domain to frequency-domain.



(a)



(b)

Figure 3. (a)Fast Fourier Transform of a lightning strike collected and processed utilizing Oscilloscope and MATLAB software (b)Intensity (in Volts) of lightning strike as it appears on the Oscilloscope.

B. Lightning Detection Utilizing NaSSP

In the final implementation, lightning impulses will be detected at far field using a dipole antenna. Each impulse will then be transmitted through an Analog-to-Digital Converter (ADC) to a Microcontroller. Once it is in the Microcontroller, it will be stored and the Global Positioning System (GPS) will apply a time-stamp to the collected data allowing for accurate cataloguing. The details of these are explained in full in the Hardware section of this paper. The data collected will be in raw format, which will eventually allow for the client to manipulate the data according to their specifications. For our purposes, we are using MATLAB to form a groundwork for future data comparisons with the eventual lightning spectrometer.

IV. Lightning Spectrometer Hardware

This section will cover the various electronic components utilized in the creation of the system. These electronic components include various boards (i.e. FPGA evaluation boards, Microcontrollers, etc...) that will further be discussed in this section. The team is currently working with industry standard boards in order to fully understand the components that will be required in the creation of the team's own prototype board. This prototype board would allow for optimal minimization of the required hardware components in order to integrate these components onto the allocated area of nano-satellite exoskeleton for the creation of the NaSSP.

A. Analog-to-Digital Converter (ADC)

The entire NaSSP depends upon an ADC, which converts the received lightning signal into digital data via the Biconical antenna. Easily Applicable Graphical Layout Editor (EAGLE) 5.9.0 software was used to create the schematic and layout of the design. A custom board was designed due to the fact that current industry standard ADCs do not meet NaSSPs requirements for the 300 Mega Samples per Second (MSPS) that is being transferred simultaneously. **Figure 4** shows a graphical image of the custom ADC board. A Littlefuse PulseGuard Suppressor is placed in the circuitry to protect the ADC from high voltages[3] when lightning strikes are close. An amplifier is used to create a low-pass anti-aliasing filter to remove any signal beyond the range of the ADC in order to look at the true data or signal coming from the lightning strike. If the signal exceeds the threshold value, a set/reset latch is triggered that informs the microcontroller to disable the system. This assists in protecting the system from high intensity lightning strikes as a storm approaches.

The signal is digitized by an ADS5463 (a very high-speed analog to digital converter chip).[4] It samples at a rate of 500 MSPS and has an input bandwidth of 2.3 GHz. The ADS5463 is clocked from a 500 MHz voltage controlled oscillator.[5] The output of the ADS5463 has a resolution of 12 bits. The sample output is transferred to the microcontroller for processing after being buffered by a Field Programmable Gate Array (FPGA).

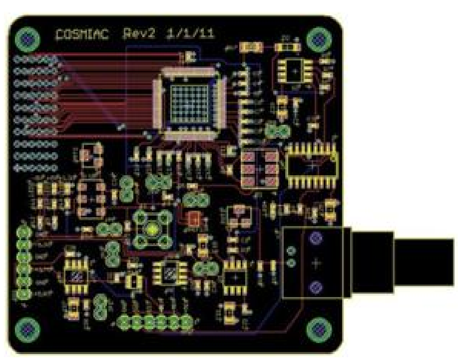


Figure 4. Custom ADC Board

B. Field Programmable Gate Array (FPGA)

Xilinxs ML403 FPGA Evaluation Platform is currently being utilized as the buffer for data transfer between the ADC and the Microcontroller. This particular board was chosen due to its re-programmability. The ML403 uses a Xilinx Virtex-4 XC4VFX12 FPGA chip. The ML403 has a 100 MHz oscillator installed for a system clock as well as a Differential Sub-Miniature A (SMA) Clock input for multiple or greater clock speeds. In order to accommodate the transfer process, the ML403 will eventually need to be clocked at its maximum 400 MHz clock rate. Since the Microcontroller cannot handle the high-speed data rates that the ADC outputs, a First-In-First-Out (FIFO) buffer is introduced on the Virtex-4 FPGA. The reason the Microcontroller cannot handle the data rate from the ADC is due to the fact that its clock cannot process the data transfer as fast as the ADC is transferring the data from the Biconical Antenna. The FPGA will be utilized to buffer the high-speed data from the ADCs differential I/O pins. The output will be sent in the correct order from the FPGA's buffer to the Microcontroller through the UART connection at a slower rate of transfer for proper collection to the Microcontroller.[6]

