Low-Cost SDR-Based Ground Receiving Station for LEO Satellite Operations

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Abstract – **This paper outlines the feasibility of using Software-Defined Radio (SDR) technology for space applications by developing and setup of a low-cost VHF/UHF ground receiving station in order to support existing and future university missions. The proposed solution is based on the integration of commercial off-the-shelf components available on the market. The paper will present some of the hardware and software related issues regarding the implementation of an educational ground station for operation with Low-Earth Orbit satellites.**

Keywords – **Station, low-cost, Cubesat, SDR, educational.**

I. INTRODUCTION

In the last several years, there has been an increased interest among academic environments in developing nanosatellites, called Cubesat [1]. These small satellites have a 10 cm cubic configuration and a mass of no more than 1 kg. Therefore, there is very little room to put highly sophisticated communication equipment. In practice, the majority of currently active university satellites are placed in Low-Earth Orbits (LEO) and operate on those sections of the VHF/UHF bands, which are allocated to the amateur satellite service. In most situations, the telemetry and scientific data is transmitted using standard analogue or digital modulation schemes at low data rates [2].

Regardless of the space mission types, one essential component represents the ground segment. The ground segment is of primary importance for mission success and represents the first and final piece in the communication link. It is responsible for tracking and communication with the LEO satellite in order to retrieve telemetry and experimental data or to transmit commands.

These days, the concept of ground segment is evolving. Traditional ground stations lack the flexibility and are tightened by the specifications of the hardware equipment. New approaches involve using Software-Defined Radio communication technologies as an alternative for the traditional radio hardware [3]. In most cases, this design implies using a broadband antenna (or different antennas for each desired bands), some analog front-end modules (amplification, filtering, down conversion), an analog-to-digital converter and a powerful processing unit. After sampling, the digital processing software takes care of acquisition and decoding the radio signals.

Usually, the effective implementation of a high-performance SDR ground station is based on commercial DSP and FPGA hardware, which are complemented by highly sophisticated software platforms for data processing [4,5]. These solutions tend to be very expensive and this represents probably the most important disadvantage. Taking into consideration the educational purposes and budget limitations of this project, a solution in developing this ground station might be integrating commercial SDR hardware with good cost-performance ratio. Fortunately, there is a wide range of solutions available that satisfies these criteria [6]. Consequently, reliable and low-cost SDR-based ground receiving stations can be designed and setup using commercial off-the-shelf (COTS) amateur radio hardware and software. This paper will present such an approach, will outline some of the most important aspects and explain some of the operational characteristics of the station.

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II. GROUND RECEIVING STATION OVERVIEW

The main objective was to design and implement a SDR-based ground receiving station that satisfies the multi-mission and multi-channel (VHF and UHF bands) requirements in a resource-efficient manner. In addition, it is worth mentioning that the current station will represent the Technical University of Cluj-Napoca (TUCN) contribution for the GENSO (Global Educational Network for Satellite Operations) network [7]. The GENSO educational project intends to develop a worldwide network of individual amateur radio and university stations, via a secure Internet communication standard, in order to increase of mission data return. The preliminary hardware standards defined by GENSO represented other critical requirements in designing the ground station [8].

A. Hardware Description

Fig. 1 depicts the architecture of the SDR-based ground station that satisfies the above-mentioned requirements.

The station has a modular architecture in order to meet different space applications, which may extend outside the scope of GENSO project. The components were chosen based on their hardware performance and popularity among amateur radio community. The indoor and outdoor hardware equipment integrated within the station are depicted in Fig. 2.

The installation on the rooftop comprises of two high-gain Yagi X-Quad [9] antennas for satellite reception in VHF/UHF frequency bands. For the VHF/UHF bands, the antennas are

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characterized by a gain of 13 dBi / 15 dBi, while the associated -3dB beamwidth has a value of 47º / 36° for both H/V planes. Both the antennas are stacked on top of a mast and configured in circular polarized mode (RHCP).

