DESIGN AND IMPLEMENTATION OF A FULL-DUPLEX GROUND STATION FOR THE QO-100 SATELLITE SYSTEM BASED ON SDR AND RASPBERRY PI

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Abstract: **This paper proposes an approach based on the Adalm-Pluto SDR and Raspberry PI to design a ground station for geostationary satellite communications. The system is designed from modules to be versatile, agile, and scalable. In this case, the usage of modules is mandatory due to the complexity of the communications system, which simultaneously operates two radio channels at 2.4 GHz for uplink and 10 GHz for downlink. Such a combination with SDR (Software Defined Radio) and classic down and up converters benefits from using a Raspberry PI 4 with a powerful processor running under Linux. The proposed system allows the usage of GNU Radio with its powerful graphical interface written in Python. User interface UI has been undertaken by the Raspberry PI's most versatile display with a touch screen of 7 inches. Another topic the paper addresses is using the helical antenna in front of the Horn antenna at the same focus point established by the dish reflector. The ground station proposed here has been successfully tested to transmit short radio packages containing data about temperature, atmospheric conditions, and voice.**

Keywords: *Software-defined radio, QO-100, Geostationary orbit (GEO), Right-handed circularly polarized (RHCP).*

I. INTRODUCTION

A geostationary orbit, or geosynchronous equatorial orbit (GEO), is a circular geosynchronous trajectory around Earth, about 35.786 km from the ground above the equator [1]. A satellite that rotates in the same direction as the earth's rotation appears motionless from our perspective on the earth's surface. Having a relatively fixed position above the sky, an antenna system doesn't need any tracking device. Once the antenna system points toward a GEO satellite, the ground antenna does not have to rotate or adjust the direction of its radiation beam. The impairment of the GEO satellite systems is the significant distance between the earth and the satellite's transponder. If the transponder is a repeater, its stages change the received frequency and retransmit the signal using another frequency. This approach reduces the path the electromagnetic wave is forced to undergo from Earth to Earth via satellite by half. Nevertheless, the transmitter and the receiver must mitigate the huge attenuation along the uplink or downlink in both directions. Considering the cost and size minimization at the ground station side, a lower frequency is allocated for the uplink. The attenuation is generally lower at low frequencies, and the fees are also low. The first geostationary satellite with an amateur radio transponder is Es'hail 2, launched from Kenedy Space Center in 2018 [2]. The satellite transponder allows operators with a ham radio license to use and do experiments following some rules under the restriction of the satellite radio band plan. Two transponders operate at 2400 MHz and 10450 MHz; the first is a narrowband linear, and the second is a wideband digital transponder. The operator uses 2.4 GHz for the uplink and 10 GHz for the downlink. In this way, the demands are kept low because the ground station can reuse the LNBs that are operational in the broadcast television system via satellites. The transmitter side at the ground station can deal with lower frequencies in this case and avoids high-cost electronic equipment. Satellite communications involve, besides microwaves, the usage of large reflectors. These reflectors are electric walls that allow different reflection angles along their surface to focus the beam on the active antenna element. The high gain is a must to compensate for the loss due to the greater distance between the satellite and the ground station. This is primarily the case when we are dealing with geostationary satellites. We are looking for a pencil beam and a large reflector, unlike in the case of low-orbit satellites where the flying height is between 500 and 900 Km. For a geostationary satellite, one must use a dish that allows at least 30 dBi gain according to the greater distance of about 36.000 km. The reflector's diameter (the dish reflector) must be at least 89 cm in rainy areas. For uplink at 2.4 GHz (S radio band), the transmitter must have at least 2-5W for narrowband modulations, such as SSB, CW, or digital FT8. A 65 cm dish with roughly 22 dBi was used in the presented paper. An RHCP signal must be used to mitigate the earth's curvature and wave depolarization effect. In this way, the transmitter is not sensible to the localization of the user (latitude and longitude of the ground station). For the downlink at 10 GHz (X radio band), one can use a smaller dish of at least 30 cm. An excellent narrow band SSB signal (-83 dBm) was received using a 30 cm dish in the experiment. Nevertheless, the same dish is recommended for both bands in a full duplex mode. In this case, some new solutions have been given, such as placing a Helix antenna in front of the Horn antenna, both at the focus point of the dish. The paper

