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Very-low-frequency radio waves detector of the first Slovak satellite skCUBE

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Abstract

skCUBE is the first satellite completely designed and built in Slovakia, which will be sent to outer space in 2016. It is a 1U cubesat and its development started 6 years ago by engineers brought together by the Slovak Organization for Space Activities (SOSA). At the time, their research and technological goals were focused on the development and launching of cubesat-like payloads attached to meteorological balloons into the Earth's stratosphere. They were designed in a modular fashion, and equipped with communication/navigation systems and sensor platforms. This technology was further developed, with multiple enhancements, and incorporated into the skCUBE over the past 4 years. Although this satellite's mission is primarily focused on the demonstration of our capabilities in the space sector and public outreach, it will also be able to measure very-low-frequency (VLF) radio signals. These signals can be used to analyse the Earth's ionosphere, magnetosphere and terrestrial lightning. The VLF receiver consists of a nearly square-shaped air-core coil antenna, commonly known as a magnetic loop. An operational amplifier amplifies the signal from the coil. The signal is then delivered to an internal analog-to-digital (AD) converter in a microcontroler, which subsequently processes it. Its digital filtration, Fourier analysis and event detection, based on a power flux density, is performed directly on-board the satellite. The receiver works in 2 modes. The first slow one allows for the monitoring of the evolution of spectral changes throughout skCUBE's orbit and the detection of potential anomalies. The second mode executes very fast sampling of the detected signal, based on an excess of power flux density over specific limits. It will allow for the analysis of fast events occurring in Earth's atmosphere. Space-born detectors with magnetic loop antennas have the advantage of being sensitive in the VLF radio band, which is very interesting from a scientific perspective. Moreover, they are small and can be easily placed on the printed circuit boards of cubesats. However, the receiver suffers from the proximity of internal electronics, hence boosting electromagnetic noise to a higher level. The pros and cons of the design have been thoroughly analyzed, leading to multiple ideas for how to improve the technology for future space missions. SOSA is currently planning on using skCube for the measurements of electric discharges originating in the atmosphere and solar storms. Furthermore, SOSA is also keen on collaborating with other researchers/institutions interested in using the VLF and other skCube data.

Keywords: space-born detectors, cubesats, radio waves, whistlers

1. Introduction

The first Slovak satellite skCUBE carries an experimental very low frequency (VLF) receiver connected to a small magnetic loop antenna. Its main purpose is to detect VLF radio waves (with frequencies up to 30 kHz) from different natural sources. We expect to detect signals originating from lightning discharges in the Earth's atmosphere called whistlers [1],[2],[3]. Emissions of a whistler-mode chorus or hiss [4],[5] at higher geomagnetic latitudes (above 65°) might be observable by this receiver as well.

1.1 skCUBE

The satellite (Fig.1) was built essentially from scratch. It was based on experiences from a precursor projects of sending probes, called skBalloon, into the Earth's stratosphere [6],[7],[8],[9],[10],[11],[12],[13]. A specialized team, brought together by SOSA (Slovak Organization for Space Activities) designed and constructed almost all of the satellite: circuit boards, sensors, parts of the testing equipment, software, testing and calibration methods. The heart of the satellite is a redundant computer with a radiation hardened processor and a custom real-time operating system [14],[15]. The communication module is redundant as well. It has a specially designed code, which ensures that it functions properly even at a low signal to noise ratio. Its primary channel operates at 437 MHz. Experimental transmission of pictures from the on-board camera is performed at 2.4 GHz with a unique patch antenna. The power supply occupies the most complicated circuit board, which gains and stores energy delivered from the solar panels. The stabilization and orientation system is a complex piece of engineering. It controls the orientation using data from a gyroscope, magnetometer, sensors looking at the position of the Sun and Earth's horizon, and active coils pushing the satellite against the Earth's magnetic field as is necessary. The VLF receiver is the main on-board scientific detector.

1.2 Orbital characteristics

The skCUBE is planned to be launched by the Falcon 9 space rocket into an elliptic orbit, with an apogee altitude of 720 km, a perigee altitude of 450 km and an inclination angle of 98°. The mission should last for at least one year, probably two [15].

