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

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Abstract

Spatially and temporally varying charge density in the ionosphere refracts RF signals passing through the atmosphere, affecting services including over-the-horizon radar. Current methods for estimating ionospheric charge density include ground-based radar soundings and airglow limb sensing in the extreme ultraviolet (EUV) spectrum. Ground-based ionospheric sounders (ionosondes) are limited by the locations of sounders and by the iris, a region above which signals transmitted from Earth may never refract back to the ground. EUV measurements are dependent on instrument sensitivity and are highly susceptible to deviations from the line-of-sight. To address these limitations, we propose a 1U CubeSat payload to receive 1-20 MHz ground-based soundings from space and to observe the 557.8 nm OI emission. The payload would contain a deployable dipole antenna and a visible spectrum photometer. The payload would take measurements from many locations along its orbital path, increasing the resolution of the charge density estimate and measuring signals that transmit through the iris. Observing in the visible spectrum would increase the sensitivity of the payload, resulting in an improved signal-to-noise ratio. Furthermore, the temporal proximity of these measurements allows the data from the two instruments to be correlated to improve data-assimilative models of the ionosphere.

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*, meaning its charge density changes with:

- Time
- Altitude
- Geographic location

Improving measurements and models of the ionosphere would improve wireless capabilities by enabling some systems to more effectively mitigate ionospheric effects and enabling other systems to more precisely exploit their effects.

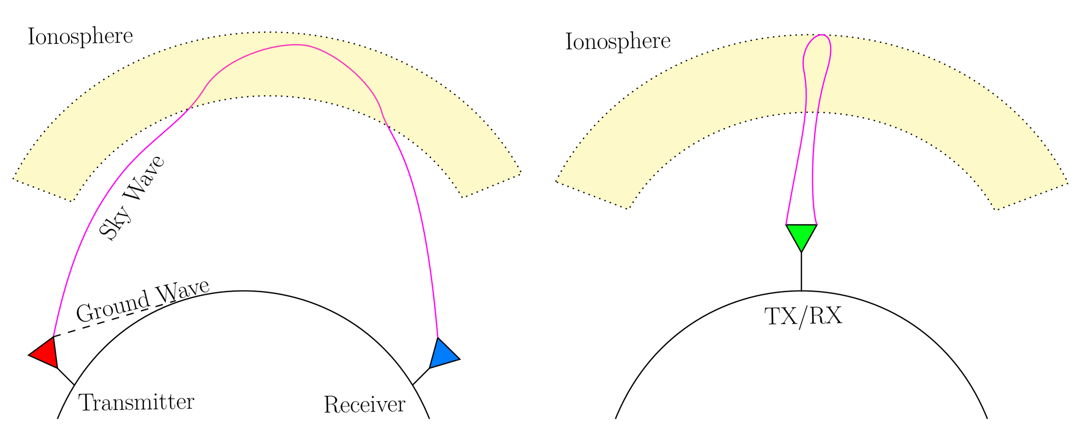

Figure 1: An oblique sounding with irregular bending as it travels through the ionosphere (left). A vertical sounding bending back down to earth (right).

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

SIRVLAS receives ionosondes from space while detecting airglow.

Benefits of Receiving Ionosondes 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
- Some signals from ionosondes never reflect back to Earth and are never used in estimating ionospheric state; SIRVLAS captures these signals
- 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
- Previous airglow detector missions only measure airglow and are not easily correlated with other measurements of ionospheric phenomena
- Spatiotemporally-correlated measurements of ionosondes and airglow could enable development of a data-assimilative model of the ionosphere

RF Instrument

SIRVLAS receives linear frequency modulated ionosondes at a variety of view geometries.

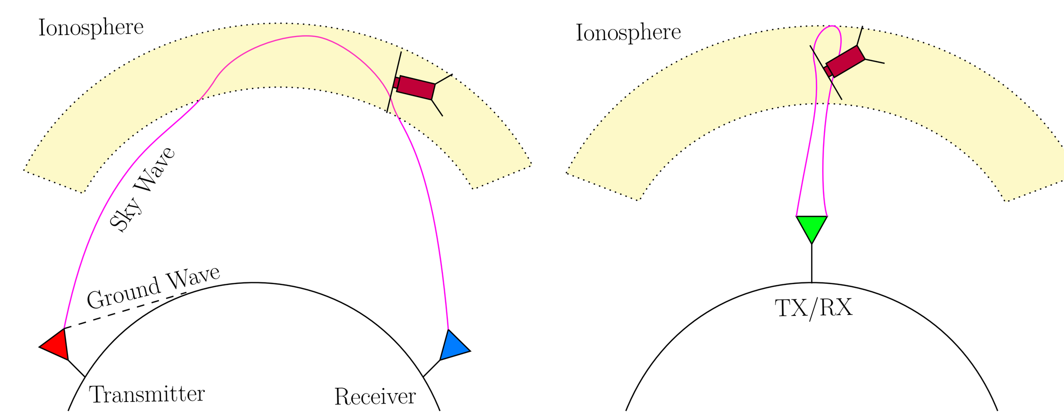

Figure 2: SIRVLAS receiving an oblique sounding before "reflection" (left). SIRVLAS receiving a vertical sounding before and after reflection (right).

