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

blair3sat proposes SIRVLAS, an instrumentation suite consisting of a limb-viewing spectrometer and short-band HF antenna, the latter of which will intercept ionosonde chirps in the F2 layer of the ionosphere. Data from both instruments will be correlated using a data-assimilative method to create a three-dimensional charge density mapping of points in the ionosphere, determined by spectrometer readings.

SIRVLAS's optical instrument will use a Wasatch Spectrometer on a limb view in order to measure electron densities below the orbital path along a line. The optical instrument's data will correlate the data from the HF instrument to estimate a 3D mapping of the ionosphere.

blair3sat also meets NASA's Strategic Objective 3.3: Inspire and Engage the Public in Aeronautics, Space, and Science. This mission unites students across the county in a valuable and challenging mission. Members of the organization gain valuable experience in the aeronautics industry and invaluable connections.

Background Science

Plasma in the ionosphere refracts EM waves, affecting: long-range terrestrial communications systems, satellite communications systems, and over-the-horizon radar.

This plasma is *anisotropic*, meaning its charge density changes with: time, altitude, and 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.

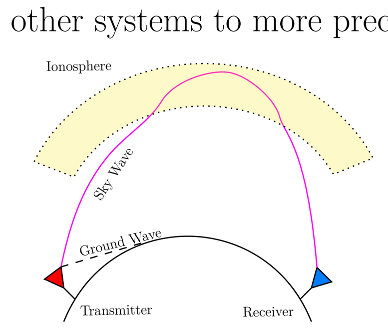

Figure 1: An oblique sounding with irregular bending as it travels through the ionosphere (left).

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 can calculate the "virtual height" at which the signal was reflected downwards. A 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 ionized atoms in the plasma. The instrument is tuned for a specific emission wavelength, and these emissions are called *airglow*.

Requirements for Success

Full Mission Success - Detection of multiple ionosonde soundings at or below 300km and the generation of a full mapping of electron density measurements throughout all optical instrument viewings.

Partial Mission Success - Detection of a single ionosonde sounding at or below 300km and multiple data points collected by the spectrometer for data correlation.

Minimum Mission Success - Deployment of the nitinol antenna, confirmation of ionosonde soundings at or below 300km, and multiple successful measurements of airglow emissions by the spectrometer.

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 practiced various forms of engineering and science, business writing, and funds 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. **Acknowledgements:** We would like to thank the engineers and scientists who have provided advice, offered their mentorship, and reviewed our designs; though we have been asked to withhold names and affiliations, we still acknowledge the individuals who have helped this team. Furthermore, we offer thanks to the *Maryland Space Business Roundtable* for funding the development of this mission concept, to Overleaf for providing their premium cloud-based LaTeX editor that this poster was created with, and to the companies that we have recently begun working with to turn this mission into a reality.

Optical Instrument

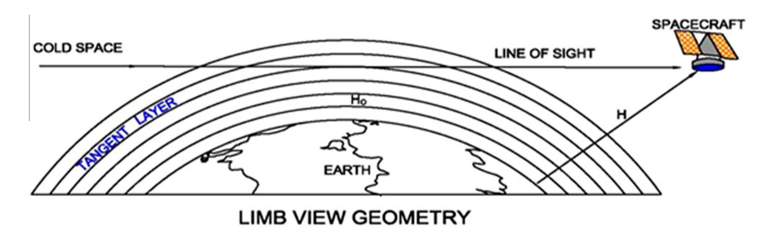

Figure 2: Diagram of Limb Geometry and Tangent Layers, Retrieved from 1

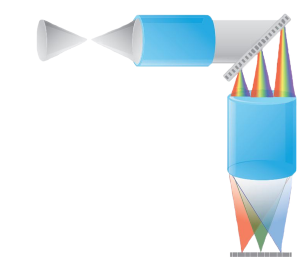

Figure 3: A Raytrace of A Generic Spectrometer

The Optical Instrument will operate in a limb view geometry with a tangent height of roughly 90 km. The measurements for electron density will utilize the green line of atomic oxygen which emits at 557.7 nm. Other wavelengths will be measured while the satellite is above 300km. These measurements will allow for the extrapolation of other atmospheric attributes through spectroscopy. Vertical resolution will be gained with the tangential view of the instrument and horizontal resolution is gained through an atmospheric sweep. The light will enter through a two way actuator shutter. Next, a baffle will limit the field of view. Finally, a Wasatch Photonics original equipment manufacturer (OEM) solution will be custom made for the application on top of a Wasatch Photonics WP VIS_NIR spectrometer. Applicable constraints include rating for space, sizing, wavelengths, and dispersion control. Scattering affects will be accounted for using a radiance transfer model. Radiance transfer models are able to predict the scattering affects will extrapolate true emissions from gathered intensity and given atmospheric parameters. The data gathered from the optical instrument will construct a set of points of known electron density values throughout the orbital path. This mapping will then be correlated with the data from the RF instrument to generate the 3D mappings of electron density. The extrapolation of electron density from airglow emissions is completed through equations which relate the electron density and the expected intensity of the emissions using the partial rate coefficient of the reaction. These equations make the assumption that the concentration of O^+ ions is equal to the electron density.

