# Band-monitoring Payload for a CubeSat Satellite

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**Abstract.** *During changing sun activity, the ionosphere is responding accordingly and therefore it is interesting to observe the propagation behavior of shortwave bands. For the above mentioned purpose we have designed a band-monitoring payload for an experimental CubeSat satellite. The payload consists of a receiver, which is able to receive SSB modulated narrowband signals in 28 MHz uplink band, and a transmitter with FM modulation in UHF downlink band. The receiver frequency is selected to be at the center of radio amateur activity with low data rate digital modulations.*

## Keywords

CubeSat, band-monitor, BPSK31, PSAT, transponder.

## 1. Introduction

During last years, members of the Laboratory of Experimental Satellites at Brno University of Technology were involved in projects related with experimental satellites [2], [3], [4]. Since early nineties we participate on satellite program of international organization AMSAT [1], [4]. In 2010, we were asked by the US Naval Academy Satellite Laboratory to develop a HF band-monitor for an experimental CubeSat-type satellite called PSAT (ParkinsonSat) [5], [6].

The device is designed on a single double-sided board of a standard CubeSat format, with dimensions 90x90 mm. Basically, it consists of two parts - the uplink receiver working in HF 28 MHz band and the downlink transmitter working in UHF 435 MHz band. The receiver is able to demodulate SSB signals in 3 kHz audio channel. This 3 kHz wide base-band signal is then FM modulated on UHF carrier. The transmitter includes a microcontroller which provides an independent telemetry channel using BPSK31 modulation. The telemetry data are used for monitoring important parameters of the transmitter and allows us to identify the transmitter signal in downlink channel.

The receiver input is centered at radio-amateur frequency band segment, which is used for experimental communication using BPSK31 phase shift keying modulation. The BPSK31 was developed by Peter Martinez [7] and it allows simultaneously several tens of communication channels with very low S/N ratio to be present in a single 3 kHz audio channel. At the transmit side, the binary phase shift keyed signal is created in base-band on an audio sub-carrier, and finally, this audio channel is SSB modulated on a RF carrier. BPSK31 uses 31.25 bit/s data rate with a Varicode [7] symbol coding. The character length is dependent on probability of occurrence of each character in communication.

## 2. Receiver

A block diagram of the HF receiver part of the band monitor is depicted in Fig. 1. We use conventional super heterodyne architecture, proven in PCSAT2 receiver [8], with several modifications - especially the BPSK31 signal sensing circuits.

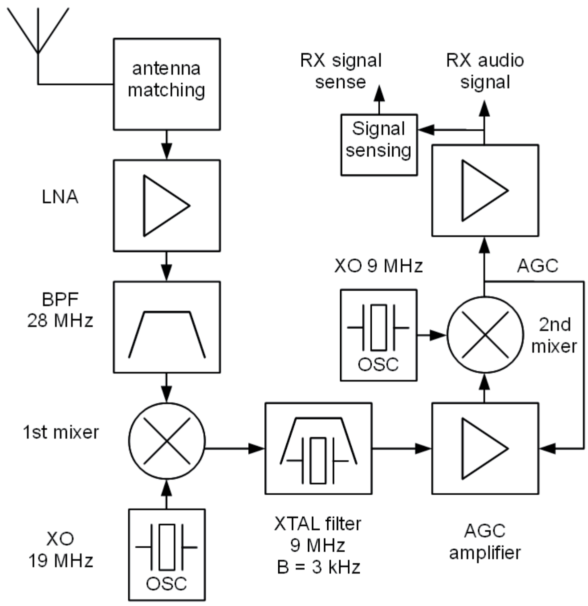


**Fig. 1.** Receiver block diagram.

The receiver includes low noise preamplifier in order to compensate electrically short receive antenna, which must be shorter than quarter of wavelength. The LNA is followed by high quality LC filter for the out of band signal suppression. Then there is the first mixer to intermediate frequency followed by a crystal filter, which defines actual bandwidth 3 kHz of monitored HF band. The intermediate frequency amplifier with the gain setting ability for automatic gain control then amplifies the received signal and it is followed by the last mixer, which converts the signals to the audio band.