C. Microcontroller and Global Positioning System (GPS)

The purpose of the GPS implementation is to synchronize time in order to triangulate the position of lightning events as well as providing a timestamp to the lightning strikes. The GPS used in this project is the FV-M8.[7] This (and corresponding evaluation boards) is chosen for power, simplified USART, and Pulse per Second (PPS) signals.[7] The GPS PPS signals will accurately time-stamp the data coming into the Microcontroller from the ADC and FPGA.

The Microcontroller board currently being utilized is the EVK1100 which uses the microcontroller chip UC3A0512.[8] The reason for including the Microcontroller is to properly store the collected data to analyze and evaluate regarding lightning strikes to help create an ionospheric image. The language used in programming the Microcontroller board and various other board components is the AVR32 C++. The GPS board is interfaced to the Atmel EVK1100 Microcontroller prototyping board. This is connected utilizing the RS232 transceiver cable which provides Universal Synchronous Asynchronous Receiver/Transmitter (USART) hardware support. General Purpose Input/Output (GPIO) pins on the prototyping board are used to bring in custom signals from the GPS to perform interrupt driven, real timing as well as provide a threshold from the ADC regarding data collection and system shutdown.

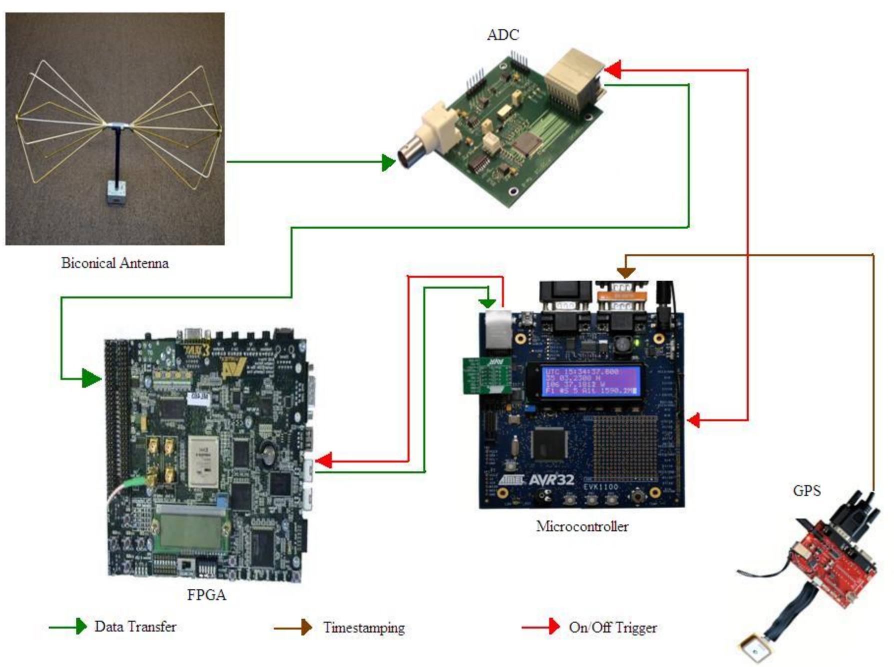


Figure 5. Block Diagram for NaSSP Prototype

V. Conclusion and Future Work

The eventual goal regarding this project is to be able to understand changing ionospheric plasma composition and its effects on capabilities (such as GPS precision) by using NaSSP to measure spectral dispersion. All major components that make up the NaSSP are well underway. The next objective after the prototyping phase will be to miniaturize these components to specific chips and boards that would allow for their integration into small satellites. Ultimately a network of small satellites in space will be able to provide an accurate and up-to-date map of the ionosphere.

VI. Acknowledgements

The Lightning Team would like to acknowledge the National Science Foundation for providing a grant allowing the team to create the NaSSP. The team would also like to acknowledge Air Force Research Laboratory for providing guidance and understanding pertaining to the creation of the NaSSP.

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