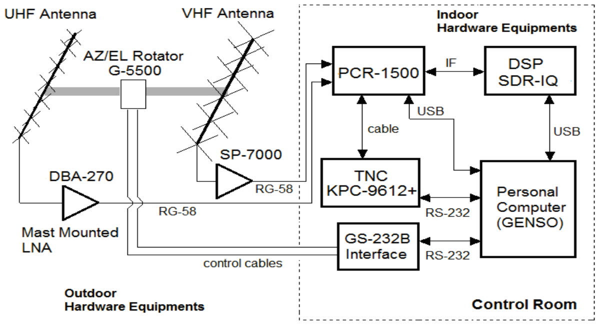

Fig. 1. Basic block diagram architecture

Fig. 2. Overview of the VHF/UHF SDR-based ground station

LNAs work by reducing the noise figure of the reception system, consequently improving the signal-to-noise ratio of the weak radio signals received from LEO satellites. Because the major factor in the noise figure represents cabling losses, the low-noise amplifiers are installed on the mast, near the antennas. For the VHF band, the DBA-270 LNA [10] provides a gain of 20 dB for a noise figure of 1.3 dB, while for the UHF band the selected SP-7000 LNA [11] provides a gain of 20 dB with a noise figure of 0.9 dB.

The Yagi antennas are oriented towards the LEO satellites using a full-azimuth and elevation rotator system. The Yaesu G-5500 is a high-performance rotator that features a turning range of 450º (360º + extra 90º) in the azimuth plane and a 180º travel for the elevation plane [12]. The built-in features of the controller allow manual or automatic operation of the rotators. The G-5500 is remote controlled through the GS-232B digital control interface [13]. This interface is based on a PIC18C412 microprocessor and features a 10-bit analog to digital converter, which provides a resolution of 0.43º/0.17º for the azimuth/elevation planes.

The selected SR (Software Receiver) offers radio coverage in the frequency domain of 10 kHz – 3.3 GHz (extension to S-band capability is foreseen, but presently not yet implemented). The IC-PCR1500 [14] is a wideband receiver with built-in DSP capabilities and typical demodulation schemes (AM, FM, SSB, CW). In addition, the unit has a data port that allows digital packet communication at data speeds higher than 9600 bps. Other important features represent the multi-channel monitor and band scope/time-line function that allows automatic monitoring and recording of multiple radio signals. The receiver is PC software controllable using proprietary and amateur radio software applications available on the Internet.

For digital satellite reception in the VHF/UHF bands, the ground station is equipped with TNC (terminal node controller) hardware. The KPC-9612+ is a versatile multi-port, multi-speed radio modem capable of 1200 / 9600 baud packet communication with different modulation schemes using the AX.25 protocol [15].

SDR-IQ [16] is a high-performance software-defined radio that operates in the frequency range of 500 Hz – 30 MHz and uses direct 14-bit AD conversion with a sample rate of 66.6 MHz. These features allow a very high-resolution bandwidth down to 0.75 Hz, providing a maximum display bandwidth of 190 kHz for real-time monitoring of the radio spectrum. This USB spectrum analyser is also PC software controllable using proprietary and open-source software applications.

The presented approach involves using the SDR-IQ receiver as a panoramic adaptor (pandapter). This extends the band frequencies above and below the centre frequency to which the PCR-1500 receiver is tuned, taking in the same time of the advantages of the receiver's internal RF front-end. The interconnection between the hardware equipment is possible by extracting the 10.7 MHz IF output from the main unit of the IC-PCR1500. According with the receiver's service specifications [17], the 10.7 MHz IF tap point is located in the second IF circuit. The tap point was chosen after the second IF amplifier but before the second IF filters. DC blocking was made using a 1nF capacitor, in order to prevent damaging the RF input of the SDR radio.

When dealing with LEO satellites, one important aspect is the Doppler Effect. The Doppler shift [18] represents the change in frequency caused by the motion of the satellite relative to a fixed position on Earth. Table I presents the maximum Doppler shift for various frequency bands used for LEO satellite operation. As observed in Table I, the Doppler shift is increasing with frequency.

TABLE I
MAXIMUM DOPPLER SHIFT FOR DIFFERENT BANDS

Frequency	Amateur Band	Doppler
145.900 MHz	2 m	±3.27 kHz
435.070 MHz	70 cm	±9.76 kHz
1269 MHz	23 cm	±28.5 kHz
2400 MHz	13 cm	±53.8 kHz

In addition, the Doppler shift varies in a non-linear way and it is highly dependent on the pass itself. For high-elevation passes, the frequency shift variation is high at the time of closest approach (in the middle of the pass) and has a near linear variation for low elevation passes.