The base-band signal is then splitted into three ways. The first signal is rectified and the obtained DC voltage controls the gain of the intermediate amplifier. The second signal is used to detect frequency of 31.25 Hz. This spectral component is a part of the BPSK31 signal modulation. After passing through the narrow bandwidth tone decoder, binary signal (RX signal sense) carrying information about presence of BPSK31 modulation is obtained. It is monitored by a control microprocessor of transmitter in order to recognize useful signal and switch the power amplifier on. The third signal (RX audio signal) is directly connected to the transmitter modulation input to modulate the UHF carrier.

# 3. Transmitter

The transmitter produces FM modulated signal in UHF frequency band. Output RF power of the transmitter is 27 dBm at 435.35 MHz. A BPSK modulator with data rate 31.25 bit/s on a sub-carrier with frequency 312.5 Hz is implemented in order to transmit telemetry data from built-in sensors. Block diagram of the transmitter is depicted in Fig. 2.

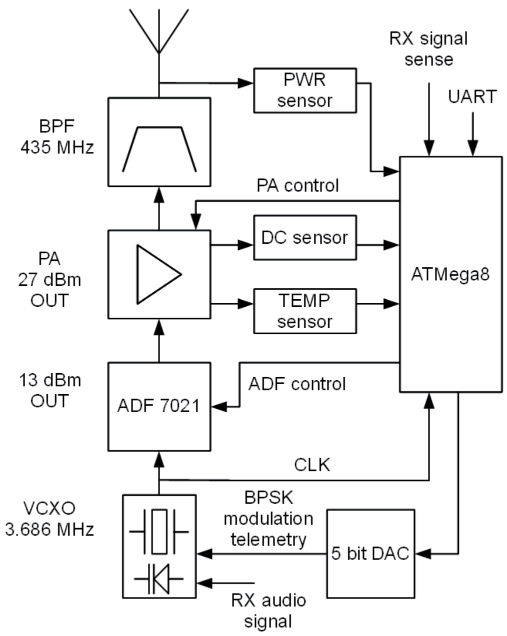


**Fig. 2.** Transmitter block diagram.

The core of the transmitter is the integrated transceiver IC produced by Analog Devices. This solution with minimum number of external components results in minimal dimensions of the PCB board. The IC quartz oscillator is directly modulated by a varicap in order to achieve FM modulation. Output power is amplified by one-stage PA with a Mitsubishi MOSFET transistor. On the board sensors are implemented which measure drain voltage, current and temperature of the PA transistor and also the output RF power. All sensors and the transceiver IC are controlled by microcontroller ATmega8. The microcontroller also drives a 5-bit parallel DA converter, which provides BPSK modulation of the telemetry data.

# 4. Prototype Board

The prototype board layout, which is made of 60 mil thick FR4 laminate, is shown in Fig. 3. As shown in Fig. 4, the board is attached to a test-bed in order to easily connect spectral analyzer and antennas. Also the ISP programming cable is soldered during firmware development and testing.