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addresses some challenges, such as frequency stabilization, antenna mutual couplings, RF module integration and RF connections, and adaptation to the antenna. All those problems are explained in the following paragraphs. Integrating the UI graphical interface on the Raspberry Pi and the coexistence of Raspberry OS with Adalm-Pluto OS, both of which run under Linux, has presented some challenges.

II. ANTENNA DESIGN

The most common approach for QO-100 ground stations relies on choosing between the microstrip patch and the Horn antenna [3][9]. Nevertheless, the microstrip patch is suited for narrow-band signals, while the Horn antenna runs broadband. Even if the first transponder is a narrow-band linear device, the second transponder is designed as broadband for digital signals like DVB. The paper addresses a design that could allow the antenna system to work broadband in the following work. This is why the Helix was selected for the presented experiment instead of the common microstrip one. Any helical antenna goes broadband and can generate circularly polarized electromagnetic waves with only one feed point. With an exquisite design, axial modes could appear [5], and its behavior could be like a traveling wave antenna rather than a common resonant one. Avoiding resonances is a critical factor that enlarges bandwidth and paves the way for broadband digital communications. The helix circumference must fulfill the condition: $C > 0.5\lambda$, where C is the helix circumference and λ is the wavelength. The previously mentioned circumference condition excites the axial modes along the helix (along z axes or to the direction of propagation). Since it will always be a 90^0 shift between E_θ and E_ϕ one gets the axial ratio starting from the expression of the electric fields in cylindrical coordinates:

$$\bar{E}_\theta = \left(\frac{j\omega\mu I S}{4\pi r}\right) exp(-jkr) sin(\theta)\hat{\theta} \quad (1)$$

$$\bar{E}_\phi = \left(\frac{\eta I k^2 D^2}{16r}\right) exp(-jkr) sin(\theta)\hat{\phi} \quad (2)$$

where:

- *S is the spacing between two consecutive turns (Helix spacing),*
- *I is the electric current through the antenna,*
- *kr is the phase of the wave at distance r measured from the feed point,*
- *D is the helix diameter,*
- *η intrinsic impedance,*
- *k is the propagation constant in free space.*

Then, the absolute value of the axial ratio $AR = E_\theta / E_\phi$ from equations 1 and 2, must be equal to unity for a balance between the fields in a circularly polarized propagation mode. That forces the condition between the diameter of the helix and its turns spacing:

$$\sqrt{2\lambda S} = \pi D \quad (3)$$

That gives the helix pitch angle:

$$\tan\alpha = \frac{\pi D}{2\lambda} = \sqrt{\frac{S}{2\lambda}} \quad (4)$$

Figure 1 shows all the critical parameters used to parameterize the Helix antenna. In this sketch, the Helix usually works (in the normal mode of operation) when its circumference is smaller than the wavelength. A tradeoff between the Horn antenna's size and circumference will be addressed. This allows the helix to be in front of the Horn antenna with minimum interference between the two. The tapper of the Horn antenna will act as a ground plane for the helix. The ground must be a plane in normal circumstances, as in Figure 1.

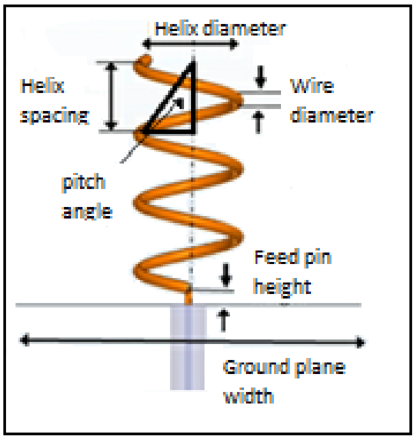

Figure 1. The Helix antenna works in the normal mode of operation in front of the ground plane at 2.4 GHz

Tables 1-3 show the dimensions of the Helix antenna depicted in Figure 1.