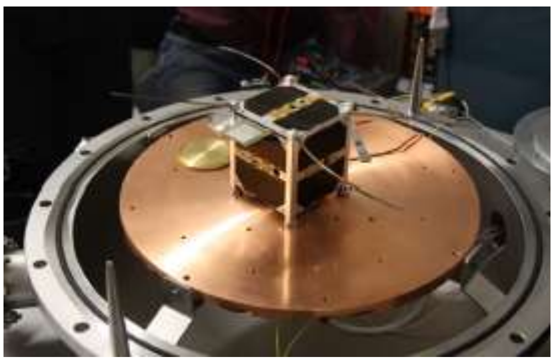

Fig. 1. skCUBE on a vacuum chamber plate at the Institute for Experimental Physics in Košice, shortly before vacuum tests.

2. Very low frequency radio waves detector

The detector consists of a nearly square-shaped air-core loop/coil (Fig.2), which serves as an antenna of the VLF receiver. An operational amplifier amplifies the signal from the coil. The signal is then delivered to an internal analog-to-digital (AD) converter in a STM32F746 microcontroler, which subsequently processes it. Its digital filtration, Fourier analysis and event detection, based on power flux density, is performed directly on-board the satellite.

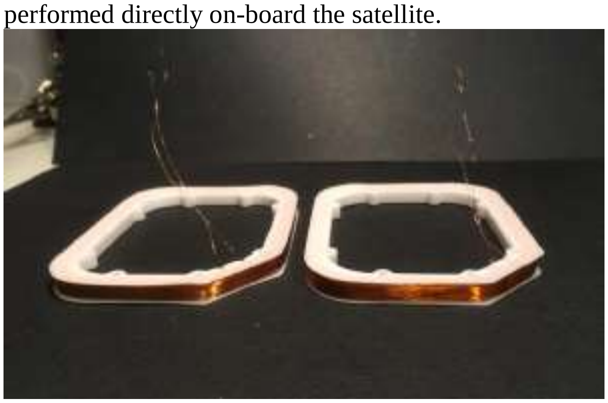

Fig. 2. Two identical coils, of which one was enclosed into a plastic container and attached to the experimental power circuit board of skCUBE.

Summary of the properties of the coil:

* N = 1000 (number of turns)
* w = 65 mm (average frame side length)
* l = 5 mm (width of winding)
* d = 0.12 mm (diameter of the copper wire)

The experiment works in 2 modes. The first slow one allows for the monitoring of the evolution of spectral changes throughout skCUBE's orbit and the detection of potential anomalies. The second mode executes very fast sampling of the detected signal, based on an excess of power flux density over specific limits, which will be set in the orbit. It will allow for the analysis of fast events occurring in the top side of the ionosphere.

Fig. 3. Power circuit board of the detector.

2.1. Properties of the magnetic loop antenna

The VLF antenna can be approximated by the diagram shown in Figure 4. It consists of an ideal voltage generator V with a value defined by the equation

$$V = 2\,\pi\,\mu_0\,N\,A\,\nu\,H_{rms}\,cos\theta$$

where V is the induced voltage in Volts, μ_0 is the permeability of vacuum equal to 4π10−7H/m, N is the number of coil turns, A is the area of each winding in m^2, ν is frequency in Hz, H_{rms} is the RMS value of the magnetic field's strength in A/m, θ is an angle between the magnetic field vector and the coil frame normal. The circuit includes further loop inductance Lloop (the inductance of the wire winding around the frame), wire inductance Lwire (the inductance of the wire of the antenna winding), wire resistance Rdc and the distributed capacitance Cloop. Each of the elements contributes to the antenna's performance and properties.

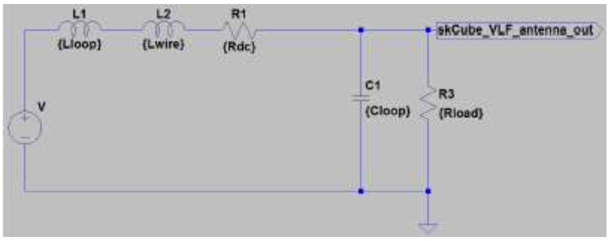

Fig 4. VLF antenna circuit mode

Measured properties:

* L = 150 mH (inductance)
* Rdc = 390 Ω (resistance)
* f0 ≈ 70 kHz (resonance frequency)

The VLF detector works with antenna's current over wide frequency band and Rload → 0.