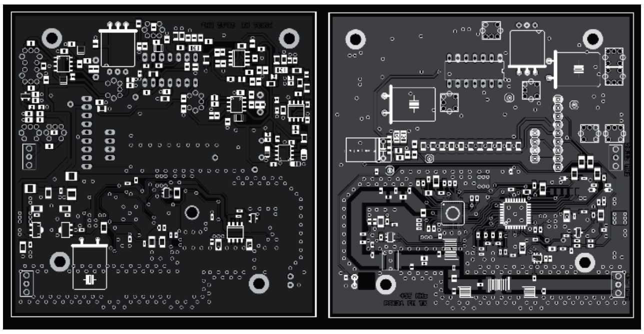

**Fig. 3.** PCB layout - top and bottom side.

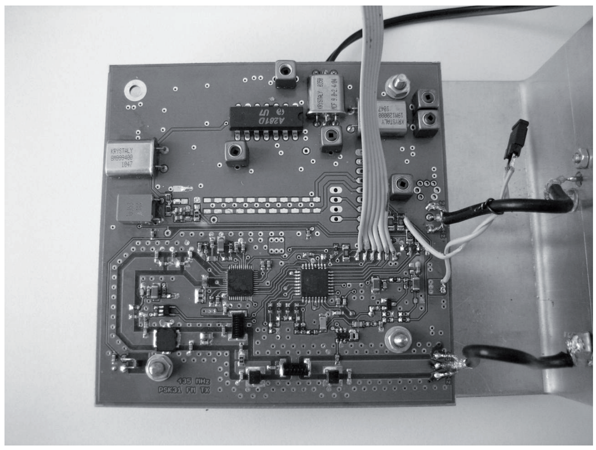

**Fig. 4.** The prototype board attached to a test-bed with connected programming cable.

## 4.1 Transmitter Measurements

Fig. 5 and Fig. 6 show wideband and narrowband output spectrum of the transmitter. The power amplifier output is filtered by a third-order bandpass filter in order to eliminate wideband noise and higher harmonics of the carrier. This is important because of other receivers which will be installed on the CubeSat in very close proximity of our transmit antenna.

Measurement has shown that the second and third harmonic suppression is better than 70 dBc. Reference spurs which are apparent approx. 160 kHz next to the carrier are at least 65 dB below the carrier level.

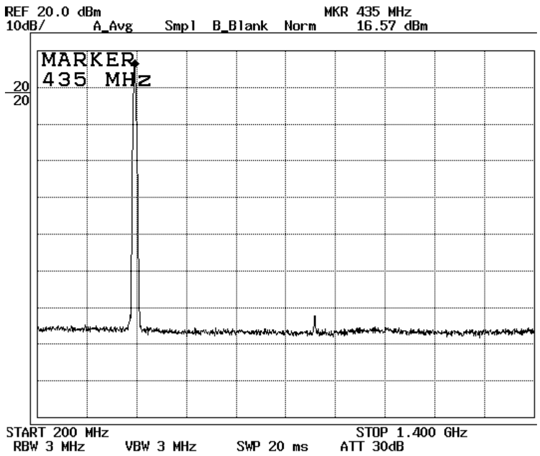


**Fig. 5.** Wideband output spectrum of the transmitter (with 10 dB attenuator).

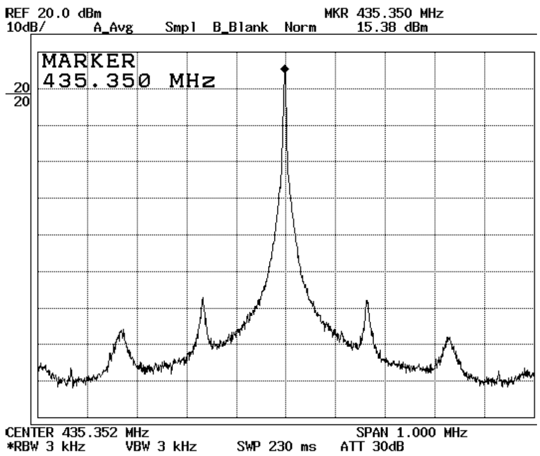


**Fig. 6.** Output spectrum of the transmitter in 1 MHz bandwidth (with 10 dB attenuator).

Fig. 7a shows measured power consumption and current of the whole device and RF power and current through PA transistor. As shown in Fig. 7b, we have calculated power added efficiency versus transmitter supply voltage. The transmitter can operate from 3.5 V up to more than 7 V, while the receiver is able to operate from 5.5 V. At maximum supply voltage 7 V, which will be available from CubeSat power system, the power amplifier is able to deliver 760 mW of RF power to 50 Ω load. This is 1.8 dB more then expected 27 dBm. Calculated power added efficiency of the power amplifier remains in the range from 44 % to 52 %.

As was written before, the transmitter can operate from approx. 3.5 V, which is minimum input voltage for the low drop 3.3 V voltage regulator, serving as a supply for the ATMega8 microcontroller and ADF7021 chip. However for a proper function of the receiver we need at least 5.5 V. Therefore full operating range of the band-monitoring device is from 5.5 V to 7 V, which corresponds to output power range 27.6 to 28.8 dBm. Of course, the output power of the transmitter can be regulated by the microcontroller, which can change ADF7021 output power.

