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Radio Frequency Spectrum Monitoring System at Low Earth Orbit by MRC-100 Satellite

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Abstract
The ongoing development of modern telecommunication technologies is leading to a steady increase in electromagnetic pollution on Earth and space. This pollution in Low Earth Orbit (LEO) can impact space-based systems and operations, making it difficult to control small satellites. Furthermore, it can interfere with scientific measurements and experiments conducted in space. The primary objective of this paper is to demonstrate the ability to design and develop a 3-unit PocketQube-class student satellite, MRC-100, as an extension of the SMOG-1 one-unit PocketQube satellite, the fourth satellite of Hungary. The MRC-100 satellite comprises several scientific payloads. The main one is a wide-band spectrum analyzer that operates in the frequency range of 30 MHz to 2.6 GHz and is used to measure electromagnetic pollution in Low Earth Orbit. This paper's measurements were conducted on an extended band ranging from (2–3.1 GHz). We present the capabilities of the extended band spectrum analyzer to measure electromagnetic pollution with the designed system's limited size 40 × 40 mm, weight, and power consumption of less than 400 mW. The working extended band spectrum analyzer was tested on the satellite flight module in the laboratory.

Keywords
MRC-100 satellite, student satellite, pocket cube satellite, spectrum analyzer, radiofrequency pollution

1 Introduction

PocketQube satellites are a type of small satellite, typically 50 × 50 × 50 mm, and have a mass of fewer than 500 g for one unit (1U). They are designed to be affordable, simple to manufacture, and easy to launch, making them desirable for various applications, including research, educational, and commercial applications [1, 2].

PocketQube satellites are covered by solar panels and rely on small batteries to store energy. They can still perform a variety of missions, including communication, remote sensing, and technology demonstrations; they have limited capabilities compared to larger satellites [3].

The main advantages of PocketQube satellites are their compact size, economical cost, and quicker manufacturing time, making them more affordable for a broader range of individuals and organizations. They can either be launched as secondary payloads on larger rockets or as a part of a dedicated small satellite launch [1, 2, 4].

In the Department of Broadband Info-communications and Electromagnetic Theory at BME University, the Microwave Remote Sensing Laboratory developed Various PocketQube Satellites experiments. The new PocketQube Satellite, MRC-100, was developed over three years through the collaboration of teachers, researchers, and students from the BME Broadband Info-communications and Electrical Engineering Department. It was named in recognition of the Polytechnic University Radio Club, which will celebrate its 100th anniversary in 2024. The club has played an essential role in developing all small satellites [1, 5–7].

The MRC-100 satellite is the most advanced in the SMOG series; it includes the sub-units necessary for its operation electrosmog testing and a position stabilization system. In addition to experiments conducted by researchers from three universities (the University of Szeged, Széchenyi István University of Győr, and the University of Debrecen) who will be onboard as "guests", will also include the measuring instruments from companies H-Ion and 27G Kft in the mission [4, 8].

The MRC-100 is a 3-Unit PocketQube (3-PQ) satellite with 50 × 50 × 178 mm dimensions and 587 g of mass. MRC-100 satellite main subsystems are Communication

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System (COMM), On-Board Computer (OBC), and Electrical Power System (EPS) [1, 5, 6].

Onboard MRC-100, various scientific payloads: special thermal insulator test, memory-based single event detector, spectrum analyzer 30 MHz to 2.6 GHz, automatic identification system receiver for vessel traffic services, 1 Mbit/s S-band down-link, UHF-band LoRa-GPS Tracking, satellite GPS + LoRa downlink (satellite identification), horizon + Sun camera, active magnetic attitude control, Total ionizing dose measurement system [1, 4–6, 9, 10]. The MRC-100 satellite flight module is in Fig. 1 and its cross-sectional view is in Fig. 2.

1.1 The previous mission

The Budapest University of Technology and Economics has a record of successfully launching PocketQube satellites, including SMOG-P, ATL-1, and SMOG-1, which were the second, third, and fourth Hungarian PocketQube-class student satellites, respectively. These satellites were developed and designed by the university's teachers, researchers, and students and were integrated into the university's educational system. Notably, SMOG-P was the world's first miniature operational satellite with dimensions of 50 × 50 × 50 mm and a mass of 183 g [8, 11]. Furthermore, SMOG-1 was launched in March 2021 and carried a scientific payload, specifically a system for monitoring and measuring the electromagnetic pollution of the public digital video broadcasting terrestrial (DVB-T) band at an altitude of 550 km [4, 5, 12, 13].

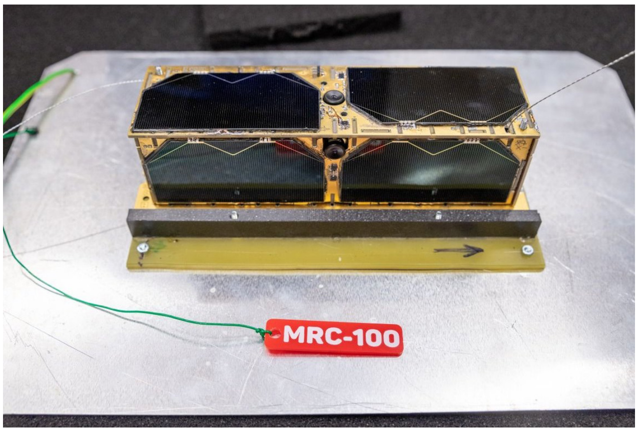

Fig. 1 MRC-100 flight module [4]

Fig. 2 Cross-sectional view of MRC-100 subsystems [4]

1.2 The new mission

The MRC-100 satellite is one of the most advanced and largest satellites in the SMOG series, with three units, and carries a variety of scientific payloads. The main objective of the satellite is to assess electromagnetic contamination in Low Earth Orbit through a wide-band spectrum analyzer that can detect various frequencies bands ranging from 30 MHz to 2.6 GHz, including the upper HF, FM, VHF, UHF, LTE, GSM, 4G, UMTS, and WiFi bands. The wide-band spectrum analyzer is divided into two subsystems, one which measures electromagnetic pollution in the range of 30 MHz to 1.8 GHz and the other in the range of 1.8–2.6 GHz (as an extended band).

