29 MHz LEO satellite SDR LFM radar for citizen ionospheric science

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Abstract

We describe a 29 MHz radar system that illuminates the ionosphere from a CubeSat in low earth orbit. The radar uses a Linear Frequency Modulation (LFM) format that matches that of the Coastal Observation Radar (CODAR). SDR receivers operated by radio Amateurs and citizen scientists running a GNURadio flowgraph are used to measure the impulse response and Doppler of the radio propagation path through the ionosphere. The system may be viewed as a bi-static radar with transmitter and receiver in different location. The measured data and metadata is uploaded to a central data repository for analysis.

One of the objectives of the project is to motivate citizen scientists and radio Amateurs to learn about radar systems, ionospheric science, SDR, GNURadio and low earth orbit satellites.

The GNURadio-related work is the development of a Toolbox for the processing of CODAR signals.

1. Introduction

A 29 MHz frequency modulated continuous wave (FMCW) bi-static radar system that illuminates the ionosphere from a CubeSat in low earth orbit (LEO) is under development. The radar transmitter uses a Linear Frequency Modulation (LFM) format that matches that of the Coastal Observation Radar (CODAR) system (COD). The frequency of 29 MHz is chosen because radio propagation at that frequency is affected by the ionosphere (HF-)(Hum), transmit antenna size is physically realizable, and the licensing at that frequency is in the Amateur-satellite service (AR).

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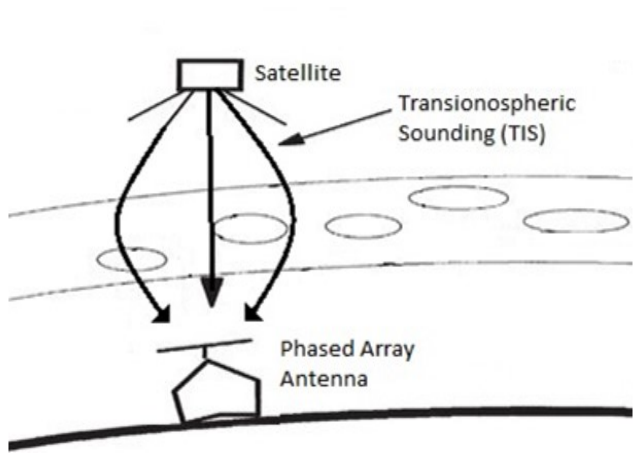

Figure 1. Trans ionospheric sounding

The 3U CubeSat called Skya'anaSat (Sky) is currently under construction by a student team at the University of Victoria, Canada, and scheduled for launch in early 2026. funded in part by Amateur Radio Digital Communications (ARDC) (ARD), and the CubeSats Initiative in Canada for STEM (CUBICS) program (CUB) sponsored by the Canadian Space Agency.

The globally distributed SDR based radar receivers are operated by radio Amateurs and citizen scientists to measure characteristics of the ionosphere. The SDR receivers run a GNU Radio flowgraph to measure the impulse response (multipath) and Doppler shifts of the radio propagation path from satellite to ground through the ionosphere. The system may be viewed as a bi-static radar with transmitter and receiver in different location. The measured data and metadata is uploaded by the citizen scientists to a central data repository operated by the project team and is made publicly available for analysis.

One of the main objectives of the project is science outreach: to motivate citizen scientists and radio Amateurs to learn about radar systems, ionospheric science, SDR, GNU

Radio and LEO satellites. Involving the public in the mission of Skya'anaSat is important to our funders.

While there are numerous papers in the literature describing FMCW radar using GNU Radio for a range of applications including observation of terrestrial CODAR signals, none exist on observation of signals originating from a LEO CubeSat. The GNU Radio flowgraphs developed for FMCW may be adapted for this project. A short-term goal is to develop robust GNU Radio CODAR Toolbox that yields results out-of-the-box.

Another objective is to provide a LEO signal source for observations using radio telescopes. The authors have access via an annual call for proposals to observing time on the Long Wavelength Array (LWA) (Ellingson, 2013)(LWA, a) based in New Mexico USA and have successfully made observations for the last five years. The LWA features a 256 element array of broadband cross-polarized inverted vee dipoles covering 10-88 MHz. Processing of LWA data can create an all-sky image of signals arriving at various azimuths and elevations (LWA, b) and will provide direction-of-arrival information and antenna gain that is not practical for citizen scientists using simple dipole or Yagi antennas.