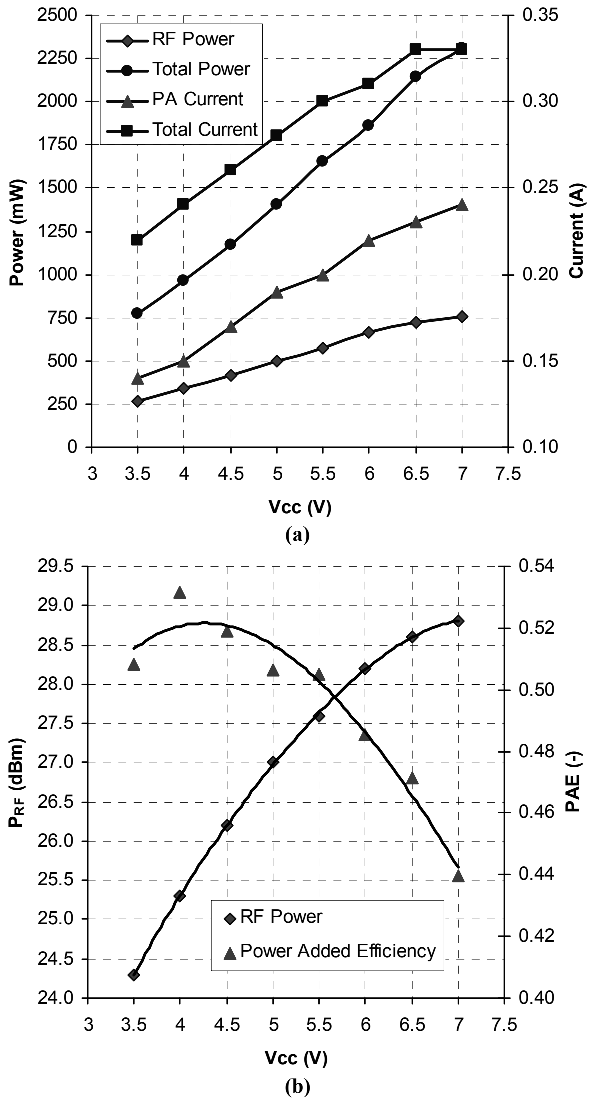


**Fig. 7.** Power and current vs. supply voltage (a). Power added efficiency and RF power vs. supply voltage (b).

## 4.2 Receiver Measurements

The receiver was tested for the dynamic range of the automatic gain control circuit. The results of the measurement are shown in Fig. 8. Approximate value of the receiver gain is estimated to be 100 dB. For the input signal level below -127 dBm, there is the output signal raising from the noise and the gain reaches its maximum value. Then, up to the input level -73 dBm, the level of the output signal is kept quite constant - in this region AGC takes control. Above -73 dBm at the input, the output signal value increases to the level where the limiter starts to limit output signal amplitude. The minimum signal which can be detected at the output corresponds to input signal level -140 dBm, therefore the receiver dynamic range is about 70 dB.

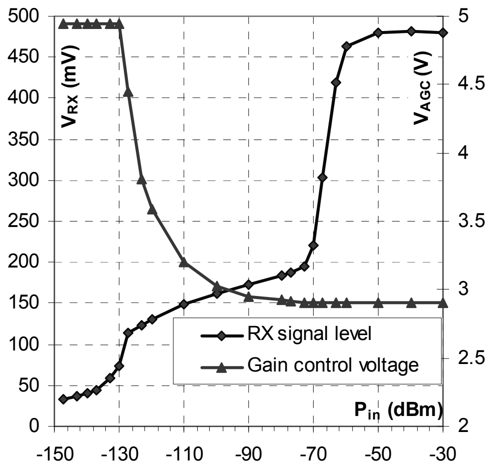


**Fig. 8.** Output signal amplitude and AGC voltage vs. input signal.

## 4.3 Receiver Antenna Measurements

Next paragraphs deal with the matching circuit for the HF receiver antenna. The task is to transform impedance of electrically short monopole to the receiver 50 Ω input. The antenna is 1.6 m long wire (which is 0.15 λ at 28.1 MHz) with 0.6 mm in diameter. The ground plane is formed only by the body of the satellite. This makes measurements of the antenna matching quite complicated. The satellite body cannot be connected with a network analyzer, SWR meter or a power supply, because these devices would create a false ground plane.