Table 1. Antenna dimensions

Helix diameter [cm]	Helix spacing [cm]	Wire diameter [cm]	Number of turns
4.1	2.77	0.6	3.3

Table 2. Feed dimensions

Coax inner radius [mm]	Coax outer radius [mm]	Feed pin height [mm]	Pin diameter [mm]
1.45	4.85	1	2.89

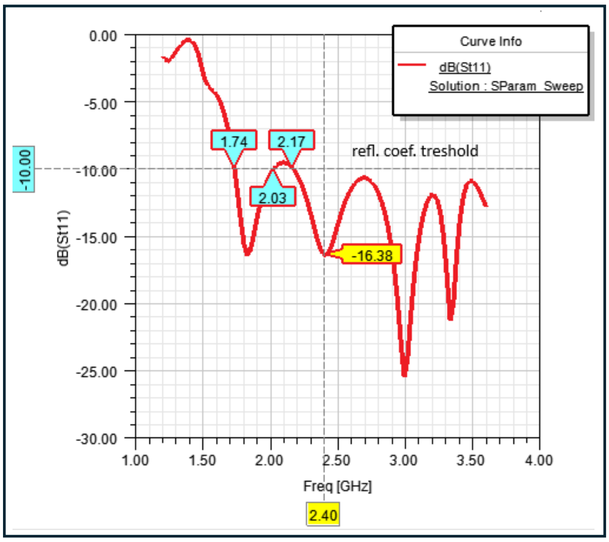

Figure 2. Reflection coefficient vs. frequency in HFSS

Table 3. Ground plane dimensions

Ground plane width [cm]	Hole radius for feed [mm]
14	1

The reflection coefficient threshold at -10 dB splits the frequency domain into two regions in Figure 2. Any drop under -10 dB of the reflection coefficient matches the antenna input impedance to the coaxial line. When the frequency exceeds 2.2 GHz, the antenna goes broadband and the coefficient S11 drops under -10 dB. The Horn antenna must be placed under the Helix antenna in this stage. This is possible if a circular slit is made through the ground plane below the Helix. The cut etching in the ground plane will change the Helix pattern and the input impedance.

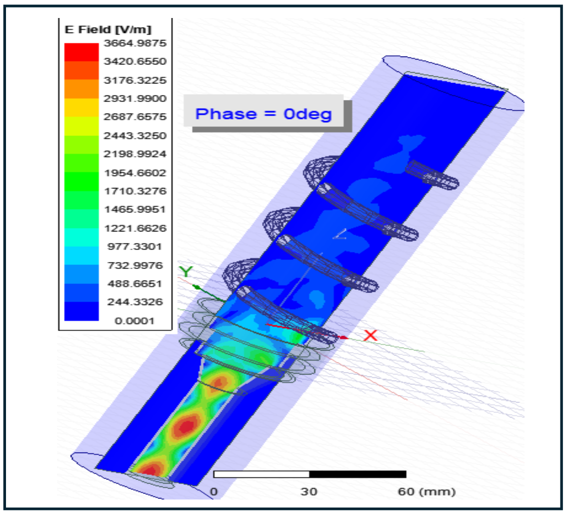

Figure 3. The Horn antenna bellow the Helix antenna – the electric point toward Y axes perpendicular to the highlight plane