In traditional VHF/UHF ground stations, the Doppler shift would significantly influence the reception performance regardless of the operation mode (CW/SSB and FM); therefore, it must be compensated. This is possible using manual or automatic tuning of the downlink operating frequency. By using a SDR-based approach, the Doppler Effect problem is overcome. This is very useful for downlink operation, increasing the probability of successful radio contacts. Moreover, the Doppler shift can be exactly determined, not estimated by orbit prediction software.

B. Software Description

The station operates using two independently software modules; one module dedicated for amateur radio satellite service, the other one dedicated for operation within GENSO network. Fig. 3 presents a basic diagram with the currently integrated software modules and associated features.

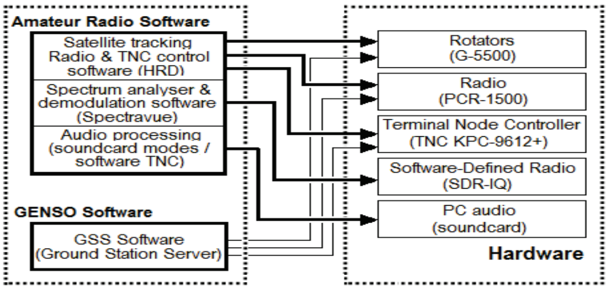

Fig. 3. Basic software modules and features

Communications with the LEO satellites rely heavily on the tracking software. The tracking software in conjunction with the selected hardware represents the core of ground station operations. Based on the orbital elements (TLE), accurate time reference and GPS coordinates, the tracking software makes real-time predictions of the trajectory of LEO satellites at any given moment. During operation, the HRD (Ham Radio Deluxe) software will automatically steer the Yagi antennas towards the selected satellite and if desired, will automatically make Doppler corrections of the downlink operating frequency. In addition, the HRD software allows full control of the existing TNC hardware within the station.

Using FFT spectral analysis software tools like SpectraVue, will allow real-time / offline processing of the entire 190 kHz of RF spectrum provided by the SDR-IQ unit and centred on the receiver operating frequency. The software has extended demodulation capabilities required for satellite reception. For other digital modulation schemes not covered by the TNC unit, the solution involves using soundcard-based software [19] in conjunction with the SDR-IQ software (software TNC). The transfer of audio streams between different applications can be done using the built-in mixer feature of the PC soundcard (if available). Other solutions involves using dedicated audio routing software, in order to create a set of virtual audio devices; each of them consisting of a pair of waveform Input / Output devices (or applications).

Access to the GENSO network will be possible using the GSS (Ground Station Server) software. This open-source Java-based software provides drivers to interface with common amateur radio equipment. Currently, most of the selected hardware is supported by software. The GSS application will perform GENSO-specific functions within the network.

III. Implementation Costs

Having low-budget constraints from the TUCN administration, the ground station was developed with the main goal of designing a low-cost SDR-based concept, which in the same time to perform critical functions as: satellite tracking, receiving and decoding in various modulation schemes and communication protocols. In order to keep the implementation costs at minimum, the ground station was built by integrating commercial off-the-shelf hardware available on the market. The use of open-source and freeware software further reduced costs, making them ideal for academic environments. In terms of expenditures, Table II clearly shows a rough estimation of the hardware and software components used in the development of the TUCN station.

TABLE II
EQUIPMENT COST BREAKDOWN

Items	Price (€)
VHF/UHF band antennas	250
Rotators	1100
Preamplifiers	500
TNC unit	400
Receiver unit	750
SDR unit	550
Digital interfaces	600
Feed lines, connectors and expendables	500
TOTAL	4650

It clearly shows that a low-cost prototype SDR-based station could be built at affordable prices for universities (≈ 5000 Euro). Moreover, this paper intends to recommend this method already successfully demonstrated and would offer assistance to those technical universities who would like to develop their own SDR-based ground receiving station for education and research.

