A design and installation of a low-cost SDR-based VHF/UHF ground receiving station for satellites

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Abstract. This paper summarizes the use of Software Defined Radio (SDR) technology for space applications by installing a low-cost VHF/UHF ground receiving station to assist existing and future space mission universities. The intended solution is based upon the utilization of RTL-SDR, which are commercial off-the-shelf components available on the market.

1 Introduction

With the advances in technologies, it became possible to explore outer space. This enabled humans to learn more about the Earth and how the solar system function, but also became a field where technological and economic competition takes place.

The exploration and use of space resources is the ultimate human quest. Organizations around the world aim to develop low-cost space missions that could pave the way to a wide array of new opportunities for space exploration.

Regardless of the space mission type, the ground segment is an essential component. It provides access to the space segment and control communications with the aim to assure satellite transmission and reception. Ground segment is of critical importance for the accomplishment of a space mission.

The concept of the ground segment is constantly expanding today. Traditional ground stations are expensive and limited by the choice of the hardware. Brand-new procedures imply implementing SDR software-defined radio technologies to create a more flexible system.

2 Space system

A space system refers to the set of space components, vehicles and technical infrastructure, which through their interactions perform a task in the space environment and ensure the efficient use of satellites. [1]

A space system consists of three elements: the space segment, which includes the spacecraft, the ground segment, which provides continuous monitoring and control of the spacecraft, and the launch vehicle, which is responsible for transporting the spacecraft. [1] [2]

2.1 Launch vehicle

Launches or launch vehicles are used to carry satellites to space. They impose mechanical constrains on the structure of the satellite, given the conditions imposed on the mass and the volume available under the fairing.

2.2 Space segment

A spacecraft includes two parts: the payload and the spacecraft bus.

The payload represents all the elements of the spacecraft that are dedicated to produce mission data and relay that data back to Earth.

The spacecraft bus provides satellite control and supports assistance to the mission payload. [1] [3]

2.3 Ground segment

The ground segment involves both the transmitting and receiving telemetry from the satellite. It interconnects users with each other and with the terrestrial system. [1] [3]

3 Design of the ground station

3.1 Ground station

Ground stations are surface-based installations designed to provide real-time communication with satellites. Among their main functions:

- Telemetry: Receiving from the satellite results of measurements, information concerning satellite operation and verification of the execution of commands.
- Command: Transmitting control signals to the satellite to change the state or mode of operation of equipment.
- Tracking: Providing the measurement of satellite position and monitor the load on the on-board computer.
- Data processing: Providing scientific and technical data depending on the type of the mission. [2]

The existing architecture of a ground station resolves mainly around its application. However, a generalized one includes the RF section, the baseband equipment and the terrestrial interface. Furthermore, all ground stations have some support facilities like monitoring and control equipment, thermal and environment conditioning unit, etc.

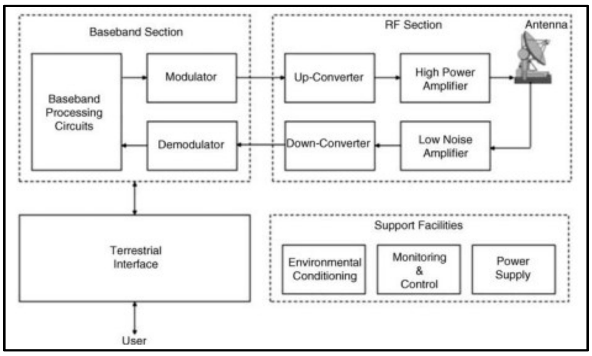

Fig. 1. Block schematic arrangement of a generalized Earth station.

The RF section consists of the antenna subsystem, the block up-converter (BUC) and the high-power amplifier (HPA) in the uplink channel and the antenna subsystem, the low noise amplifier (LNA) and the digital down-converter (DDC) in the downlink channel.

Equipment redundancy can be used in the RF section in order to ensure system reliability and continuity of service. The up-converter in the up-link channel converts the low baseband frequency signal to a higher frequency. Figure 2 shows the schematic diagram of up-converters. [4]

The HPA amplifies the up-converted signal to the desired level in order to have a satisfactory uplink performance.

Likewise, the LNA amplifies low-power signals that the antenna is receiving and minimizes additional noise. It is an element of great importance in the downlink path. A typical LNA may supply a power gain of 20 dB.