In order to find the impedance of the antenna and to synthesize the matching circuit, we have made two full-wave simulations using different solvers. The CubeSat was modeled as a conductive double-cube with dimensions 10x10x20 cm and with a wire antenna 1.6 m long. We have made simulation of the antenna impedance with the model in free space and with a ground plane 1.7 m below the model. The results are summarized in Tab. 1. The configuration with a ground plane was used in order to prepare for later experiment - to find out how much the impedance will change, if we are close to the ground. However, the simulation has shown that impact of the ground is not very significant.

| Ansoft High Frequency Structure Simulator HFSS | | |
|---|---|---|
| impedance | R (Ω) | X (Ω) |
| free space | 5.2 | -j 650 |
| ground plane | 6.0 | -j 651 |
| CST Microwave Studio | | |
| impedance | R (Ω) | X (Ω) |
| free space | 5.0 | -j 616 |
| ground plane | 7.2 | -j 650 |

**Tab. 1.** Simulated input impedance of the HF antenna.

Based on the values from the table, the matching L-network was designed as shown in Fig. 9. After that, we have performed an experiment in order to evaluate the impedance matching function. For this purpose, we have fabricated a model of a double CubeSat body, which was hung 1.7 m above ground. The tested device was placed inside this cube with a small accumulator as a power supply.

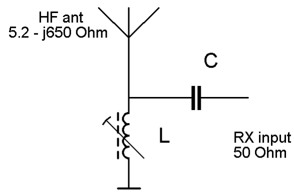


**Fig. 9.** HF antenna matching circuit (L = 2.8 uH, C = 2.7 pF).

A photograph and a block diagram of the experimental setup is shown in Fig. 10. The CubeSat model has a hole allowing us to turn with the ferrite coil core in the matching circuit. In order to monitor level of the received signal, we use one port of the microcontroller's A/D converter to measure AGC output voltage. This value is then transmitted in a telemetry channel at the downlink frequency.

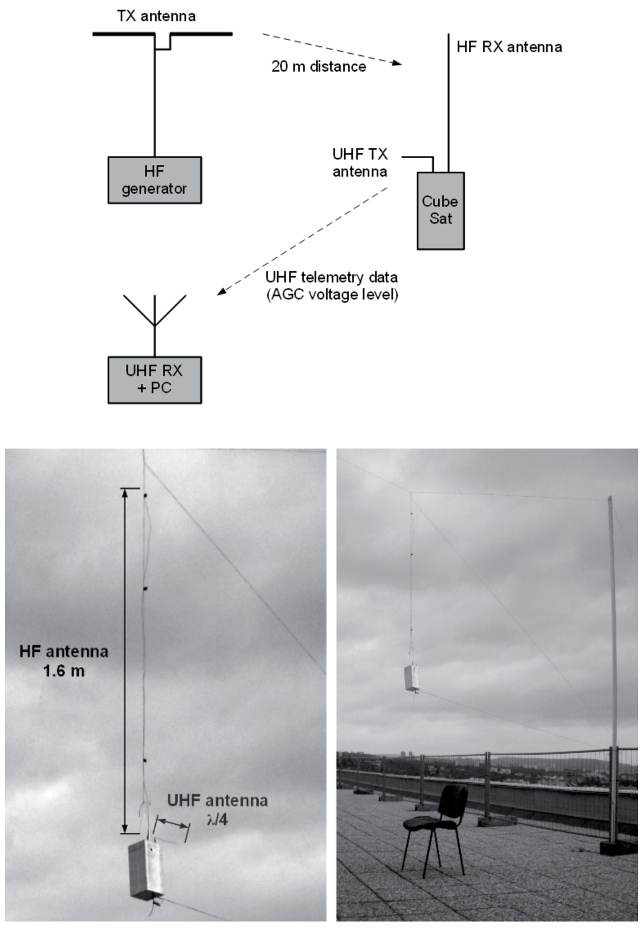


**Fig. 10.** Tests of HF antenna with a model of a double CubeSat.

Using the described experimental setup, we have measured the dependency of the AGC level on the HF generator output power. Then the TX power was set to -20 dBm in order to achieve the region of the steepest slope (see Fig. 11). In this way, from AGC level we are able to calculate the change of the signal level at the receiver input in decibels.

