Ultra-Sensitive Broadband Remote Sensing Instrument for Longwave Radio Reception

Gurses Baris Volkan[1], Whitmore Kevin Thomas[1], and Cohen Morris[1]

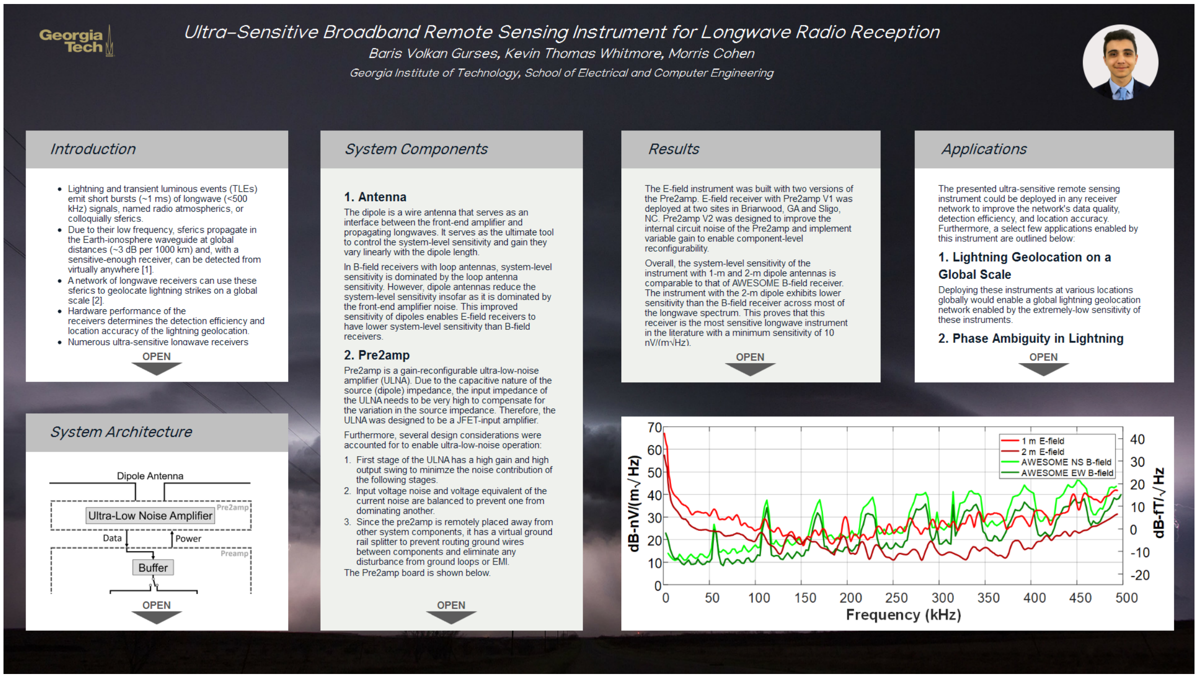
[1]Georgia Institute of Technology Main Campus

November 16, 2022

Abstract

Lightning and transient luminous events (TLEs) emit a short burst (˜1 ms) of broadband electromagnetic waves, whose frequencies can range from a few Hz to the optical band, but the bulk of their energy is radiated as longwaves (<500 kHz). These longwave radio signals are named radio atmospherics, or colloquially sferics. Due to their low frequency, sferics can propagate in the Earth-ionosphere waveguide at global distances with relatively low attenuation (˜3 dB per 1000 km). This allows a sparse network of longwave receiver stations, placed hundreds of kilometers apart, to geolocate lightning strikes at a global scale. Hardware performance of the receivers at these stations significantly impacts the data quality and determines the detection efficiency and location accuracy of the lightning detection network. In this work, we present a low-frequency remote sensing instrument for lightning geolocation in the form of an ultra-sensitive broadband electric field receiver. It is capable of detecting extremely weak sferics, enabled by its ideal sensitivity of 1 nV/(m[?]Hz), or 0.003 fT/[?]Hz. We present this receiver's antenna-amplifier co-design and the design considerations to achieve this low sensitivity. We then report its performance characteristics, validated both theoretically and empirically. Finally, we present some of the novel applications of this device in the scope of lightning geolocation and remote sensing.