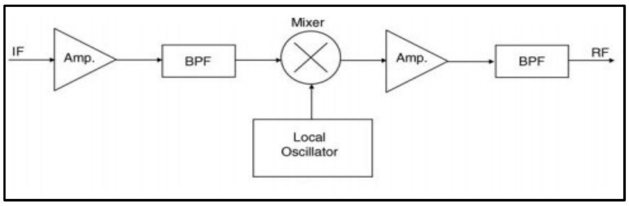

Fig. 2. Schematic diagrams of up-converters.

The amplified RF signal is then converted by the DDC to the intermediate frequency level before being fed to the modem in the baseband section. Figure 3 shows the schematic diagram of down-converters. [4]

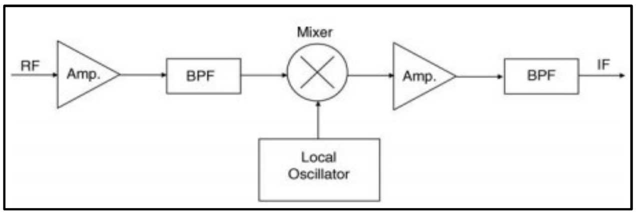

Fig. 3. Schematic diagrams of down-converters.

The baseband section assures modulation and demodulation. The basic blocks of this section are mainly baseband processing circuits, modulators / demodulators (modem) and multiplexers / demultiplexers.

The baseband section is linked to the terrestrial network via the terrestrial interface. It connects the Earth station to users. The complexity of every terrestrial interface rests on the services provided by every ground station. [4] [5]

3.2 Software Defined Radio (SDR)

An SDR system is a radio communication system that utilizes software to modulate and demodulate radio signals. This concept allows a high degree of flexibility in hardware components. Software-defined radio aims to replace traditional radio hardware such as mixers, modulators, demodulators and associated analog circuits that cannot easily be re-configured. SDR offers software-configurability and control, improves system performance and reduces system size. [6]

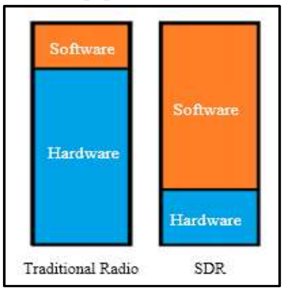

Fig. 4. Traditional Radio and SDR.

SDR receiver uses an RF tuner to down-convert the analog signal IF.

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The signal is then sampled and digitized using an ADC (Analog to Digital Converter). The samples are fed to the DDC (Digital Down Converter). It is the preliminary element of the SDR system. It includes three central elements: a digital mixer, a digital local oscillator and a Finite Impulse Response (FIR) low-pass filter.

The digital mixer and the local oscillator change the IF digital samples to baseband, while the FIR low-pass filter limits the final signal bandwidth.

Finally, the digital signal processor DSP (Digital Signal Processor) performs demodulation, decoding and associated tasks. Figure 5 shows the block diagram of an SDR receiver.

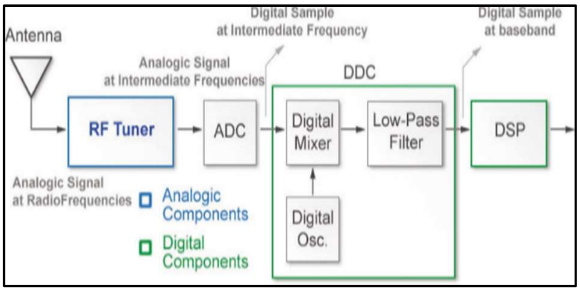

Fig. 5. Block Diagram of the SDR Receiver.

Among the most widely used SDR receivers the RTL-SDR. It is a low priced, simple to use USB device that receives RF signals. Originally, these devices were designed to be Digital Video Broadcast-Terrestrial (DVB-T) receivers, however, and thanks to a number of engineers and developers, they are now used as SDRs. They are then able to receive any signal in the range their tuner operates over. This range varies from a device to another depending on the elements used, but is most often from 25 MHz to 1.75 GHz. [6] [7]

3.3 Design of the ground station

After doing some research, we decided to use the RTL-SDR V3, which is an upgraded RTL-SDR dongle. It is a very affordable dongle and is considered a great option for a first approach to the technology. It operates in the VHF and UHF bands, and is well known in the amateur radio world. It has the following characteristics:

- Bandwidth: Up to 2.4 MHz stable.
- ADC: RTL2832U 8-bits.
- Frequency Range: 500 kHz – 1766 MHz (500 kHz – 24 MHz in direct sampling mode).
- Typical Input Impedance: 50 Ω.
- Typical Current Draw: 270 – 280 mA.