Data Correlation

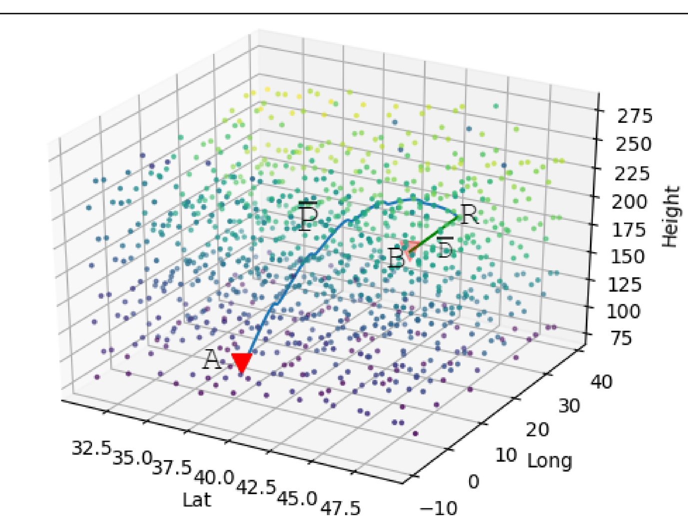

Figure 4: Model of the data-assimilative simulation. Colored points represent starting densities (matrix M). An ionospheric ray-tracing program takes A, along with a psuedorandomly generated vector, and outputs its path, P. The distance between the final point R and the target final point, B, is measured, and M is transformed accordingly to minimize the distance between the two points. Transformations on M are constrained by a line of known densities between A and B, which is provided by the optical instrument.

Spacecraft and Mission

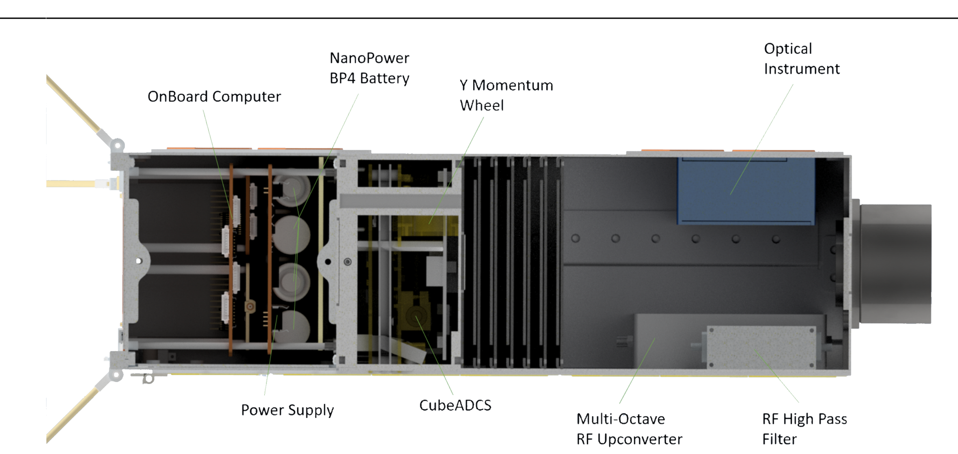

Figure 5: Artist's depiction of *blair3sat*

RF Instrument

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

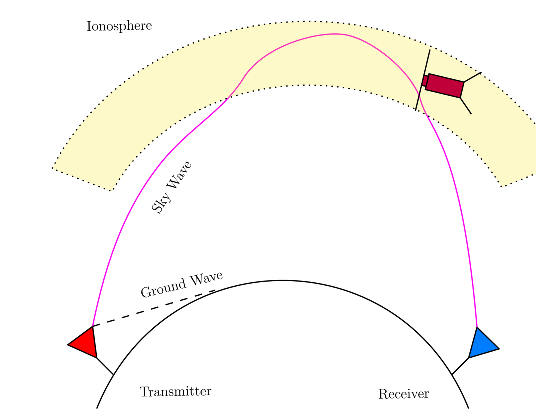

Figure 6: SIRVLAS receiving an oblique sounding before "reflection" (left). SIRVLAS receiving a vertical sounding before and after reflection (right).

