Space-based Ionosonde Receiver and Visible Limb-viewing Airglow Sensor (SIRVLAS): A CubeSat Instrument Suite for Enhanced Ionospheric Charge Density Measurements

Andrew Healey, Benjamin Cohen, Santiago Lisa, and Ryan He

Montgomery Blair High School

Abstract

Spatially and temporally varying plasma in the ionosphere refracts passing electromagnetic waves, affecting services including over-the-horizon radar, global positioning systems, and long-distance amateur radio communication. The reliability of these services requires accurate measurements of the charge density of ionospheric plasma. Current methods for estimating ionospheric charge density include ground-based radar soundings in the high frequency (HF) band and airglow limb sensing, typically in the extreme ultraviolet (EUV) spectrum. SIRVLAS is a low-cost, compact instrument suite for these measurements designed by blair3sat, a high school satellite team based in Montgomery County, Maryland. It takes electron density measurements below the F peak of the ionosphere by receiving ionosonde soundings with an onboard VHF antenna and measuring airglow with a limb-view scanner. The payload will take measurements from many locations along its orbital path, enabling high-accuracy electron density mappings in previously unmapped regions. In addition, data correlation between the radar receiver and the airglow detector allows for verification of the instruments' operation and increased accuracy of local mappings. blair3sat plans to launch a 1U CubeSat in 2022 to demonstrate the feasibility of SIRVLAS. SIRVLAS' novel method of ionospheric electron density data collection can be utilized on future missions to extend and enhance global ionospheric databases, essential for many radio services and applications. The presence of VHF antenna systems on existing satellites similar to the antenna system on SIRVLAS may allow SIRVLAS RF measurements to be implemented on many satellites using a software modification, allowing existing fleets to contribute towards ionospheric datasets.

Background Science

Plasma in the ionosphere refracts EM waves, affecting:

- Long-range terrestrial communications systems
- Satellite communications systems
- Over-the-horizon radar

This plasma is *anisotropic*; its charge density changes with:

- Time
- Altitude
- Geographic location

Better ionospheric measurements and models could allow for better OTH radar and a deeper understanding of heliophysics.