A prototype of the extended-spectrum monitoring system 2.2–2.6 GHz was previously tested in the laboratory to Measure the RSSI values by establishing a demonstration system using a Software-Defined Radio (USRP B200 SDR, Austin, TX, USA) transmitter as a QPSK signal generator. We validated the sensitivity and the dynamic range of the system's prototype [5]. This article evaluated the satellite flight module's extended-spectrum analyzer 2–3.1 GHz. We measured the whole spectrum, the system's sensitivity, and the time required to measure the entire band. The structure of this article is as follows:

- Section 2 overviews the base subsystems, power budget Estimation, and the orbital movement estimation for the MRC-100 satellite.
- Section 3 discusses the designed extended-band spectrum analyzer, the system's antenna, and the system's working mechanism.
- Section 4 discusses the validation of the designed system and the spectrum measurement results.
- Finally, the article's conclusion and prospects for the MRC-100 satellite are presented in Section 5.

2 MRC-100 base subsystems

The MRC-100 satellite orbit is polar, circular, and sun-synchronously at Low Earth Orbit (LEO) with an apogee and perigee of 600 km.

2.1 Base subsystems

MRC-100 satellite Electrical Power System (EPS) is responsible for producing, conserving, and supplying electrical power to the other subsystems and typically consists of 8 solar panels, batteries, and a Maximum Power Point Tracking (MPPT) system. The solar panels generate electricity from sunlight, which is then stored in the batteries (Li-Ion batteries) for use when the satellite is in the Earth's shadow.

MRC-100 satellite On-Board Computer (OBC) controls all satellite subsystems' missions and collects and handles the onboard data.

MRC-100 satellite Communication subsystem (COMM) is responsible for transmitting and receiving data and commands to and from the satellite. Due to the onboard antenna's size, which has to be opened from the satellite, the radio communication is working on the radio amateur band, mainly on 437 MHz (70 cm UHF band).

2.2 Power budget estimation

The mean distance between the Sun and the Earth is around 150 million kilometers. The mean power density of sunlight around the Earth's surface is about 1367 W/m^2. Eight solar panels cover MRC-100 with three-layer 80 × 40 mm cells made by Azur Space [14]. The efficiency of the three-layer solar cells is 28% with dimensions 40 × 80 mm, producing DC power of 1.1 W. The orbital period of MRC-100 at an altitude of 600 km is 90 min, with 60% of the time in sunlight and 40% in the Earth's shadow. So, the average DC input is 0.684 W, with a peak power of 1.7 W (on LEO, DC input will be more than 36%). All systems onboard the MRC-100 satellite had a current limiter and were single-point-failure tolerant and cold-redundant [1, 4–6, 9, 15].

The peak power resulting in 1.7 W estimation depends on the cut-off edge of the solar cell 13.5 × 13.5 mm and the dimension of the three-layer solar cell 80 × 40 mm for one unit cube 100 × 100 mm, and we can estimate it by the Eq. (1). Fig. 3 shows the three-layer solar cell cover MRC-100 satellite [1, 4–6].

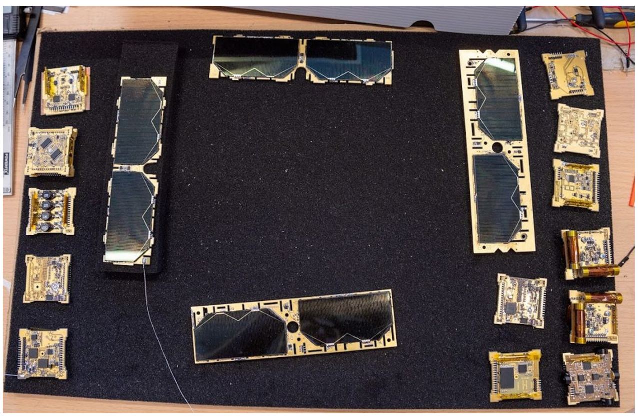

Fig. 3 MRC-100 solar cells [4]

$$\frac{(80\times 40)-(13.5\times 13.5)\times 2}{(100\times 100)}=60\% \tag{1}$$

The solar power density around the Earth's surface equals 1000 W/m^2 (for a 10 cm^2 cube equals 10 W/cm^2). So, it is necessary to estimate the overall DC power, the maximum DC input, the mean DC power, and the mean DC input in one orbital period (90 min) by Eqs. (2)–(5).

$$\text{OverallDC}_{\text{power}}=10\ \text{W}\times 60\%=6\ \text{W} \tag{2}$$

$$\text{MaximumDC}_{\text{input}}=6\ \text{W}\times 28.5\%=1.71\ \text{W} \tag{3}$$

$$\text{MeanDC}_{\text{power}}=1.71\ \text{W} \tag{4}$$

$$\text{MeanDC}_{\text{input}}=1.14\ \text{W}\times 60\%=0.684\frac{\text{W}}{90\ \text{min}} \tag{5}$$