The RTL-SDR V3 rests on the RTL2832/ R820T2 combination. The RTL2832U down-converts from IF to baseband, digitizes the signal and reduces the sampling rate. The R820T2 is the tuner chip which down-converts a band of RF signal to an IF frequency.

Fig. 6. RTL-SDR V3.

RTL-SDR V3 is coming with SMA connector, which is most frequently used, hence the possibility of using several more efficient antennas, adapted to the intended operating bands.

After purchasing the RTL-SDR V3, we inserted it into the computer's USB port and proceeded to install it by downloading the SDRSharp software from Airspy. SDRSharp is an approved free software defined radio program available with RTL-SDR support.

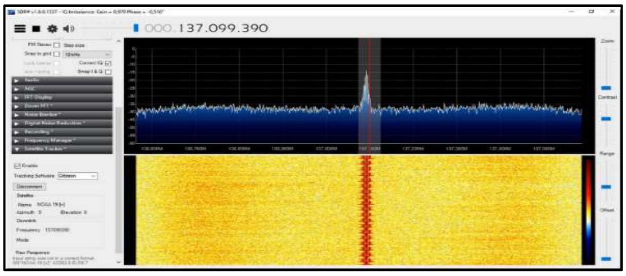

Fig. 7. SDRSharp software.

4 Results

After purchasing the RTL-SDR V3, we wanted to test it to check that it works properly after installation and configuration. To do so, we used an indoor TV antenna as showed in figure 8. It is a magnetic-based, omnidirectional antenna capable of receiving VHF (170-230 MHz) and UHF (470-869 MHz) frequencies. Figure 9 illustrates the preliminary ground station for testing the SDR dongle.

Fig. 8. Indoor TV antenna.

Using this station, we have managed to test a variety of applications, which we will present in the following paragraphs.

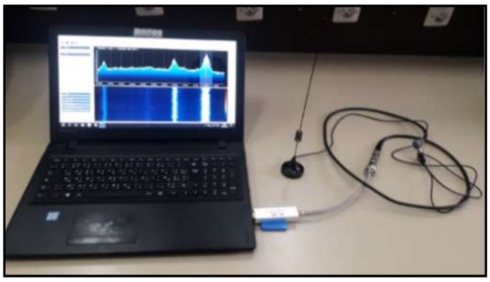

Fig. 9. Preliminary ground station.

4.1 Listening to FM Radio

We started by listening to every-day FM radio. To do so, we first launched SDRSharp and selected WFM (Wide Frequency Modulation). We then set a FM station frequency. We managed to listen to all FM stations picked up in Marrakech. Figure 10 illustrates listening to MEDI 1, which broadcasts at a frequency of 105.3 MHz.

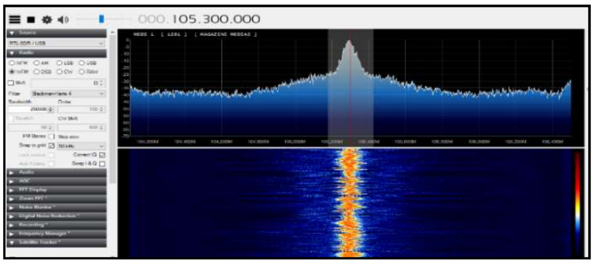

Fig. 10. Listening to FM radio using RTL-SDR V3. (MEDI1)

4.2 Listening to ATIS

We were also able to pick up and listen to the ATIS (Automatic Terminal Information Service). It is a continuous message on a loop that provides general information about the airport, runway conditions and weather. This information is broadcast on 121.950 MHz in Marrakech.