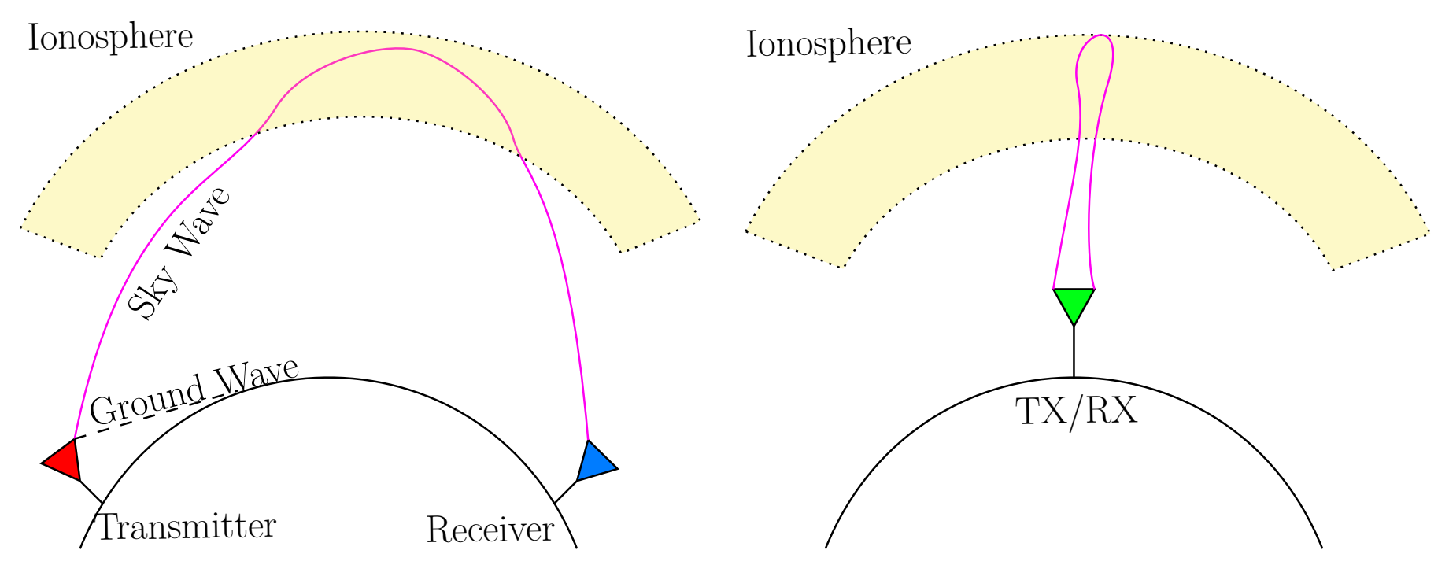


Figure 1: An oblique sounding with irregular bending as it travels through the ionosphere (left). A vertical sounding bending back down to earth (right).

Existing Observation Methods

1. Ionosondes: radar sounders that sweep from roughly 2-20 MHz. Different frequencies reflect at different heights, so time-of-flight of each frequency component yields the "virtual height" at which the signal reflected. The plot of frequency versus virtual height is called an *ionogram*.
2. Airglow Detectors: optical detectors that measure electron density by observing the photons emitted by the ionized atoms in the plasma. The instrument is tuned for a specific emission wavelength, and these emissions are called *airglow*.

SIRVLAS Instrumentation

Benefits of Receiving Soundings from Space

- Current (ground-based) ionosondes only take measurements along the path from TX antenna to RX antenna; SIRVLAS measures everywhere along the orbital path, adding another dimension to the data
- SIRVLAS can intercept ascending waves that could otherwise never be received
- Combining RF data from SIRVLAS with ionosonde data would allow more spatially precise mapping of the ionosphere

Benefits of Measuring Airglow Concurrently

- More information about the ionosphere leads to better estimates of 3D charge density profiles
- Previous airglow detector missions only measure airglow and are not easily correlated with other measurements of ionospheric phenomena
- Spatiotemporally-correlated measurements of ionosonde soundings and airglow could enable development of a data-assimilative model of the ionosphere

Educational Mission

We are a 100% student-run organization that intends to be the first high school team to deploy a scientifically valuable instrument on a CubeSat, as well as the first high school team to do so through a private launch provider. Students involved practice various forms of engineering and science, business writing, and fund seeking. Students also work with mentors from around the country. In addition to constructing our instrument, we are also involved in outreach programs aiming to increase interest in science and research in younger students. Furthermore, by the end of our mission, all data and code will be made public.

RF Instrument

SIRVLAS will receive linear frequency modulated ionosonde and Digisonde soundings in a variety of view geometries.