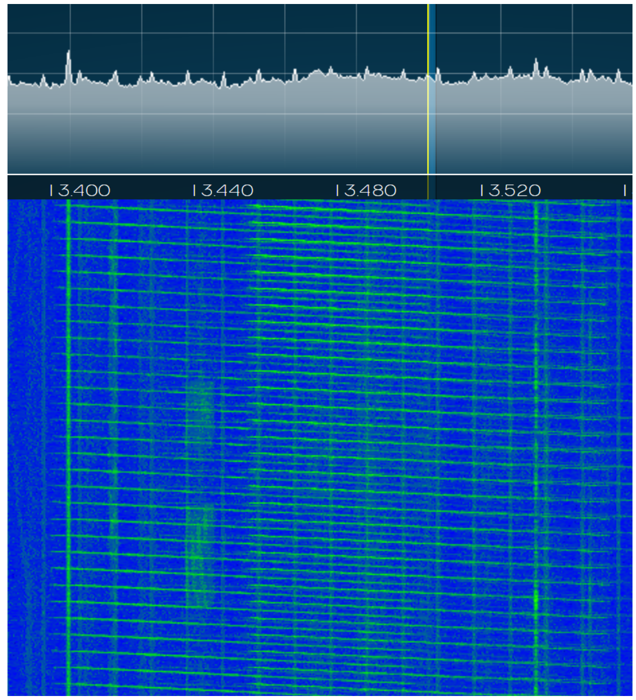

Figure 2. overlapping CODAR linear frequency modulation (LFM) spectrograms at 100 KHz bandwidth centered at 13.440 and 13.500 Mhz along with bursts of data at 13.335 MHz, all received with a dipole antenna

2. Using CODAR for observing the ionosphere

A RAdio Direction finding And Ranging (RADAR) transmitter uses a waveform that enables the receiver to measure the direction, range and velocity of objects at some distance from the transmitter. A repeated sequence of short (im)pulses is suitable, since the transmitted pulses will reflect from objects to the receiver which measures the amplitude and delay of the received pulse compared to the transmitted pulse. In effect, the receiver measures the impulse response of the channel between the transmitter and receiver. To minimize the peak power required from the transmitter, a waveform that is spread out over time but can be compressed into a pulse by the receiver is commonly used. One such waveform is Linear Frequency Modulation (LFM) commonly used for radar in many different applications. LFM may also be referred to as a sweep waveform, since the frequency is repeatedly swept over a bandwidth defined by a lower and upper limit at a periodic rate.

The received signal is correlated with the same LFM waveform and the output of this processing is a sequence of pulses. For a typical channel, the output will be a sequence of a cluster of pulses, where each cluster represents the impulse response of the channel. The individual pulses in each cluster represent a different path between the transmitter and receiver with a different path length and thus a different delay. The impulse response shows the multiple paths in a so-called multipath channel. The clusters may change over time as the impulse response may change over time due to movement of the objects.

The ionospheric channel is a multipath channel where the delay and amplitude of each path changes with time as the ionospheric layers move. The physics of the ionosphere and its layers has been studied extensively (Hum)(HF-). Some characteristics of the ionosphere may be simulated using prediction programs such as VOACAP (VOA) that trace the multiple paths (rays) between transmitter and receiver, commonly called ray-tracing.

Coastal Observation Radar (CODAR) (COD, 2013) uses an LFM waveform with a period of 0.5 or 1 second and a bandwidth of 100 KHz. The signal processing (correlation) is commonly done in the frequency domain as explained in detail in (Lipa & Barrick, 1990). The signal processing output is the impulse response pf the channel which in general will be different from one period to the next.

For many radar systems including CODAR, the receiver is co-located with the transmitter. A so-called bi-static radar has the receiver located at some distance from the transmitter. For observations of the ionosphere, we "borrow" a CODAR transmitter as a "signal of opportunity" and set up a bi-static radar system with the receiver at another location. The bi-static radar system measures the impulse response and shows the how the multiple paths change with time. At the risk of oversimplification, each of the multiple paths represents an interaction with a different layer of the ionosphere, and thus the time-varying impulse response is a measurement of the characteristics of the ionosphere.

The time varying impulse response may be plotted in a colour-coded strip that appears somewhat like a spectrogram, where each scanning line is an impulse response (instead of a frequency response). Such a plot will show how the multiple paths change their amplitude and delay.

3. Trans-ionospheric sounding

The bi-static radar using CODAR transmitters performs so-called ”bottomside sounding” of the ionosphere, where both transmitter and receiver are below the ionospheric layers. In contrast, ”top-side sounding” or ”trans-ionospheric sounding” (Igor Ivanov & Zhbankov, 2019) the transmitter is on a satellite above the ionospheric layers. There is a small literature of trans-ionospheric sounding experiments using carrier waves (Igor Ivanov & Zhbankov, 2019) and references therein, but no literature was found using radar waveforms such as LFM for trans-ionospheric sounding.