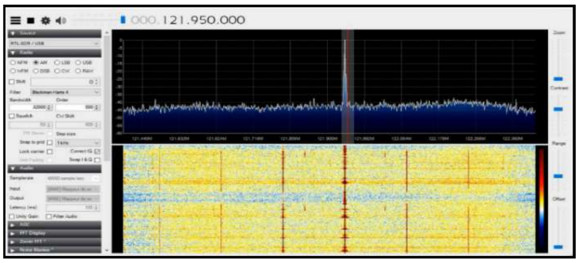

Fig. 11. Listening to ATIS using RTL-SDR V3

4.3 Receiving ADS-B signals

Modern planes use an Automatic Dependent Surveillance-Broadcast (ADS-B) Mode-S transponder, which periodically transmits precise location of the aircraft position. ADS-B operates as a UHF signal at 1090 MHz. Ground stations and other aircrafts can receive this signal.

Using RTL-SDR, it is possible to listen to ADS-B signals. The preliminary ground station allowed us to track aircrafts in flight without needing a much expensive radar.

For ADS-B decoding, we used dump1090. It is a popular command line ADS-B mode S decoder, commonly used with RTL-SDR devices. It allows robust decoding of weak messages on 1090 MHz and gives access to multiple information such as altitude, speed and aircraft position. We connected this software to Virtual Radar Server (VRS), which is a visual display of the received and decoded aircraft data. VRS will collect data from dump1090 and generate a map where all the aircraft found by dump1090 are shown in real time. Figures 12 and 13 illustrate an example where we were able to detect two aircrafts in flight over Marrakech on March 14, 2021 at 08h34min.

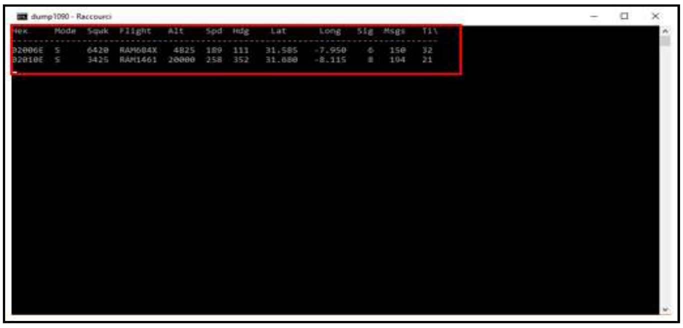

Fig. 12. ADS-B decoding using dump1090.

4.4 Receiving satellite telemetry

After testing the RTL-SDR V3 dongle, we have concluded that it can be used in a variety of applications to receive radio signals at ground level or on aircraft.

The SDR dongle allowed us, in addition to the applications mentioned above, to receive signals from satellites in low orbit. For that, we used the Quadrifilar Helix Antenna (QHA). It consists of two bifilar helical loops oriented in mutual orthogonal relationship on a common axis. The terminals of each loop are fed in antiphase and the currents in the two loops are in phase quadrature. QHA is a right hand circular polarized omnidirectional antenna

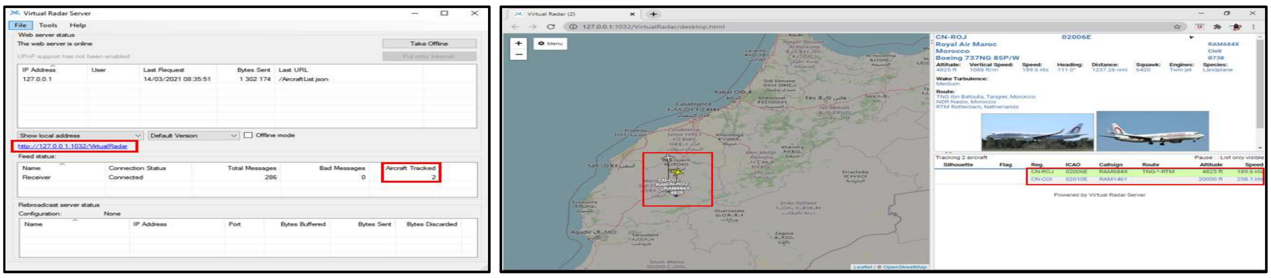

Fig.13. Displaying data on a map using VRS.

that allows optimal reception from the horizon to the zenith and vice versa.

Table 1 shows the specifications of this antenna. [8]

Table 1. QHA characteristics.

Frequency	137 MHz
Gain	5 dBi
Bandwidth	5 MHz
Polarization	Right hand circular
Input impedance	50 Ohms
TOS	≤1.5

Since the cost of this antenna can go up to 300€ and since it is not available on the local market, we decided to build it ourselves using a PVC pipe, a copper tube and a coaxial cable. After building the antenna, we measured its input reflection coefficient S_{11} using the network analyzer available at the Hyper-Frequency laboratory of the Royal Air Academy.