2.3 Orbital movement estimation

The distance of the MRC-100 satellite from the ground station at an altitude of 600 km (apogee/perigee) when the elevation angle is zero, is the distance from the center of the Earth to the point on the surface directly beneath the satellite. This distance equals the satellite's altitude plus the Earth's radius. The maximum distance at the horizon when the communication is at a zero-degree elevation angle can be estimated by Eq. (6).

$$d=\sqrt{(R+h)^2-R^2}=2830\ \text{km} \tag{6}$$

Where the satellite's altitude (h) is 600 km, and the distance between the satellite and the ground station (d) is 2830 km, considering the radius of the Earth (R) as 6,371 km. Of course, the distance will change as the satellite moves in its orbit (Fig. 4) and as the elevation angle of the satellite changes. When the satellite is at perigee, the distance between it and the ground station will be the closest (Zenith). The distance Will be greater at other points in the orbit (Horizon). The speed of the satellite must move to remain in a circular orbit at an altitude of 600 km above the surface of the Earth can be estimated by Eq. (7).

$$v=\sqrt{\frac{G\times R}{1+H/R}}=7.55\ \frac{\text{km}}{\text{s}} \tag{7}$$

Where G is the gravitational constant.

3 The MRC-100 satellite's main payload

MRC-100 satellite's main scientific payload is a wide band spectrum analyzer (as a spectrum monitoring system).

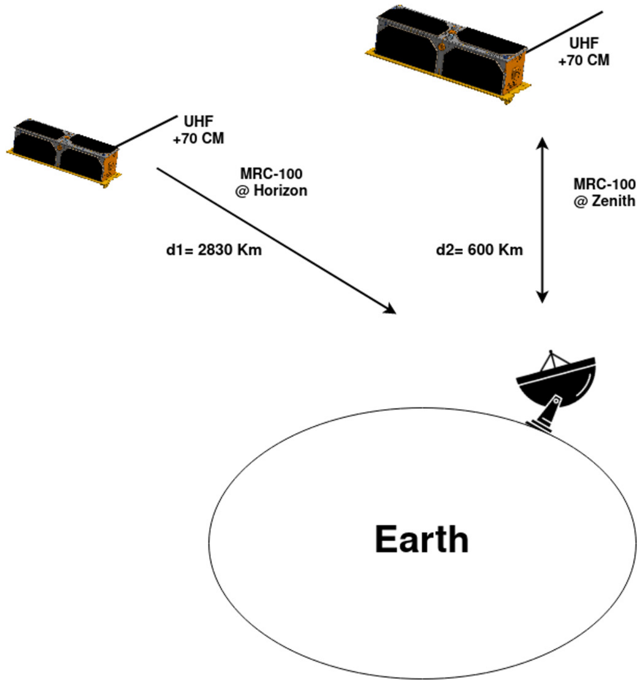

Fig. 4 Diagram of MRC-100 orbital movement

As mentioned before, the wide-band spectrum analyzer is two subsystems that measure electromagnetic pollution in the Frequency ranges of 30 MHz to 1.8 GHz and 1.8 GHz to 2.6 GHz, respectively, as an extended band. This paper focuses on the extended band spectrum analyzer in the frequency range of 2 GHz to 3.1 GHz.

3.1 Wide band spectrum analyzer

The wide-band spectrum analyzer is a single-chip radio transceiver (in receiver mode) from Silicon Laboratories SI 4464. This receiver works from 119 to 960 MHz with 1 to 850 KHz bandwidth. We executed qualifying measurements on the system in the frequency range of 30–1800 MHz (first phase) and calibrated its broadband antenna with a measurement system. The measurement system was tested on the top of the roof of building V1 at BME University and in an An-echoic chamber. We were able to show that there is significant radio frequency smog caused by the upper HF band, FM band, VHF band, UHF band, LTE band, GSM band, 4G band, and UMTS band. This is relevant to the main mission of the MRC-100 satellite [1, 9]. In Sections 3.2–3.4, we focus on the extended-band spectrum analyzer.

3.2 Extended band spectrum analyzer

The extended band spectrum analyzer is a single-chip (EFR32MG24) from Silicon Laboratories in receiver mode. This receiver operates between 2–3.1 GHz with a 100 Hz to 2.53 MHz bandwidth [5]. The EFR32MG24 chip's receiver is a standard superheterodyne receiver with a low- Intermediate Frequency (IF) receiver architecture. It is fully integrated with a fractional-N frequency synthesizer with low noise and high performance. It comprises an IF analog-to-digital converter (IFADC), Automatic Gain Control (AGC) module, Low-Noise Amplifier (LNA), I/Q down-conversion mixer, and a digital modulation-demodulation module that supports 2(G)FSK [5, 16]. Fig. 5 is the block diagram of the extended band spectrum analyzer.

The dimension of the designed spectrum analyzer is 40 × 40 mm. The receiver part of the transceiver works in Radio Frequency sensing mode (as an RF scanner) at a given bandwidth and Frequency 2–3.1 GHz. It can sense the Received Signal Strength Indicator (RSSI) level with sufficient accuracy and dynamic range. Fig. 6 shows the extended band spectrum analyzer Printed Circuit Board (PCB).