Different view geometries must be handled in different ways. For example, if SIRVLAS receives an oblique ionosonde before "reflection," it may deduce a lower bound on charge density at the satellite's altitude, but it has insufficient data to deduce a complete charge density profile. However, if SIRVLAS receives a vertical ionosonde both when the signal goes up and when the signal comes back down, then SIRVLAS may deduce the complete charge density profile above the satellite.

HF Signal Chain

The RF instrument generates a template signal that represents SIRVLAS's best estimate of the transmitted ionosonde signal.

- *Mode 1*: template matches transmitted ionosonde perfectly
- *Mode 2, 3*: template is an arbitrary starting guess

The RF instrument mixes the ingested signal with the complex-conjugated template (match filtering), downsamples, and sends the resulting signal to the signal path corresponding to the operating mode:

1. Compute spectrogram (ionogram) and zoom to start time and frequency
2. Estimate start time using the horizontal-only Hough transform
3. Estimate start time and chirp rate using the complete Hough transform

In *Mode 1*, the output of *Signal Path 1* is immediately stored and downlinked. In *Mode 2* and *Mode 3*, once desired parameters are estimated from *Signal Path 2* and *Signal Path 3*, the template is adjusted to match the parameters and the circuit is toggled to *Signal Path 1*.

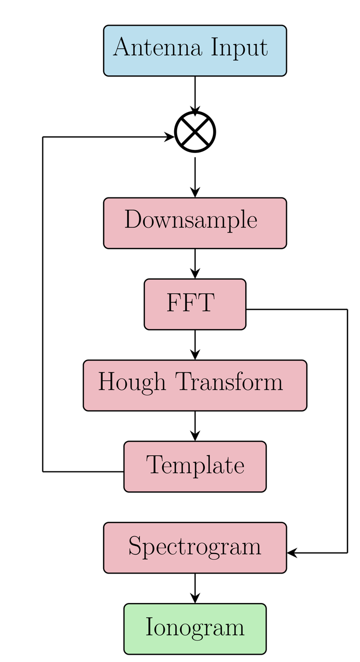

Figure 3: Streamlined signal processing chain.