The measurements showed that from 120 MHz to 140 MHz, S_{11} is far below 0 dB. It can be concluded that the QHA is an UWB (Ultra-Wide Band) antenna for VHF frequencies.

Fig. 12. Designed QHA.

We used a software called Orbitron to track the satellites and predict their passage over Marrakech. During the first tests, the signals received were of very low power and very noisy. Therefore, we decided to add an LNA (Low Noise Amplifier) to the antenna output in order to amplify the signals. We chose an open area, far from obstacles, to place the station to minimize the losses. Figure 15 illustrates the satellite telemetry receiving ground station.

Fig. 13. Telemetry receiving ground station.

We were able to receive the International Space Station (ISS). It is a large spacecraft in orbit around Earth where crews of astronauts and cosmonauts live. It travels at 28.000 km/h and orbits Earth at an average altitude of about 400 km. The ISS transmits signals at 145.825 Mhz. Using Orbitron to predict the ISS passes and SDRSharp, we were able to pick up a signal at this frequency. Figures 16 and 17 respectively represent the ISS passing over our position on May 13, 2021 at 8:00 PM and the signal received by our ground station.

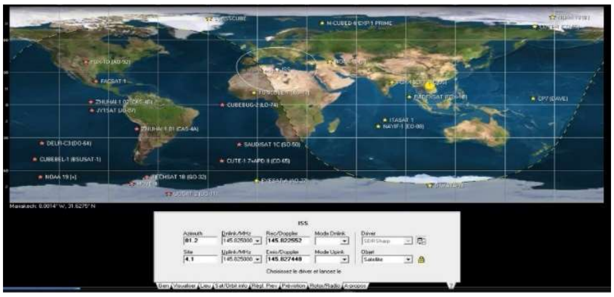

Fig. 14. ISS pass on May 13 at 8 PM.

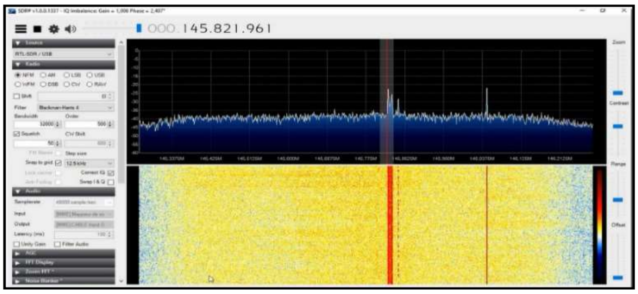

Fig. 15. ISS signal.

We were also able to pick up the signal from ZHUHAI-1 01, also called CAS-4A. It is a Chinese microsatellite developed by the Zhuhai Orbita Control Engineering Company. It is part of the Chinese Earth observation satellites. It transmits signals at 145.880 Mhz. We were able to pick up a signal using SDRSharp on May 13, 2021 at 08:04 PM.

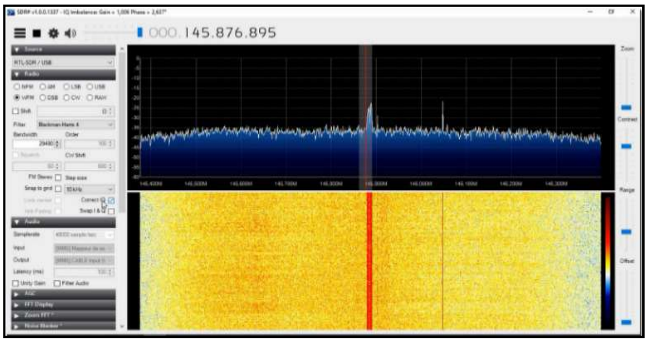

Fig. 16. ZHUHAI-1 01 signal.

5 Conclusion

With the selected equipment, this ground station prototype based on SDR technology is capable of receiving VHF and UHF radios and establishing satellite communications. The station is perfect for academic environments.

The SDR technology allowed us to use the same hardware platform for several applications. We were able to change performance by only updating the software. This offered us a dynamic configuration and great flexibility compared to traditional restrictive systems.

The prime asset provided by this approach is its low-priced implementation, providing the same capacities with other university ground stations.

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