3.3 The extended band spectrum analyzer's antenna

The extended band spectrum analyzer antenna is a 470 mm monopole-type quarter wavelength antenna for 2-meter band frequencies, which can be used for a wide range of frequencies. The antenna is directly connected

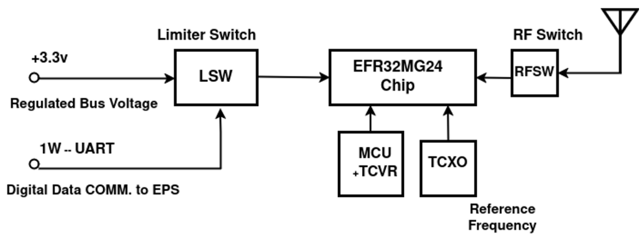

Fig. 5 Block diagram of the extended-band spectrum analyzer [5]

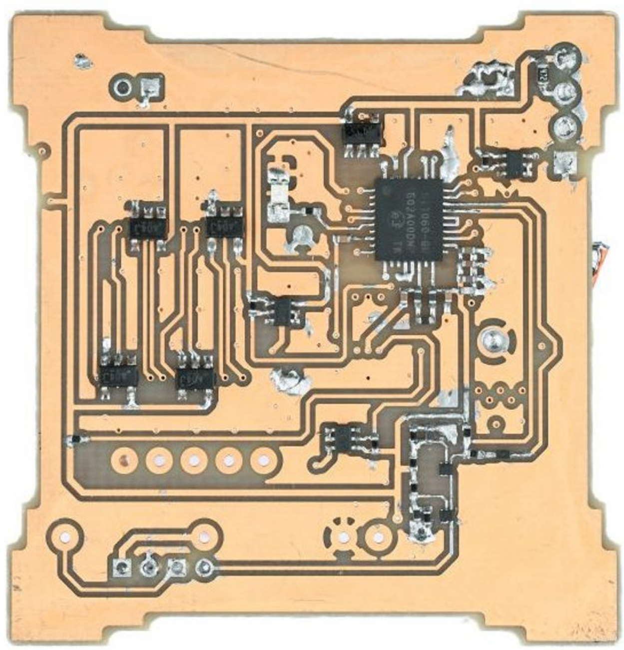

Fig. 6 The extended-band spectrum analyzer printed circuit board

to the receiver input without any matching circuit and has an input impedance ranging from 1–1000 Ω. To obtain accurate RSSI values, measurements were taken in an anechoic chamber using frequency steps of 1000 kHz with a wide-band log-periodic antenna at a set distance and specified transmit power (calibration method). As a result, the receiver of the extended-spectrum analyzer has a calibration vector stored in the signal processing program at the ground station. Once the ground station receives the satellite's Frequency versus the initial time-stamped RSSI measurements, it applies the Necessary adjustments based on the calibration vector (post-processing). Figs. 7 and 8 show the 47 cm antenna in the cube-skeleton and the radiation pattern of the extended band spectrum analyzer at 2 GHz and 3.1 GHz in Figs. 9 and 10.