Ultra-Sensitive Broadband Remote Sensing Instrument for Longwave Radio Reception



Baris Volkan Gurses, Kevin Thomas Whitmore, Morris Cohen

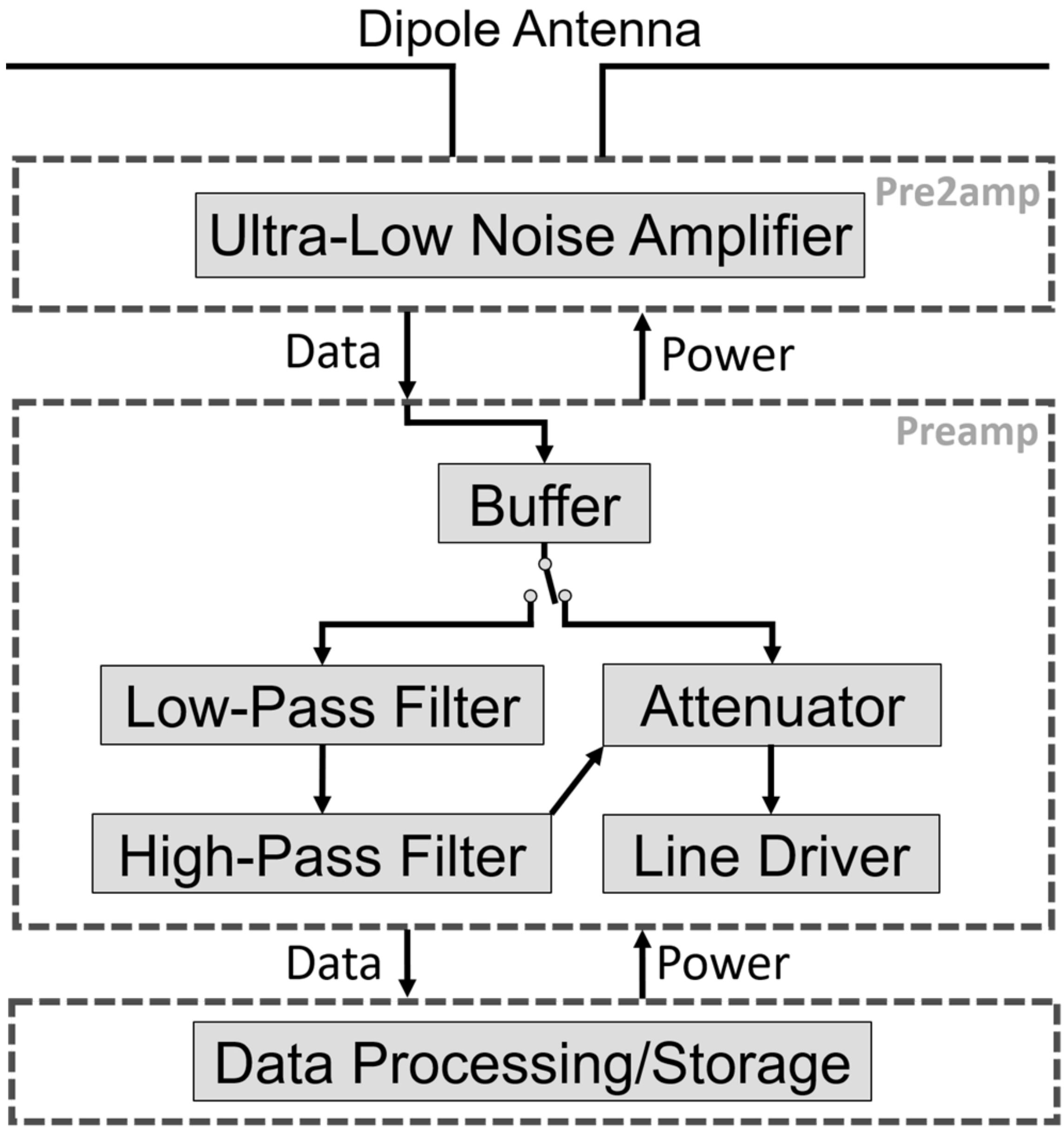
Georgia Institute of Technology, School of Electrical and Computer Engineering

PRESENTED AT:

INTRODUCTION

- Lightning and transient luminous events (TLEs) emit short bursts (~1 ms) of longwave (<500 kHz) signals, named radio atmospherics, or colloquially sferics.
- Due to their low frequency, sferics propagate in the Earth-ionosphere waveguide at global distances (~3 dB per 1000 km) and, with a sensitive-enough receiver, can be detected from virtually anywhere [1].
- A network of longwave receivers can use these sferics to geolocate lightning strikes on a global scale [2].
- Hardware performance of the receivers determines the detection efficiency and location accuracy of the lightning geolocation.
- Numerous ultra-sensitive longwave receivers have been developed and in use. The AWESOME magnetic-field (B-field) receiver is the most sensitive longwave receiver with 0.03 fT/√Hz sensitivity.
- We present a novel ultra-sensitive electric-field (E-field) receiver with an ideal sensitivity of less than 1 nV/(m*√Hz), or namely 0.003 fT/√Hz.