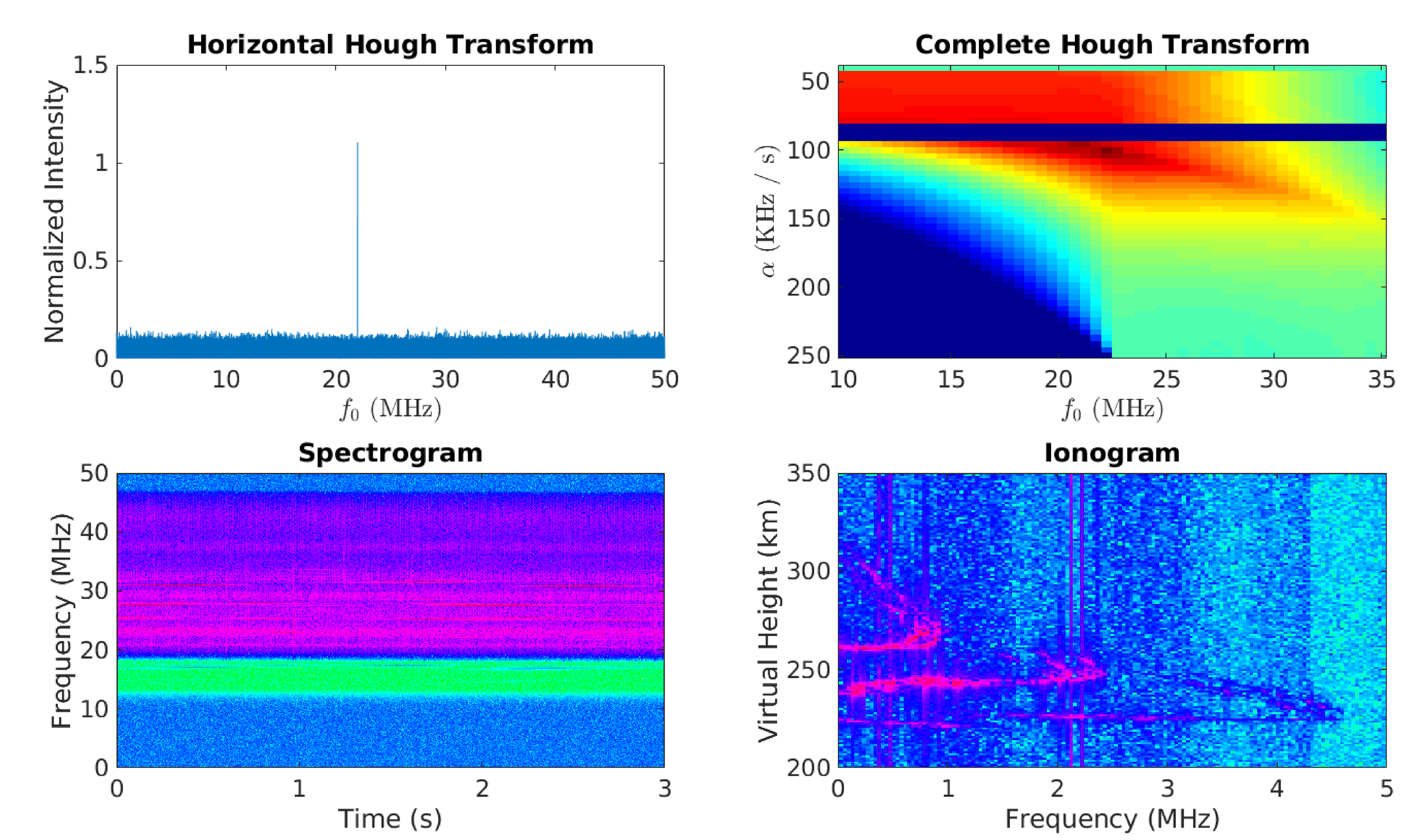

Figure 4: Visualizations of each step of the signal processing chain.

Optical Instrument

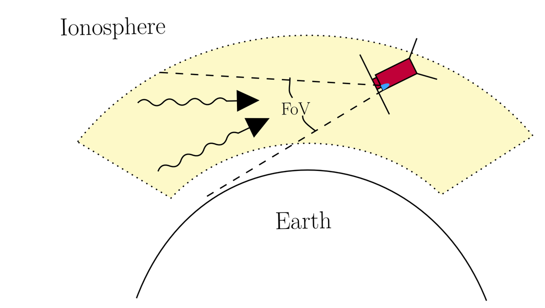

Figure 5: View geometry of the optical instrument.

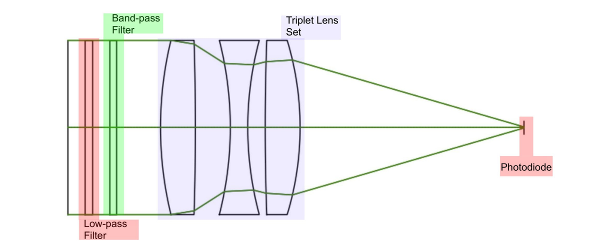

Figure 6: A labeled diagram of the path a ray will take through the optical instrument.

Airglow detector targets 557.8 nm band, the green line for atomic oxygen. Airglow detector has a 10 degree field of view, looking at and below nadir.

After a wave enters the instrument, it passes through both a low-pass and band-pass filter, followed by a triple lens set, finally narrowing together the beam to enter the photodiode.

Spacecraft and Mission

SIRVLAS is intended to deploy on *blair3sat*, a 3U CubeSat currently being developed by Maryland high school students.

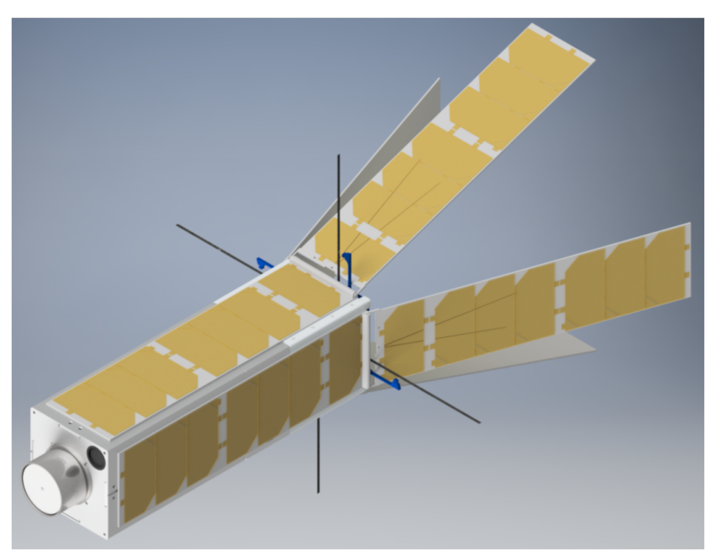

Figure 7: Artist's depiction of *blair3sat*

Orbital Plan

blair3sat plans to launch from the ISS at an initial launch altitude of 408 km. Currently, *blair3sat* plans to fly in nadir-pointing orientation and is expected to weight between 4 and 5 kg and stay in orbit for 9 months to 1 year. From this altitude, SIRVLAS will primarily observe the F2 region of the ionosphere.

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

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. Students involved practice various forms of engineering and science, business writing, and fund seeking. Students also work with mentors from several prestigious research laboratories in the DC area. 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.

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