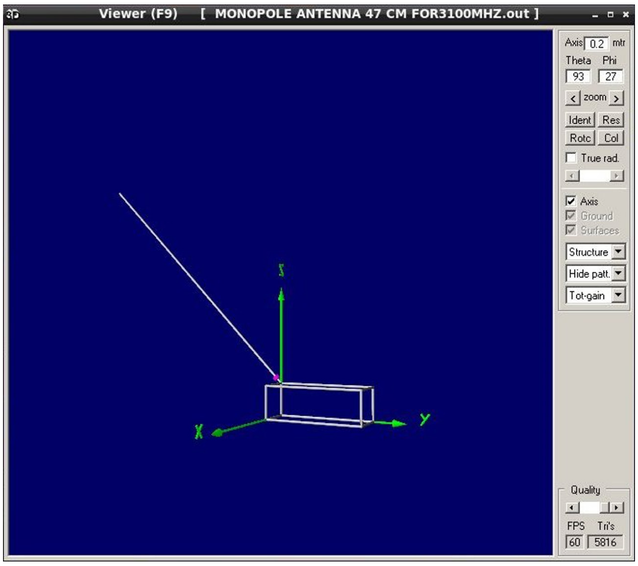

Fig. 7 47 cm antenna in the cube-skeleton

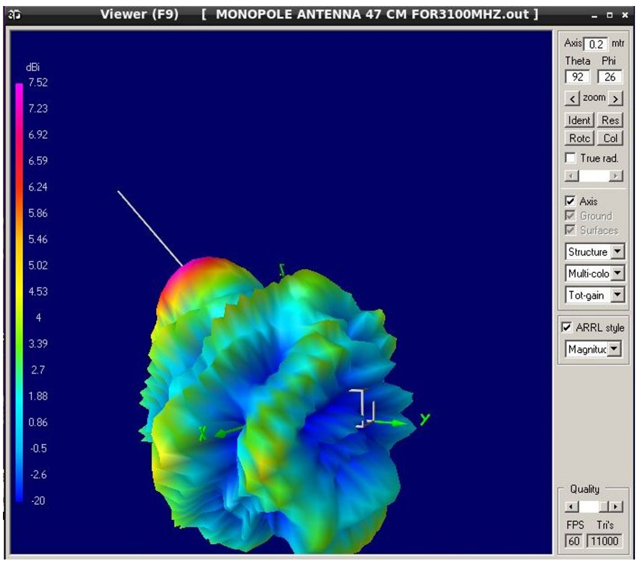

Fig. 8 47 cm antenna radiation pattern

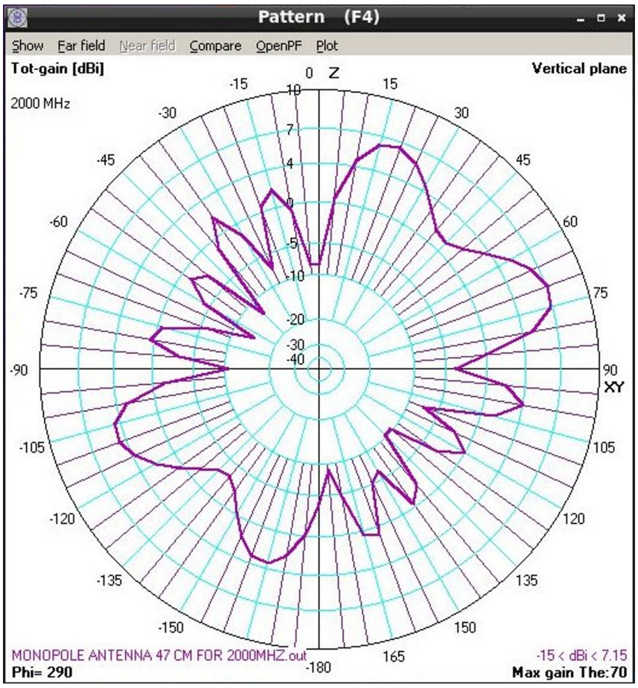

Fig. 9 2 GHz antenna radiation pattern

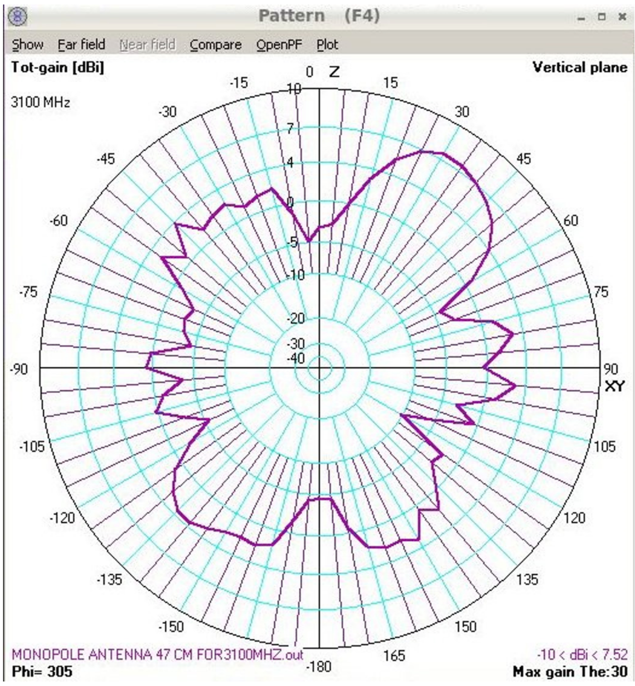

Fig. 10 3.1 GHz antenna radiation pattern

3.4 The working mechanism of the extended band spectrum analyzer

The onboard computer (OBC) of the MRC-100 satellite controls all satellite operations and can also control the extended-spectrum analyzer by receiving telecommand from the ground station. The primary ground station at (BUTE) is automated. It has remote control capabilities and contains a Raspberry PI single-board computer (SBC) that can control the azimuth-elevation antenna rotator, which can also calculate the tracking satellite's trajectory and the RF signal's Doppler shift.

The mechanism of the internal operating program of the block-by-block information graph of the Flowchart, which is illustrated in Fig. 11, explains the control of the operating the inside micro-controller programming code of the extended-spectrum analyzer after receiving the telecommand from the ground station and the OBC. These processes are the following:

- Process 1: When there is a telecommand from the ground station to operate the spectrum analyzer, then the OBC sends the command of the new parameter settings (Start Frequency in (Hz), Stop Frequency ≤ Start Frequency, Step Frequency, and Resolution Bandwidth (RBW)) to the spectrum analyzer subsystem.
- Process 2: Whenever new parameters are available, load the parameters.
- Process 3: When OBC gives a spectrum analyzer command (SP), set the fractional Phase Locked Loop (PLL), turn on *Rx* (in receive mode), read RSSI values, save to RAM, and increase the Frequency by the loop (for (f = start; $f \leq$ stop; $f+$ = step)).
- Process 4: Transfer the RSSI data packets to the flash memory of the onboard computer (OBC).
- Process 5: Repeat the process if there is an SP command from the OBC or telecommand from the ground station.

4 Spectrum measurement results and discussion

The extended-spectrum analyzer system was tested inside the flight module of the MRC-100 satellite at the laboratory. The system can measure the extended band's Received Signal Strength Indicator (RSSI) with sufficient sensitivity, accuracy, and less power consumption