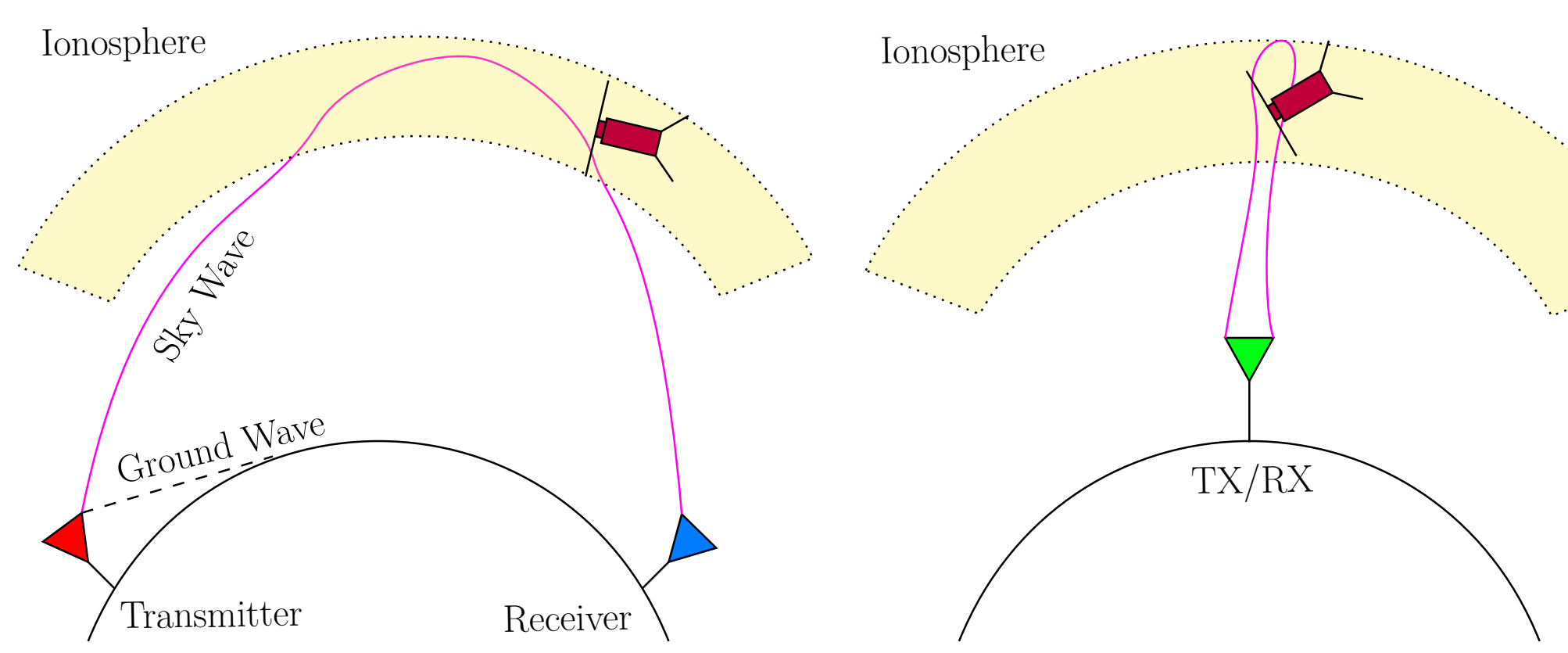


Figure 2: SIRVLAS receiving an oblique sounding (left) and a vertical sounding (right).

SIRVLAS's RF instrument is active on a duty cycle determined by the scheduled soundings times of "cooperative" ionosondes, which provide the time, frequency, and geographic location of their soundings.