SYSTEM ARCHITECTURE



SYSTEM COMPONENTS

1. Antenna

The dipole is a wire antenna that serves as an interface between the front-end amplifier and propagating longwaves. It serves as the ultimate tool to control the system-level sensitivity and gain they vary linearly with the dipole length.

In B-field receivers with loop antennas, system-level sensitivity is dominated by the loop antenna sensitivity. However, dipole antennas reduce the system-level sensitivity insofar as it is dominated by the front-end amplifier noise. This improved sensitivity of dipoles enables E-field receivers to have lower system-level sensitivity than B-field receivers.

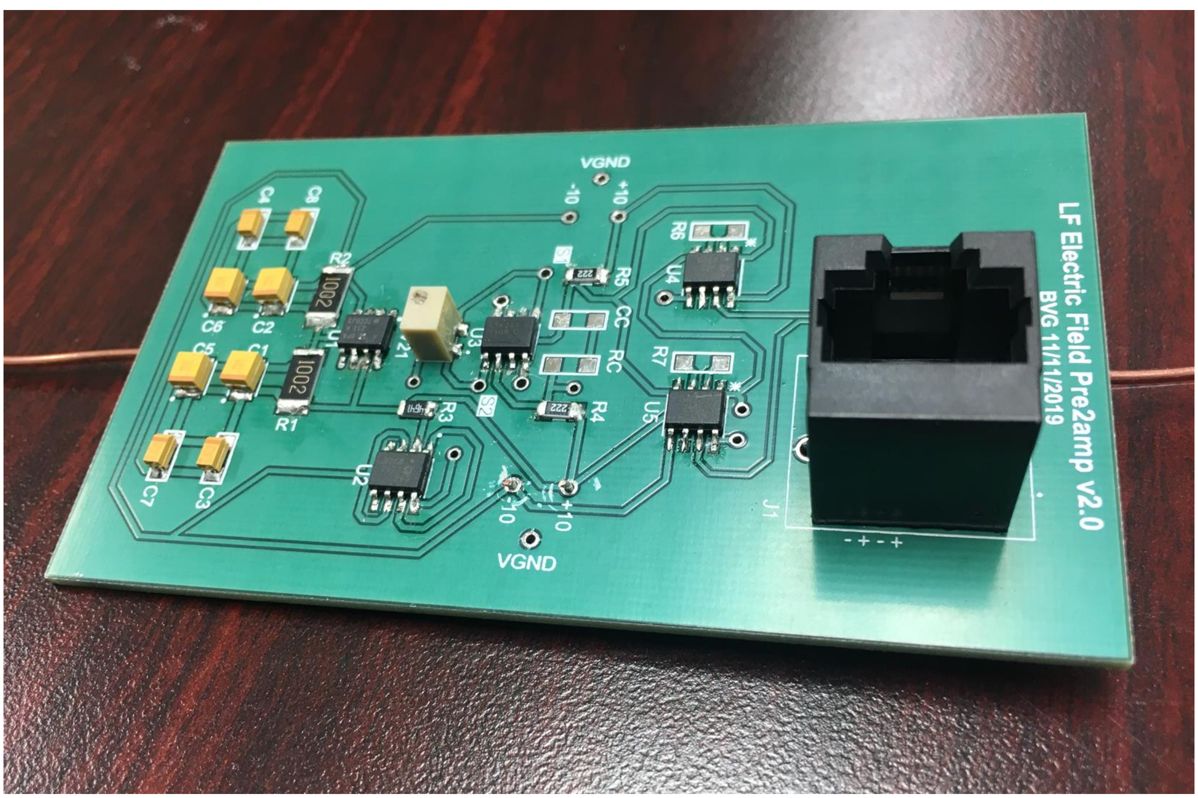
2. Pre2amp

Pre2amp is a gain-reconfigurable ultra-low-noise amplifier (ULNA). Due to the capacitive nature of the source (dipole) impedance, the input impedance of the ULNA needs to be very high to compensate for the variation in the source impedance. Therefore, the ULNA was designed to be a JFET-input amplifier.