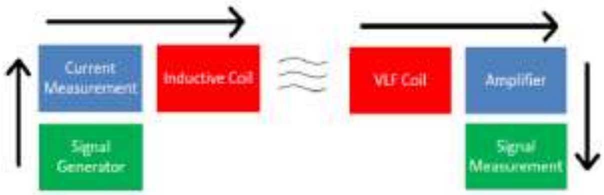

Fig 5. Schematic view of a sensitivity measurement performed on the receiver. Arrows indicate measurement sequence from signal generation, with pre-determined properties, up to its amplification and final detection. The signal generator (PC sound card); current measurement (Fluke 287 multimeter); inductive coil (one loop with a diameter of 25 cm, distance 17 cm from the detection VLF coil); amplifier (OPA2314); signal measurement (Creative X-FI USB sound card).

2.2 Sensitivity of the detector

A schematic view of a sensitivity measurement performed on the receiver is shown in Figure 5. The sensitivity of the detector was measured by putting it at distance z = 17 cm from one loop coil, fed by a measured electric current I from a PC sound card. The radius of the coil was R = 12.5 cm. It was possible to calculate the magnetic field induction B_Z generated by the inductive loop using this equation:

$$B_Z = \frac{\mu_0}{4\pi} \frac{2\pi R^2 I}{(z^2 + R^2)}$$

Then, the generated signal at the level of the receiver's noise was observed by using the program HDSDR [16]. It was found that the minimum magnetic induction of electromagnetic waves for signal detection above the MCU (microcontroler) noise is $B_Z \sim 5.3 \times 10{-}11$ T (equivalent to the intensity of a magnetic field 4.2×10^{-5} A/m).

2.3 Signal processing

The signal processing has a hardware part and a software part (Fig.6). The hardware part consists of an antenna, the air-core VLF coil, which is connected to a transimpedance amplifier (TIA) and which transforms the current from the coil to voltage. The output voltage is therefore directly proportional to the magnetic flux. That signal goes further into an anti-aliasing filter with a threshold frequency of 25 kHz.

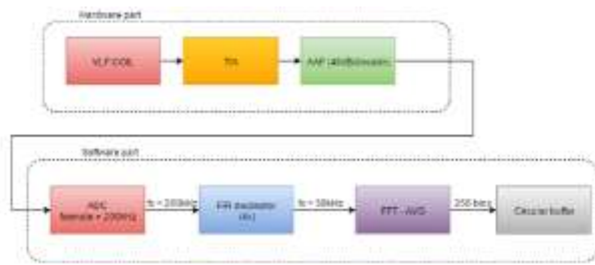
Fig 6. Block diagram of the signal processing. TIA (Transimpedance Amplifier), AAF (Anti-Aliasing filter), ADC (Analog-to-Digital converter), FIR (Finite Impulse Response), FFT (Fast-Fourier transform) .

The software part begins with an internal analog-to-digital converter of a microprocessor, which samples the signal at a frequency of 200 kHz. When samples reach buffer limits, the FIR decimates the under-samples input signal by a factor of 4. These output samples then undergo spectral Fourier analysis using 256 frequency bins. The signal is further averaged in the spectral domain. The spectral signal is stored in a circular buffer.

Summary of the basic signal processing parameters:

* ADC resolution: 12 bits
* number of input channels: 3[†]
* sampling frequency of ADC: 200 kHz
* simultaneous sampling: no
* decimation: 4x - 80 TAPS FIR
* buffer size: 50000 samples
* buffer processing period: 125 ms
* buffer processing time: 40 ms
* FFT: 256 bins

3. Pros and cons of an air-core magnetic loop antenna for use in space

Mass and volume are two of many critical parameters, which determine what hardware can be put

[†] The multiple channels are connected to active coils utilised primarily for the stabilization of the satellite, but they are able to detect VLF radio waves as well. We plan to describe them more in detail in our future publications.

into a rocket and sent into outer space. Air-core magnetic loop antennas can be light and compact. They are therefore optimal for light-weight missions in space.

Scientists typically use search coil magnetometers for magnetic field measurements in outer space in the VLF range. They are copper coils wound around a high magnetic permeability core, placed at the end of a boom away from the satellite's main electronics. However, such magnetometers are relatively heavy. The search coil magnetometer on-board the THEMIS satellite weighs 2 kg (including boom, cable and blankets) [17]. The weight of the search coil magnetometer itself on-board the DEMETER satellite is almost 0.5 kg [18]. skCUBE's air-core magnetic loop antenna weights roughly only 26 grams. On the other hand, it was placed inside the satellite and thus suffers from the electromagnetic noise of the microcontroler unit. No core means less sensitivity to magnetic fields.