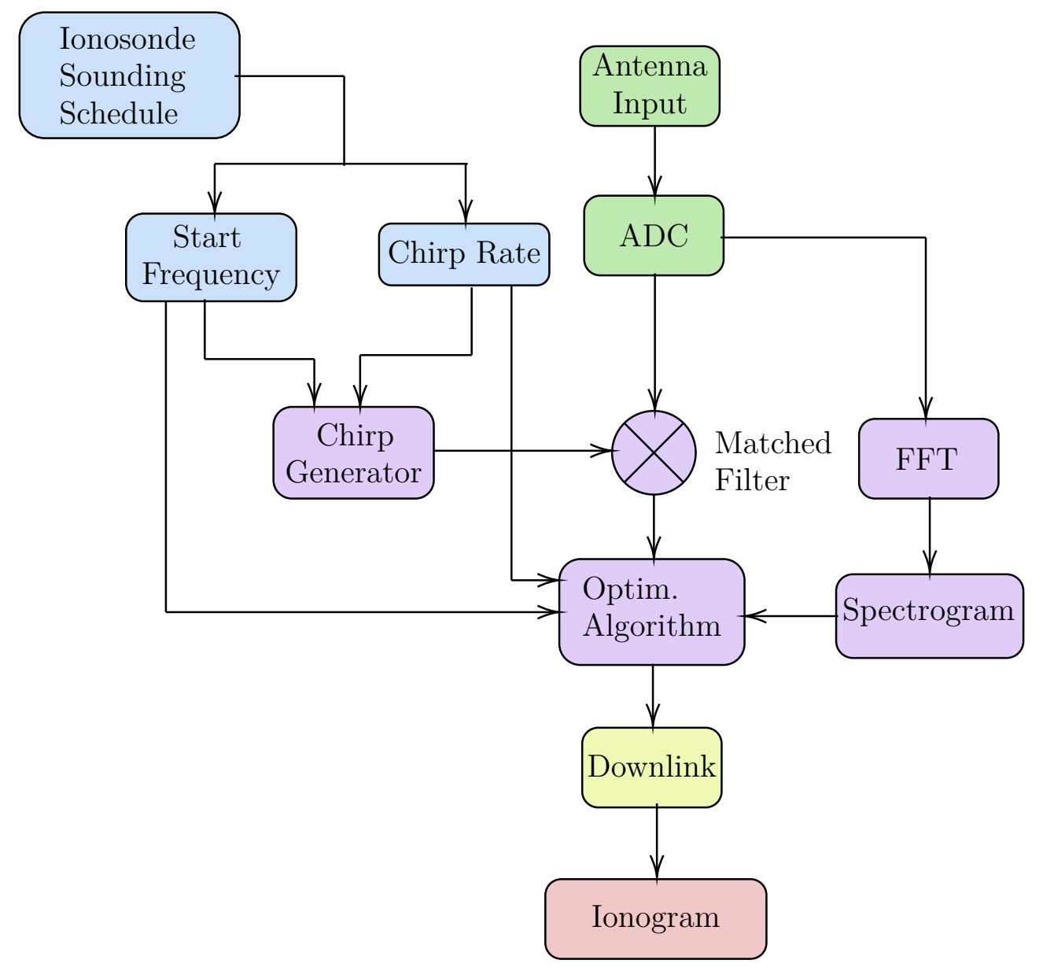
When SIRVLAS is above the F2 peak, it will receive ascending soundings and record what frequencies it receives at what times. This is the simplest mode of data collection and allows SIRVLAS to test the validity of global ionospheric nowcasts.

When SIRVLAS is below the F2 peak, it will receive soundings as they ascend and descend and use a generalized form of ionosonde path length geometry to identify the location of reflection (and thus the virtual height) of sounding frequencies.

Because SIRVLAS is travelling at orbital speeds while taking precise measurements of radio waves with unknown attitudes, it must correct for the effects of Doppler shift. Because the location of reflection affects the Doppler shift, and neither reflection location or Doppler shift are known, it is impossible to analytically isolate either variable. As such, SIRVLAS uses a customized optimization algorithm to estimate the location of reflection of the sounding wave and Doppler shift at once. Other sources of noise that contribute to measurement error include hardware limitations and FFT integration time; our simulations suggest that virtual height error caused by these sources is capped in most situations to 5-10 km.

Below-F2 measurements output a list of virtual heights for each frequency received by SIRVLAS, where each virtual height is paired with a location (latitude and longitude) and an error margin.

HF Signal Chain



The RF instrument will be active only when an ionosonde is scheduled to sound near SIRVLAS. The raw antenna input will be ingested by the onboard LimeSDR, where samples will be streamed to the flight computer. The flight computer will generate a spectrogram from the samples.

For each unit of time (one FFT) in the spectrogram, the flight computer will use its onboard database of ionosonde sounding schedules to generate the template waveform of the transmitted sounding. It will use this to calculate the predicted frequency at the given time, then find the difference between the expected and received frequency (or frequencies) in the given time. It inputs this (these) differences into the optimization algorithm, which uses the onboard GNSS and the pre-programmed location of the ionosonde to estimate the location of reflection of each received frequency (and its associated error bars).