Furthermore, several design considerations were accounted for to enable ultra-low-noise operation:

1. First stage of the ULNA has a high gain and high output swing to minimze the noise contribution of the following stages.
2. Input voltage noise and voltage equivalent of the current noise are balanced to prevent one from dominating another.
3. Since the pre2amp is remotely placed away from other system components, it has a virtual ground rail splitter to prevent routing ground wires between components and eliminate any disturbance from ground loops or EMI.

The Pre2amp board is shown below.

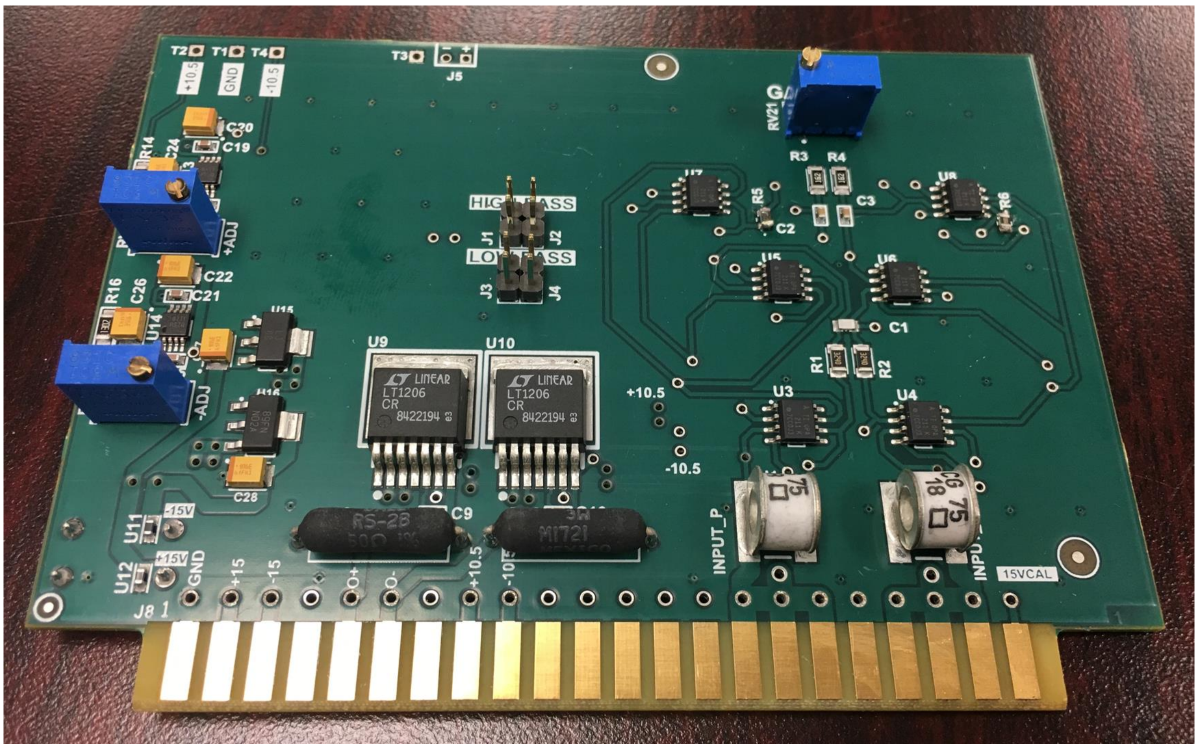


3. Preamp

Preamp is comprised of a buffer to receive the signal from the Pre2amp, optional low and high-pass filters to filter out unwanted signals from power lines and AM transmissions, a gain-reconfigurable attenuator to attenuate the signal, and drivers to drive the signal to the back end. Again, several design considerations were accounted for in the Preamp design to ensure ultra-low-noise operation of the receiver:

1. Passive filters are used instead of active filters to minimize the noise contribution of the preamp.
2. A passive attenuator was used as the preamp last stage to attenuate the amplified signal from the pre2amp down to the saturation level of the back-end ADC.

The Preamp board is shown below.



4. Back end

Back end is a data processing and storage system and is extensively described in [3]. The back-end ADC has a 16-bit dynamic range and 1 MHz sampling rate with a saturation level of ±5 V.