In Figure 3, the aluminum Horn antenna is working at 10 GHz. It is a commonly used antenna of the size and shape of an ordinary LNB (low-noise broadband amplifier) used for satellite television receivers in the X band. The horn's taper is corrugated with small steps from the middle cone to the Helix. The diameter of the circular split must be equal to the diameter of the Horn taper, which is 6 cm if we consider the plastic case of the LNB. An increase from 4.1 cm to 6 cm will affect the axial mode, so the helical antenna must remain in front of the Horn and will degrade its gain with 3 dB at most. The benefit justified the mean because we can use the same reflector for both antennas. Figure 4 depicts the input reflection coefficient vs. frequency at the Horn antenna feed point. The VNA uses the Smith chart to outline the reflection parameters vs. frequency between 2.2 – 2.5 GHz. As one can see, the antenna goes broadband with the reflection coefficient inside the constant VSWR circle where RL > 10 dB. The effect of the circular slit degrades the RL near its limit of 10 dB. The marker indexed with "*1*" in Figure 4 marks the point where the reflection coefficient stands for 2.4 GHz, where the ground station transmits. The VSWR is 1.5:1 for this frequency, and the RL is 14.41 dB. As one can remark from the upper right side of the plot, the input resistance is 35 Ω, and the input reactance is 5 Ω (very close to resonance). Any impedance adapter we would use to improve the matching between the antenna and the coaxial line will degrade the antenna frequency band.

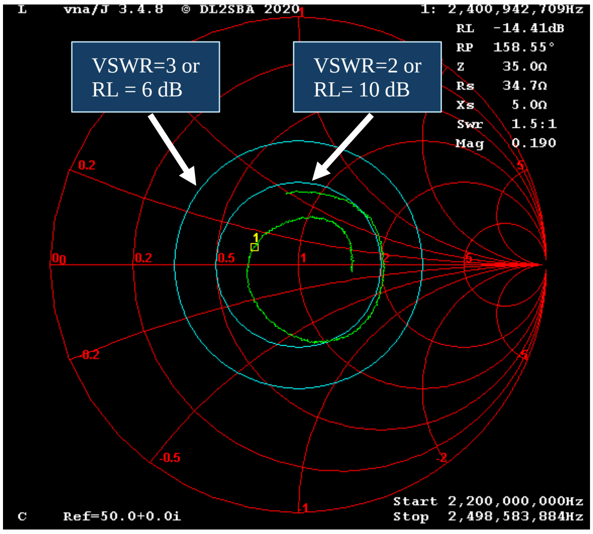

Figure 4. Measurements with the VNA-Tiny to the Horn input (at the feed point)

The second upper circle in Figure 4, for which the VSWR is 3, and RL is 6 dB, outlines the limit for which one should not pass. Outside the circle is the forbidden zone where the reflected wave can destroy the final stage of the transmitter.

III. THE LNB AND THE GROUND STATION FOR QO-100

The LNB is the first frequency downconverter near the Horn and the Helix antennas. A common LNB downconverter shifts a 10 GHz signal to 739 MHz. In [6], a minor modification translates the 739 MHz intermediate frequency to 432 or 144 MHz, where a radio ham can operate according to its designated band plan license. The modification introduces a second mixer stage to translate this frequency. The modified LNB is available on the market and has other outstanding characteristics. Besides the frequency shift that allows the usage of commonly used ham operator equipment, there is also a significant improvement that enables the user to discipline the PLL synthesis of the LNB.

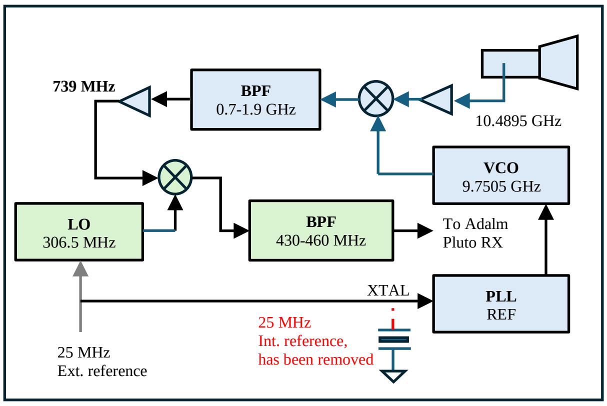

Figure 5. The schematic diagram of the modified LNB (modifications marked with green)