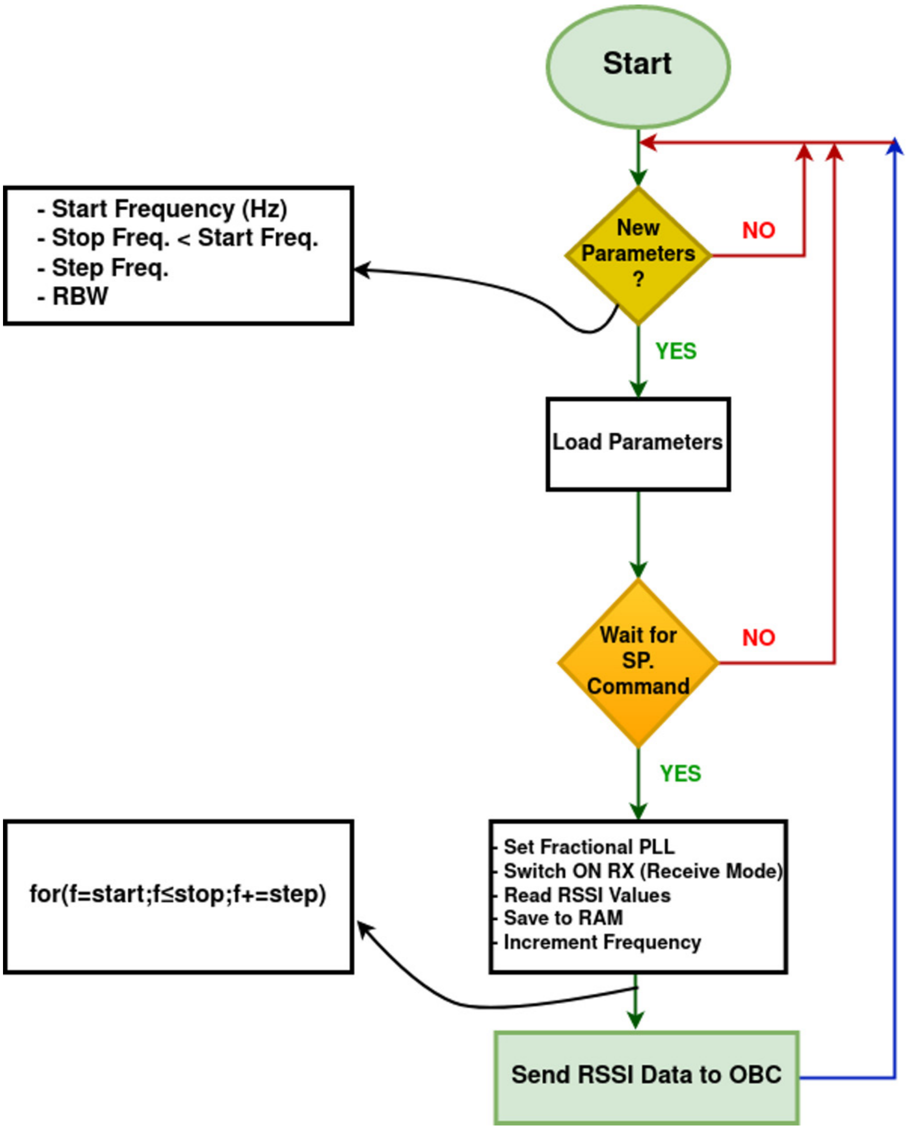

Fig. 11 Flowchart of the internal operating program [5]

(330 mW). In Section 4, we validate the designed system's dynamic range and sensitivity, in addition to the measurement results of the whole band of the extended-spectrum analyzer 2–3.1 GHz.

4.1 Validation of the designed system

The extended-spectrum analyzer system was functionally validated in the laboratory environment of the satellite flight module. The designed system was tested by creating a demonstrational system using a transmitter of Software-Defined Radio (USRP B200 SDR, Austin, TX, USA) as a signal generator that sends continuous wave (CW) at 2.41 GHz, and 3 GHz with fixed transmitted power (*Ptx*) is −43 dBm. The main aim is to measure the system's sensitivity and determine the frequency gaps in the whole band. Figs. 12 and 13 illustrate the measurement of the amplitude transfer function of the Intermediate Frequency (IF) filter of the EFR32MG24 chip when continuous waves are transmitted with different Resolution Bandwidths (RBW).

Figs. 14 and 15 show the capability of the system to sense the signals at the highest frequency range of the system 2–3.1 GHz by transmitting wide-band and narrow-band continuous waves. As shown in Fig. 16, the amplitude transfer function of the Intermediate Frequency (IF) filter of the EFR32MG24 chip has been measured by transmitting continuous wave signals when the resolution bandwidth is 12 MHz.

According to the datasheet of the EFR32MG24 chip [16] and the laboratory measurements, we have proven that the chip can detect signals with a maximum strength of −16 dBm and a minimum strength of −106 dBm — this results in a measured dynamic range of 90 dB for the chip. The Received Signal Strength Indicator (RSSI) levels can be determined by utilizing the value in the RSSI register and applying a calibration vector modification of RSSIdBm = (RSSIreg/2) − 130.

4.2 Spectrum measurement results

The receiver chip is configured to operate within a 1.328 MHz bandwidth, within the chip's maximum