5. Calibration

Calibration of E-field receivers are difficulty to achieve due to the varying capacitive coupling of the receiver and the surrounding environment. However, this process was facilitate for this receiver by utilizing sferic waveform data from the AWESOME B-field receiver. By obtaining a broadband sferic waveform on both B and E-field receivers and assuming the sferic is in far field, the already-calibrated B-field data could be multiplied by the speed of light and divided by the E-field data to get the E-field calibration numbers over frequency.

RESULTS

The E-field instrument was built with two versions of the Pre2amp. E-field receiver with Pre2amp V1 was deployed at two sites in Briarwood, GA and Sligo, NC. Pre2amp V2 was designed to improve the internal circuit noise of the Pre2amp and implement variable gain to enable component-level reconfigurability.

Overall, the system-level sensitivity of the instrument with 1-m and 2-m dipole antennas is comparable to that of AWESOME B-field receiver. The instrument with the 2-m dipole exhibits lower sensitivity than the B-field receiver across most of the longwave spectrum. This proves that this receiver is the most sensitive longwave instrument in the literature with a minimum sensitivity of 10 nV/(m√Hz).

It is important to note that the instrument was characterized at a noisy site. Hence, the coupled noise from 60-Hz power lines severely degrades the sensitivity at the lower end of the spectrum. More accurate measurements will be taken at a quiet site to achieve even lower expected system-level sensitivities.

This sensitivity could also be improved by simply increasing the dipole length. Additionally, Pre2amp V2 will further improve the sensitivity. While the instrument with Pre2amp V2 has not been characterized, its sensitivity was validated through SPICE simulations and numerical models. With Pre2amp V2, the instrument attains an ideal sensitivity of 2 nV/(m√Hz) with a 2-m dipole and 0.8 nV/(m√Hz) with a 5-m dipole.

APPLICATIONS

The presented ultra-sensitive remote sensing instrument could be deployed in any receiver network to improve the network's data quality, detection efficiency, and location accuracy. Furthermore, a select few applications enabled by this instrument are outlined below:

1. Lightning Geolocation on a Global Scale

Deploying these instruments at various locations globally would enable a global lightning geolocation network enabled by the extremely-low sensitivity of these instruments.

2. Phase Ambiguity in Lightning Geolocation

Detecting only the B-field component of a sferic, as is the case for all magnetic field receivers, leaves a 180-degree phase ambiguity in the sferic's arrival azimuth, a key data point for geolocating its source. Sensitive E-field detection resolves this ambiguity by adding another data point to the analysis.

3. Detection of Intracloud Strokes Associated with Cloud-to-Ground Strokes

Detecting extremely weak sferics, enabled by the receiver's ultra-low sensitivity, allows the identification of not only cloud-to-ground strokes (CG) but also intracloud lightning (IC) associated with each CG due to most of IC being low amplitude events (<5 kA) [4].

4. Near-Field Behavior of Lightning

Simultaneous long-term detection of E and B-fields allow the characterization of sferic waveforms in the near field. This enables improved characterization of lightning as a voltage or current source in understanding its transient behavior.

ABSTRACT

Lightning and transient luminous events (TLEs) emit a short burst (~1 ms) of broadband electromagnetic waves, whose frequencies can range from a few Hz to the optical band, but the bulk of their energy is radiated as longwaves (<500 kHz). These longwave radio signals are named radio atmospherics, or colloquially sferics. Due to their low frequency, sferics can propagate in the Earth-ionosphere waveguide at global distances with relatively low attenuation (~3 dB per 1000 km). This allows a sparse network of longwave receiver stations, placed hundreds of kilometers apart, to geolocate lightning strikes at a global scale. Hardware performance of the receivers at these stations significantly impacts the data quality and determines the detection efficiency and location accuracy of the lightning detection network. In this work, we present a low-frequency remote sensing instrument for lightning geolocation in the form of an ultra-sensitive broadband electric field receiver. It is capable of detecting extremely weak sferics, enabled by its ideal sensitivity of 1 $\mathrm{nV/(m\sqrt{Hz})}$, or 0.003 $\mathrm{fT/\sqrt{Hz}}$. We present this receiver's antenna-amplifier co-design and the design considerations to achieve this low sensitivity. We then report its performance characteristics, validated both theoretically and empirically. Finally, we present some of the novel applications of this device in the scope of lightning geolocation and remote sensing.