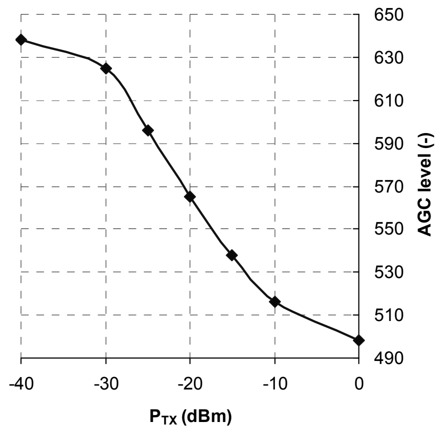


**Fig. 11.** AGC level after A/D conversion vs. generator output power.

The aim of this experiment was to find the maximal RX signal level by tuning the coil core. We started with a coil wound by 32 turns, which approximately corresponds to calculated 2.8 µH. However, the experiment has shown, that the inductance is too high. In order to find the optimal inductance we replaced the coil as shown in Fig. 12.

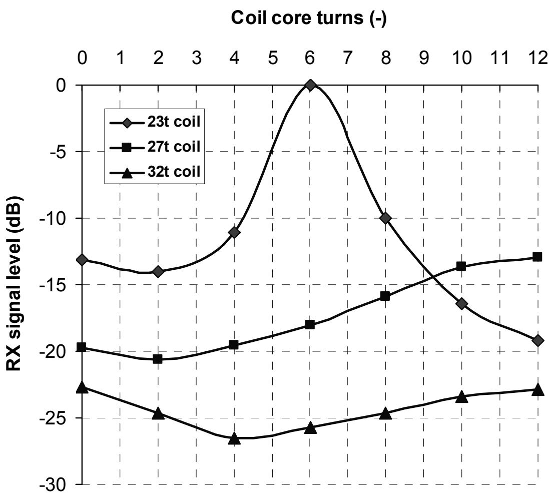


**Fig. 12.** Tuning the matching circuit of the RX antenna. RX signal level is normalized to the best result.

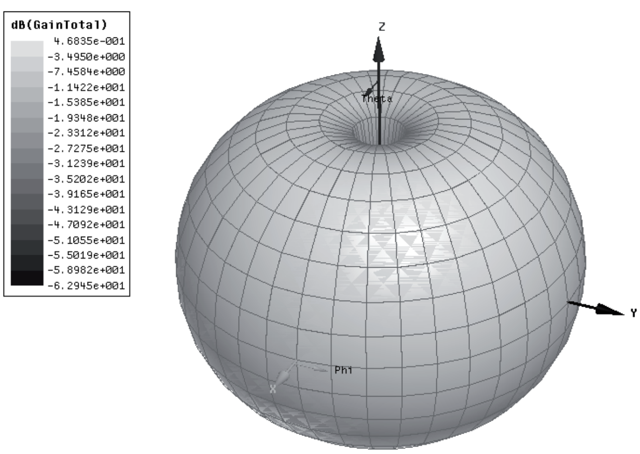


**Fig. 13.** Expected radiation pattern of the receiver antenna. Antenna is oriented in z-axis.

Finally, we have found the best impedance matching with a coil wound by 23 turns. Compared with initial conditions, RX signal level was increased by 26 dB. Measured inductance of the coil is 1.5 µH. This points to the fact, that the antenna impedance seems to be a half of the simulated value. Results of this experiment are somewhat confusing, because recently we cannot explain the difference between the simulated and experimentally measured antenna impedance.

In free space, we expect omnidirectional radiation pattern with maximal gain about 0.5 dB in direction perpendicular to the antenna (see Fig. 13).

## 4.4 Band-monitor Tests

As shown in Fig. 14, we have tested the BPSK31 telemetry modulator together with the receiver. Fig. 14 shows a part (0 to 2 kHz) of the baseband spectrum, recorded using UHF receiver and PC soundcard. There is BPSK31 modulated telemetry channel at 312.5 Hz subcarrier, which is directly synthesized by the microcontroller.