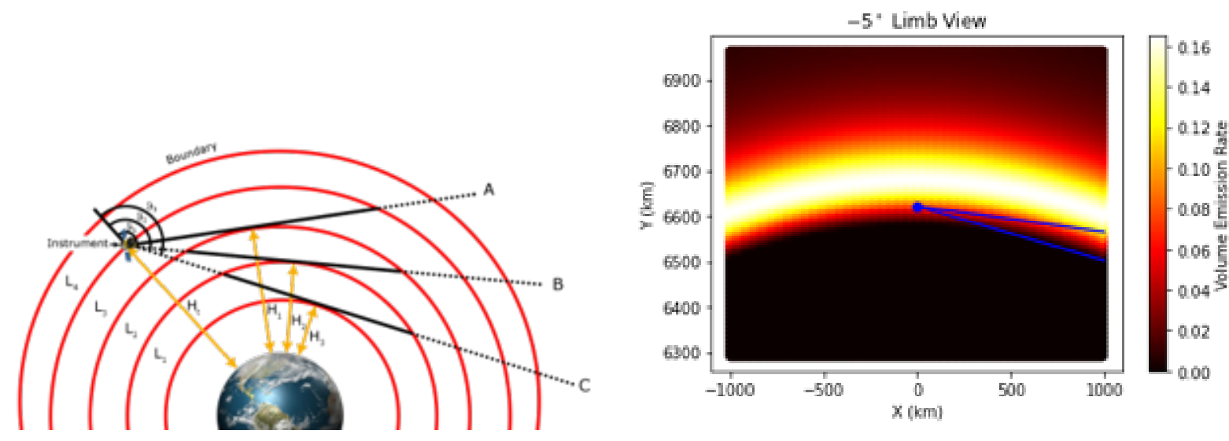
This calculation will be repeated for one in every thousand units of time in the spectrogram. The calculated values will be downlinked using the S-band data downlink system.

Downlinked data will be mapped in an "ionogram" where each frequency is mapped to a point in 2D space along the flight path of SIRVLAS.

Acknowledgements

We would like to thank the engineers and scientists who have mentored us and reviewed our designs. We also offer thanks to the *Maryland Space Business Roundtable*, *General Dynamics Mission Systems*, and *Dell* for funding the development of this mission concept, *EnduroSat* for their generous discounts on mission components, the *University of Maryland* for free scheduled high-altitude ballon launches, and *Overleaf* for providing their premium cloud-based LaTeX editor.

Optical Instrument



(a) (b)

Figure 4: View geometry of the optical instrument.

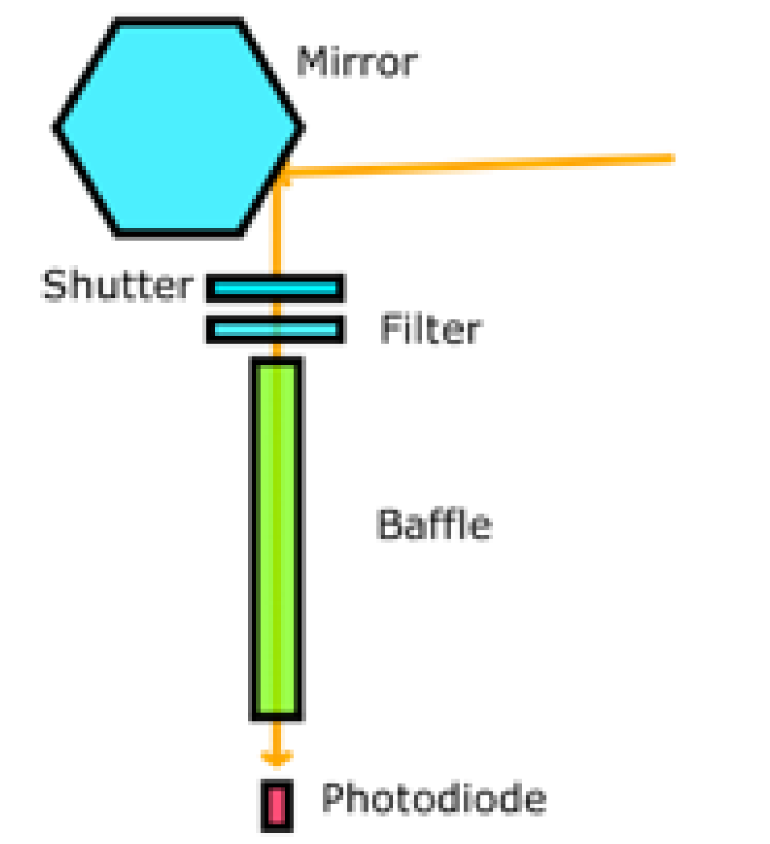


Figure 5: A labeled diagram of the path a ray will take through the optical instrument.