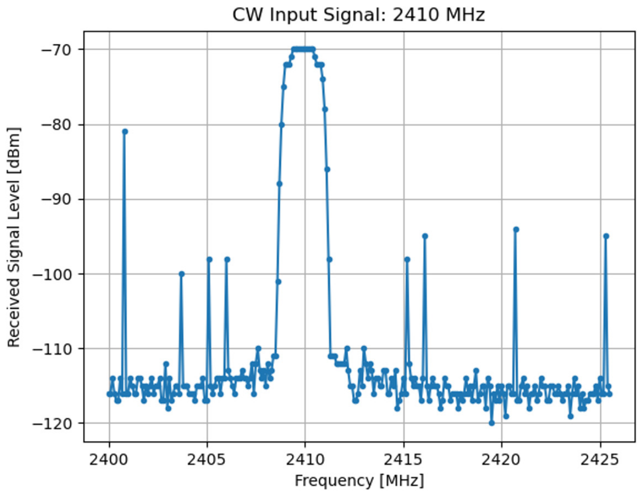

Fig. 12 Continuous waves with 1.5 MHz resolution bandwidth

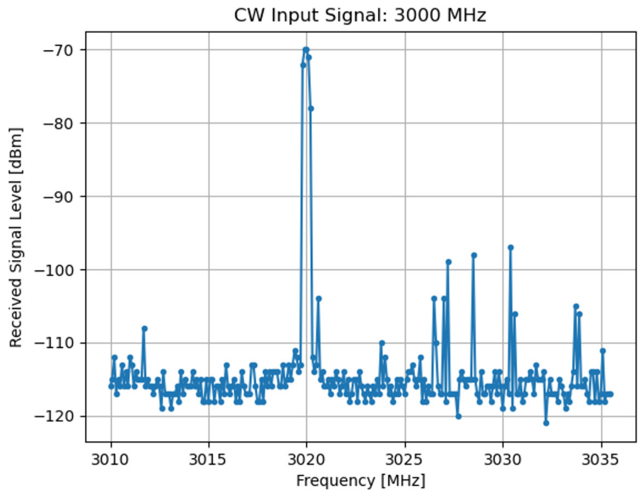

Fig. 14 Narrow-band continuous waves with 100 kHz resolution bandwidth

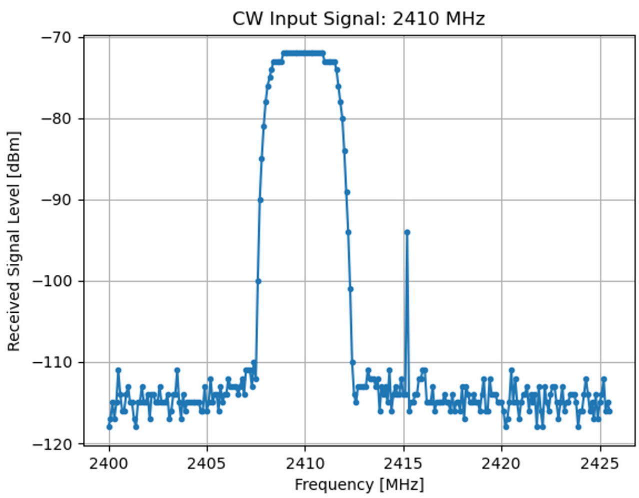

Fig. 13 Continuous waves with 3 MHz resolution bandwidth

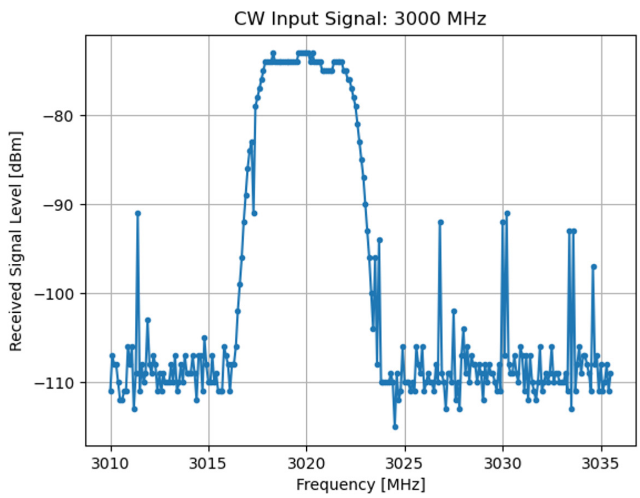

Fig. 15 Wide-band continuous waves with 4 MHz resolution bandwidth

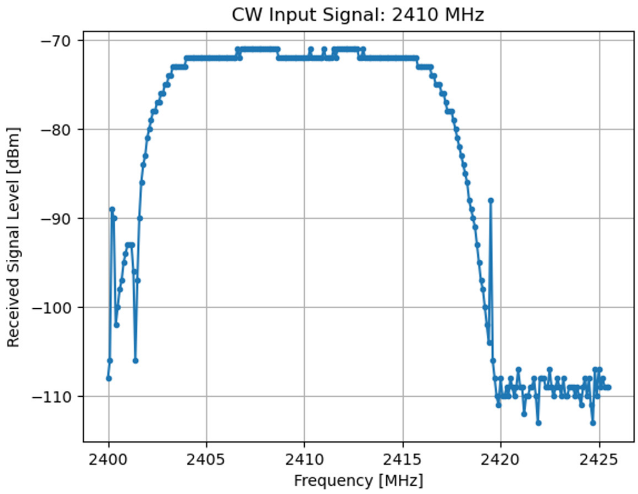

Fig. 16 The transfer function of the intermediate Frequency (IF) filter of the EFR32MG24 chip when used as a spectrum analyzer

capability of 2.53 MHz, and the configuration system controls this. Therefore, it is essential to calculate the total measurement points. The total points are determined by minimum Frequency, maximum Frequency, step frequency, and resolution bandwidth (RBW).

$$\text{RBW} = 1.5 \times \text{DataRate} \quad (8)$$

$$\text{DataRate}_{\text{GMSK}} = 2^{\text{RBW}} \quad (9)$$

$$\text{StepFrequency} = \left(\frac{\text{RBW}}{4}\right) \quad (10)$$

$$\text{TotalPoints} = \left(\frac{f_{\max} - f_{\min}}{f_{\text{step}}}\right) \quad (11)$$

$$\text{MinimumTime} = (\text{TotalPoints}) \times \left(\frac{1}{\text{RBW}}\right) \times 10 \quad (12)$$

As shown in Fig. 17 the spectrum analyzer measures the spectrum of the WiFi band. It was observed that a significant amount of RF power is emitted from multiple WiFi transmitters. The total measurement points are equal to 98 points according to Eq. (11) when the step frequency