This critical issue must mitigate the phase and frequency jitter a narrow-band communication system encounters. An external OCXO (oven-controlled crystal oscillator) oscillator stabilizes the LO of the LNB using a GPS-based module. This module offers 10 MHz and stabilizes an external OCXO, which gives the reference VCO+PLL synthesis of the LNB. ADF 4351 provides a stable signal of 25 MHz, which is used as a reference for the modified LNB shown in Figure 5. Figure 6 presents the simplified schematic of the ground station for the QO-100 satellite. Below the dash line are blocks from the upconverter made by DXPATROL. No modifications have been made inside the DXPATRON upconverter. The input signal of 432.5 to 433 MHz is applied from an RF transceiver and must be an upper-side band-suppressed carrier SSB. This is a narrow band signal up to 2.5 KHz. FM or other modulations are not allowed. The SSB signal is upconverted to 2.4 GHz, and the power amplifier feeds the Helix antenna terminals. The output signal is up to 10 W, depending on the input excitation.

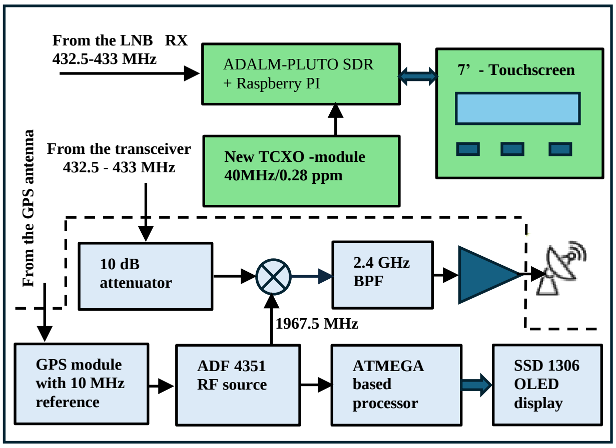

Figure 6. The simplified diagram of the modified QO-100 ground station made by DXPATROL (modifications marked with green)

Nevertheless, the DXPATROL is not running in full duplex mode. Additional blocks above the dashed line (marked in green) have been added to monitor the signal during transmission. The downconverter stage of the DXPATROL has been replaced with a system built with an Adalm-Pluto SDR, a Raspberry PI 4, and a display. The DXPATROL works in semi-duplex mode, so one can only receive or transmit at a time. The downconverter stage (marked in blue) uses a GPS-based disciplined oscillator of 10 MHz to stabilize the 1967.5 MHz sinusoidal signal. Unfortunately, the 25 MHz reference for the LNB is not generated during transmission because ADF 4351 is in use. In this respect, the 25 MHz reference signal must be generated using another GPSDO. The downconverter side with the Adalm-Pluto SDR cannot benefit from the GPS module reference because Adalm-Pluto v.2 is not designed to use an output reference, and its internal TCXO (temperature compensated crystal oscillator with a frequency shift of 30 ppm) is unsuitable for narrow-band signal processing. The solution adopted was to replace the original TCXO with a more stable one with a better stability of only 0.28 ppm. This new TCXO increases the performance of the PLL device inside the SDR on Adalm-Pluto, having comparable stability with one of the transceivers. Despite this improvement, a 25 MHz reference with 0.28 ppm is improper for the LNB as a reference. An external GPSDO that generates a stable sinusoidal signal of 25 MHz is a must to discipline the LNB-LO. A description of this module is depicted in the next section. The microSD containing the OS on the Raspberry PI is preconfigured to be used with the Adalm-Pluto SDR. It includes, besides the preinstalled packages, the GNU-Radio package. The UI (user interface) has been uploaded with a new graphical interface to the microSD. The concept of a UHF SDR transceiver is presented under the name of the "*Langstone project*" and is available on GitHub [7]. Due to the low quality of the sound produced by the Raspberry PI board, an external sound dongle has also been attached to the USB port (Figure 7).