Construction:

1. Rotating hexagonal mirror used for limb scan
2. Low-power shutter to protect internal components
3. Bandpass filter used to constrain wavelength
4. Optical baffle used for field of view reduction
5. Photodiode used for optical detection

The data gathered from the optical instrument on the 777.4nm wavelength will be used to construct a 2D mapping of electron density during the mission through the global-fit retrieval procedure. Specifically, this is done through the simultaneous fitting of a single limb-scan through a least-squares technique. The extrapolation of electron density from airglow emissions is completed through the specific wavelength's volume emission equations which relate the emission rate of the wavelength to recombination reactions of atomic oxygen. As, within the lower ionosphere, atomic oxygen's concentration is approximately equivalent to the electron density, this equation allows for a direct relation between the measurement and the variable of interest. The generated mapping will then be compared with the data from the RF instrument to gain a better understanding of the profiles.

Spacecraft and Mission

SIRVLAS is intended to deploy on blair3sat, a 1U CubeSat currently being developed by Maryland high school students. blair3sat will use the EnduroSat 1U platform for communications, power generation and management, and RF data collection through the VHF dipole of an integrated hybrid VHF/UHF antenna. EnduroSat's proprietary On-Board Computer (OBC) will be paired with a custom ARM processor for the control and data collection of the optical instrument.

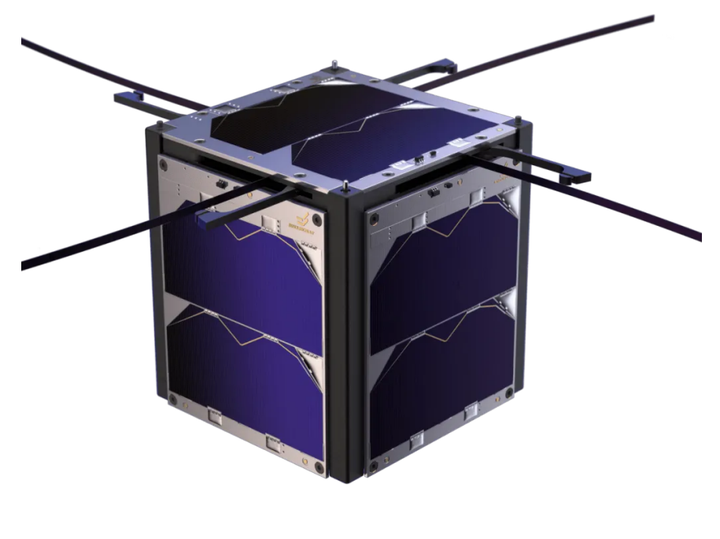


Figure 6: EnduroSat 1U Platform

Orbital Plan

blair3sat plans to launch from the ISS at an initial launch altitude of 408 km. Due to long orbital decay times from 500-600km deployment heights, as well as the need for nightside optical measurements, typical SSO deployments are not applicable. During the initial months of operation, SIRVLAS' RF instrument will listen for sounding frequencies that penetrate the F2 layer or pass through the iris, while the optical instrument will perform initial test and calibration measurements. Once SIRVLAS' orbit decays to 350km, the optical instrument will begin actively measuring airglow on the nightside, and the RF instrument will begin to receive ionosonde soundings on ascent and descent for its primary measurement.

Communications System Details

Communications System			
Link	*Band*	*Data Rate*	*Modulation*
Command Uplink	UHF	55 Kbps	GMSK
Spacecraft Status Downlink	UHF	55 Kbps	GMSK
Data Downlink	S-band	6.6 Mbps	BPSK

Duty Cycle Estimate	
Mode 1	15 minutes / orbit
Mode 2	7 minutes / orbit
Mode 3	3 minutes / orbit