IV. Experimental Results

In order to prove the technical feasibility of this SDR-based ground receiving station, experimental tests were conducted especially in the VHF/UHF bands with active university Cubesats and OSCAR (Orbiting Satellites Carrying Amateur Radio) microsatellites. The station is capable of real-time tracking, receiving and decoding telemetry data in various modulation and data formats. Other experiments involved post-processing of the captured RF spectrum in order to characterize in-orbit satellites within the radio range of the station. As for exemplification, Fig. 4 illustrates a sample of RF spectrum associated with the MASAT-1 university satellite. It presents the evolution in time of the received signal during the high-elevation (59°) portion of the pass. The data was collected during 15 minutes of radio contact (13:05 – 13:20 UTC) in March 25th, 2013. As it can be observed, the MASAT-1 satellite transmits its telemetry using analog (CW) and digital (2-GFSK) modulation on a frequency of 437.345 MHz, according to a pre-programmed schedule. In addition, Fig. 4 illustrates a section of the S-shaped Doppler curve associated for that pass (characterized by the A-B-C points). Doppler shift variations can be measured at any given time; consequently, can be determined the precise moment of closest approach, which is 13: 13 UTC (marked with point B).

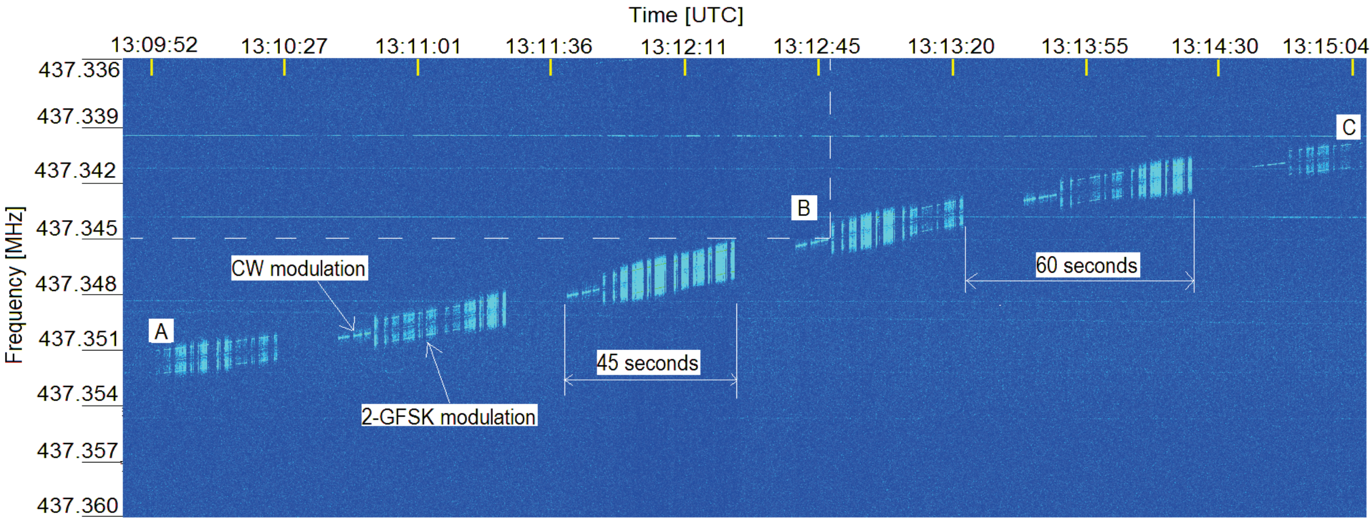

Fig. 4. Sample spectrum of MASAT-1 satellite received in 25th of March, 2013 (Orbit #5767)

V. Conclusions

With the selected equipment, this educational SDR-based ground station prototype is capable of establishing satellite communications and receiving data from satellites operating in the VHF and UHF amateur radio bands employing either analog or digital modulation techniques. The station is ideal for academic environments and it will serve as a teaching and learning tool for TUCN engineering students.

The main advantage offered by this approach is its low-cost implementation offering from a certain point of view, similar capabilities with other university ground stations. Its modular architecture, offers the possibility of integrating new S-band communication with minimum costs.

Its low-cost implementation represents also its major vulnerability. Compared with other SDR-based ground stations mentioned in this article, this current approach has some technical and performance limitations and doesn't fully satisfies the requirements of a high-performance SDR-based station capable of simultaneously operating in multiple frequency bands and supporting multiple missions. Moreover, the lack of a dedicated high-powerful software platform for processing the incoming RF data, limits its flexibility in a certain way (complex demodulation schemes not supported).

Finally, it should be emphasized that using high-quality SDR hardware platforms it would lead to a better receiver system consequently, improving the overall performance of the station.

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