4. VLF radio waves in low-Earth orbit and related scientific research

Sources of VLF radio waves in the Earth's low orbit will be primarily lightning discharges, the ionosphere, charged particles in the magnetosphere and human-related activity. The spectrum of such radiation depends on the properties of the source and the location of its origin. If the location of the source is close to the ground, the signal must pass through the ionosphere. Plasma in the ionosphere changes the waves' original properties. The characteristics of such waves can thus reflect the charged particle densities in the ionosphere and the properties of the omnipresent magnetic field.

4.1. Whistlers

Whistlers are typical radio signals in the VLF band from dispersed frequency components of the lightning spectrum. Travel through the ionosphere causes high frequencies to arrive first (Fig.7). Their sources near skCUBE's low orbit will be thunderstorms over which the satellite will fly [2]. This means that whistlers will come into the VLF detector from below. The characteristics of whistlers depend on the properties of the lightning itself, together with the free electrons, ion density and the magnetic field in the ionosphere [19],[20],[21],[22].

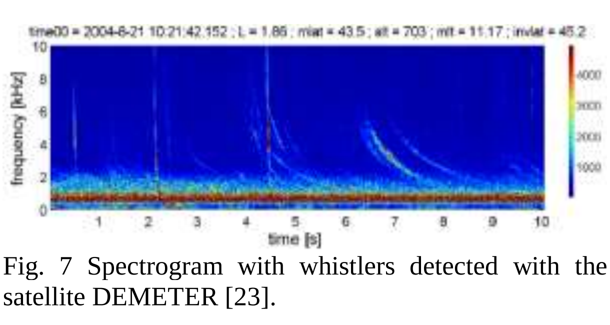

Fig. 7 Spectrogram with whistlers detected with the satellite DEMETER [23].

The properties of the whistlers can be approximately explained by Appleton's equation, which expresses the phase refractive index for electromagnetic waves passing through magnetized plasma [19]. In this case, it will be the Earth's ionosphere, due to ultraviolet radiation and X-rays coming from the Sun, which ionize upper parts of our atmosphere [19]. Appleton's equation considers only the effects of free electrons and for more precise understanding of whistlers, free ions will need to be taken into consideration [20],[21],[22]. Therefore, the analysis of whistlers will also bring new information about the ionosphere, which is ultimately important for any radio communication and position measurements between the Earth and satellites in space.

4.2 Chorus

Another type of radio signal visible in the VLF band, with a potential to be detected by the skCUBE receiver, is a chorus (Fig.8), generated by the interaction of radio waves with energetic electrons at around 3-10 Earth radii from its core. A chorus can reach skCUBE from above along magnetic field lines at higher geomagnetic latitudes [4],[5].

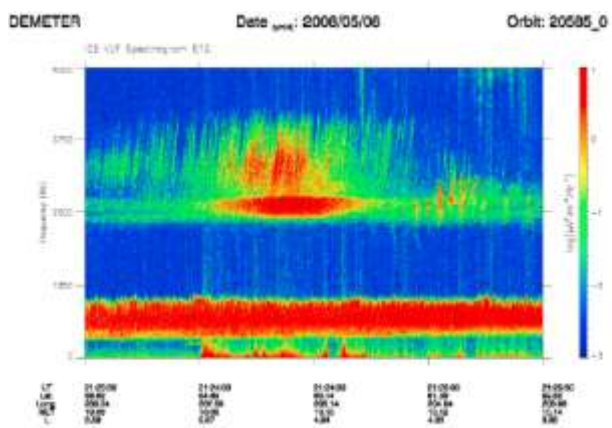

Fig. 8 Spectrogram with two frequency bands of chorus, one under 1000 Hz and the other one above 3000 Hz, detected by the satellite DEMETER [5].

5. Summary

Our experimental air-core loop receiver is set up for wide band detection of very low frequency radio waves with a minimum intensity of a magnetic field around 4.2×10^{-5} A/m ($B \sim 5.3 \times 10^{-11}$ T). At this level, we should primarily hear radio signals from lightning, called whistlers. One of the problems of the current detector is its proximity to the internal electronics, whose noise influences the sensitivity of the detector. A potential technological solution of this issue could be to place the detector on the boom outside of the cubesat's skeleton.

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