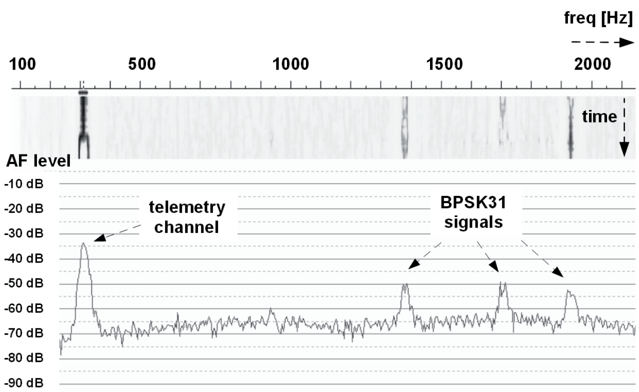


**Fig. 14.** Base-band spectrum (and spectrum in time) of demodulated signal from 0 to 2000 Hz.

There are also 3 signals received in uplink and transmitted to downlink. The upper part of the figure shows the spectrum in time.

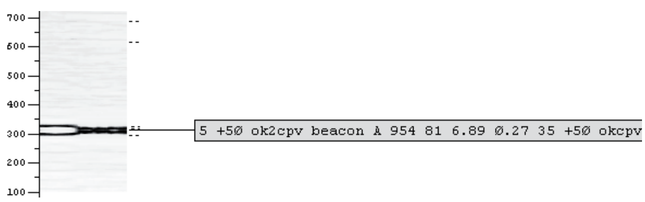


**Fig. 15.** Spectrum in time and decoded data of the telemetry channel. (Horizontal axis - time, vertical axis - frequency in Hz).

In Fig. 15, there is an example of decoded telemetry data. The format of the telemetry frame is as follows:

```
CALL beacon MODE NOF DET VC IC PWR TMP
```

where:

CALL identification of the beacon (callsign)

| | |
|---|---|
| beacon | keyword indicating beginning of data |
| MODE | A or B (A - transmitter always on, B - transmitter turns on if BPSK31 signal is present) |
| NOF | number of frame (0 ... 999) |
| DET | percentage of BPSK31 detection (%) |
| VC | supply voltage (Volts) |
| IC | power amplifier current (Amps) |
| PWR | detected output RF power (0 ... 100) |
| TMP | temperature of PA transistor (deg C) |

An example of real frame (with test callsign ok2cpv, device in mode A, frame number 33 from last restart, 0% detection of BPSK31, power supply voltage 6.93 V, current through PA transistor 240 mA, output RF power 66, PA temperature +37 deg C) is written below:

```
ok2cpv beacon A 033 00 6.93 0.24 66 +37
```

## 5. Conclusion

We have developed and tested a band-monitoring device for a CubeSat satellite. Measurement results have shown that the measured parameters satisfy the requirements. The device is fully operational from 5.5 V with 27.6 dBm output RF power and 1.65 W total power consumption, while the transmitter itself starts operation from 3.5 V with 24.3 dBm RF power. Maximal voltage in CubeSat power network is expected about 7 V, which corresponds to 28.8 dBm RF and 2.31 W total power. The dynamic range of the receiver is approximately 70 dB, while minimal detectable signal was measured -140 dBm.

The device is able to operate in automatic mode (with automatic detection of BPSK31 modulation in communication channel) or in CubeSat-controlled mode. The downlink includes independent telemetry channel with data frame format described in this paper. The aim of future work will be integration of the device into the CubeSat.

## Acknowledgements

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement no. 230126. This work has been supported by the research grant GACR (Grant Agency of Czech Republic) No. P102/10/1853 "Advanced Microwave Components for Satellite Communication Systems". Support of the project CZ.1.07/2.3.00/20.0007 WICOMT, financed from the operational program Education for Competitiveness, is gratefully acknowledged.

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**Miroslav KASAL** (born in 1947 in Litomyšl, Czech Republic) graduated in Communication Engineering from the Faculty of Electrical Engineering, Brno University of Technology, in 1970. In 1984 he obtained his PhD degree in metering engineering. He was the head of the NMR Department and Electronics Laboratory of the Institute of Scientific Instruments, Academy of Science of the Czech Republic (1991 – 2002). Since 2002 he has been with the Department of Radio Engineering, Faculty of Electrical Engineering and Communication, Brno University of Technology, as professor. Dr. Kasal is a senior member of the IEEE. He has authored or coauthored a number of papers in scientific journals and conference proceedings.