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.

Different view geometries must be handled in different ways. For example, if SIRVLAS receives an oblique ionosonde sounding 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 an oblique ionosonde sounding both before and after reflection, then a complete charge density profile above the satellite can be generated.

Doppler shift can significantly affect results of the data collected by SIRVLAS in certain cases. In the case of soundings passing through the iris, the only data that can be gathered is an upper bound on charge densities below SIRVLAS. Since Doppler shift causes a maximum of 756 Hz error, which is relatively small in comparison with the magnitude of the HF band (1 MHz). The remaining danger posed by Doppler is on the majority of soundings received by SIRVLAS. The error in up to 756 Hz, when multiplied by the speed of light to calculate the virtual height, explodes to create an error of up to 1133 km in virtual height. This problem can be solved by calculating Doppler effect on the ascending wave and using that to correct the Doppler effect on the descending wave. This uses a few assumptions, all of which are valid:

1. The ionosphere is stratified, meaning that charge densities are uniform in same-altitude portions of the ionosphere; and second, that
2. the radio wave will be refracted only trivially when it is received by SIRVLAS during its ascent.

The latter is supported by the fact that SIRVLAS will receive these soundings at 300-250 km, below the nominal height of the peak density in the F2 layer. In other words, Doppler effect is either trivial or solved completely in all cases of relevance to SIRVLAS.

HF Signal Chain

The RF instrument will be active only when an ionosonde is scheduled to sound near SIRVLAS. The schedule stored on SIRVLAS will contain the start frequency and chirp rate of every sounding, allowing SIRVLAS to generate a template signal of the sounding. First, the antenna input is digitized with the proper sampling rate to achieve a 1km range resolution.

The RF instrument match filters the digitized antenna input with the generated chirp and downsamples it. The maximum of the matched filter output can determine if the antenna input is likely an ionosonde sounding. The digitized antenna input is Fourier transformed to create a spectrogram. After a period of high correlation with a template sounding, SIRVLAS may determine that it has received a sounding. At this point, the spectrogram will be compressed for downlinking:

1. Zoom the spectrogram to scheduled start time and frequency
2. Select all points on the spectrogram within a certain time and frequency of the scheduled chirp "line"
3. Discard all other points in the spectrogram

The compressed spectrogram will then be downlinked and decompressed at the ground station. Decompression involves assuming that all points discarded from the original spectrogram have an intensity of 0, since they are not of interest to SIRVLAS. Next, Doppler effect will be solved for with the algorithm aforementioned, and an ionogram will be generated with industry-standardized techniques.

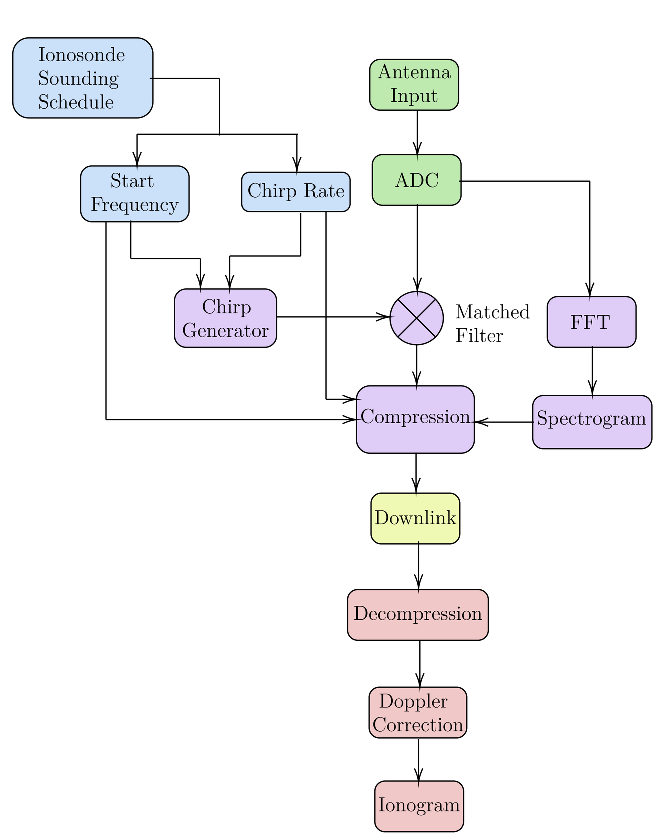

Figure 7: Signal Processing Chain.