4. Citizen Science

The 256-element LWA radio telescope uses the principles of interferometry using multiple pairs of antennas with different spacings and orientations.to generate an all sky image showing the radio sky as observed at one location on earth. The signal processing algorithm that outputs the all-sky image assumes there is only a single path from the (celestial) source to the receiver. When multipath is introduced by the ionosphere, then a given point source will appear in multiple locations in the image. This effect occurs both for bottomside sounding where the image will show multiple points of reflection from the ionosphere arising from one transmitted signal, and for trans-ionospheric sounding where the image will show the multiple paths of transmission through the ionosphere arising from the one signal transmitted from a satellite. In both cases the time variation of the multiple paths can be observed.

Citizen scientists cannot compete with the capabilities of the LWA, but as a group they have the advantage that they can receive signals from many widely separated locations. Citizen scientists with a single element antenna can measure the time-varying impulse response of the trans-ionospheric channel. If measurement are GPS time stamped and simultaneous, then the impulse response will be measured at multiple locations of the ionosphere, thus making it possible to discern the structure of the ionosphere. With a sufficient number of citizen science observations, it may be possible to use interferometry to obtain an image.

5. Imaging of ionospheric waves

One scientific objective is to image Earth-disturbing events by creating images using radio waves transmitted from Earth's surface through the Earth's ionization layers where they are refracted on their way to the Earth's surface and captured by the LWA [4]. These images may be created either by bottomside sounding or trans-ionospheric sounding.

Earth's ionization layers have two superlative qualities. They are the most sensitive Earth entity being lighter than air. They are also Earth's largest sensor to disturbances whether from space or from Earth itself. The waves existing on their surface have been monitored in ionosondes, equivalent to having one pixel in an image which is insufficient to determine the properties of the ionization layer's waves.

The waves existing in the Earth's ionization layers (trans-ionospheric disturbances or TIDs) are created by Earth disturbing events such as big weather systems, earthquakes, lightning strikes, forest fires, etc and solar events such as the sun's solar flares, solar wind, magnetars. Knowledge enabled by the LWA observations will provide new information about the Earth enabling the power, energy and location of occurrence of the Earth disturbing events.

Figure 3. Long Wavelength Array

Ionospheric waves have been imaged using the Murchison widefield array and EISCAT but at much higher frequencies 80300.

The LWA data provides means to produce phase images of the waves of the Earth's ionization layers. A Fourier transform of the phase image separates all the Earth ion-

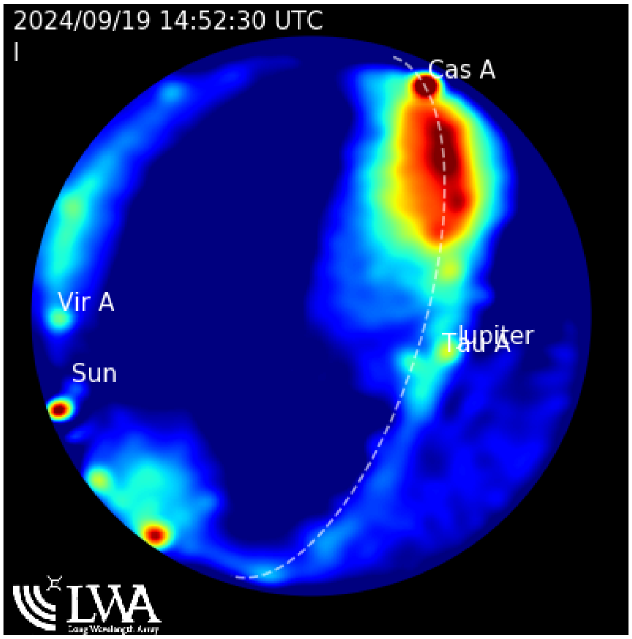

Figure 4. All-Sky image at 38 MHz from the Long Wavelength Array

ization layer's waves of different amplitudes and frequencies (wavevectors), providing valuable information about an earth-disturbing event that created the wave.

6. Discussion

Skya'anaSat with a LFM radar transmitter offers the opportunity for both citizen scientists and professionals to obtain unique trans-ionospheric sounding data in the form of time varying impulse responses that reveal aspects of the ionospheric structure and ionospheric waves. Citizen scientists and radio Amateurs can learn about GNURadio via a software package containing a GRC flowgraph that processes the received LFM signal and generates a colour coded strip map of the impulse response versus time. Citizen scientists can download the software package when Skya'anaSat has been launched and can upload their processed data to a public data repository. The data thus collected is available for download and analysis by anyone and may lead to new insights about ionospheric waves and structure.

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