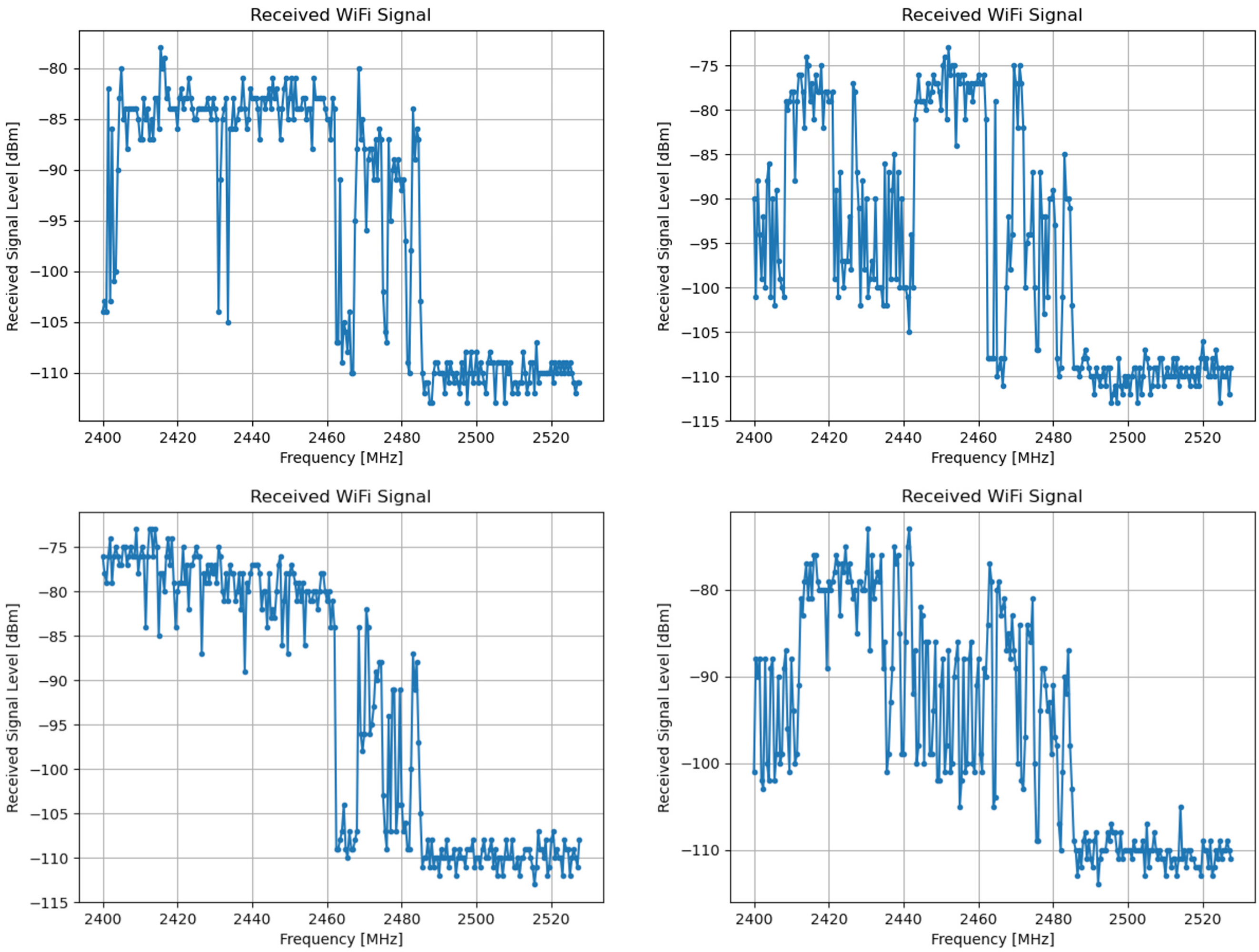

Fig. 17 Received spectrum of the WiFi band

equals 1.328 MHz, the maximum Frequency is 2.53 GHz, and the minimum Frequency is 2.4 GHz. So, the time required to measure the RSSI values is 0.05 s, calculated depending on Eq. (12).

According to Eq. (11) and Eq. (12), the total measurement points measured by the extended-band spectrum analyzer 2–3.1 GHz equals 828 points, and the time required to measure the RSSI values equals 0.4 seconds when the step frequency equals 1.328 MHz.

As per the estimated time from Eq. (12), it is possible to analyze the extended band spectrum every 20 seconds.

The On-Board Computer (OBC) of MRC-100 has a maximum flash memory of 16 MB, which allows for storing 828 measurement points using 828 bytes of memory space. Each Received Signal Strength Indicator (RSSI) value requires 1 byte of memory size.

In the four graphs in Fig. 17, we observe fluctuations in the WiFi signals received by the extended-band spectrum analyzer. These fluctuations are due to multipath propagation, where WiFi signals are reflected from nearby surfaces. Consequently, RSSI values change dynamically, even in different transmission and reception scenarios.

5 Conclusion

The extended-band spectrum analyzer was evaluated in the flight module of the MRC-100 satellite within a laboratory setting. It can measure Received Signal Strength Indicator (RSSI) values within the 2–3.1 GHz range. The designed system has adequate sensitivity and dynamic range to expand the primary spectrum monitoring system, which operates within the 30 MHz to 2.6 GHz range. This is the primary scientific payload of the MRC-100 PocketQube satellite, which aims to monitor RF pollution in Low Earth Orbit (LEO) worldwide. The designed system can also be used as a traditional single-channel spectrum analyzer, with a current consumption of less than 120 mA from a +3.3 V standardized bus voltage and a PCB size of 40 × 40 mm. MRC-100 was installed on the satellite platform in February 2023 and launched into outer space via Falcon-9 rocket from the USA in June 2023.

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