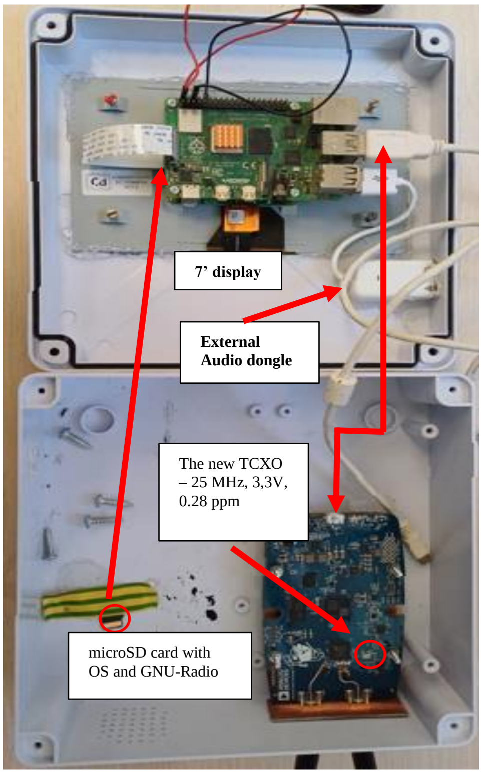

Figure 7. The receiver's blocks inside the case (marked in green in Figure 6)

The Adalm-Pluto board was covered with a double-layer PCB to mitigate EMI (electromagnetic interference). In Figure 7, only the bottom plane is present to make the electronic board's layer visible.

IV. EXPERIMENTAL RESULTS AND MEASUREMENTS

The main problem encountered in the experimental approach is with the LNB-LO reference during transmission. In reception mode, the DXPATROL, presented in Figure 6, uses ADS 4351 to synthesize the 25 MHz reference signal to discipline the LNB's LO. The ADS module generates an RF carrier at 1600 MHz. Then, it uses a divider to 64 to apply a 25 MHz sinusoidal signal to the LNB as a reference. During the transmission, the upconverter shown in Figure 6 uses the ADS module to synthesize the 1967.5 MHz signal to obtain the carrier at

2400 MHz. The design of the DXPATROL does not allow the discipline of the LNB during transmission. The solution adopted is to use an external generator as a reference, starting from a GPSDO and a multiplier. The GPSDO module is set to offer 10 MHz as a sinusoidal or rectangular. An external module can divide the 10 MHz signal by two and then multiply the resulting signal by 5 to obtain precisely 25 MHz. In Figure 8, one can see the adopted solution. The upper left device makes the division and multiplication, and the resulting signal of 25 MHz is applied to the LNB-LO. On the right bottom side is the GPSDO, and one of its outputs is used to apply the 10 MHz reference to drive the divider input of the next stage.

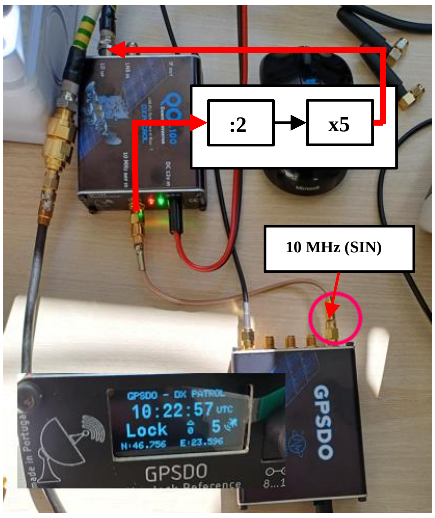

Figure 8. The adopted solution for the second GPSDO was used during transmission.

Figure 9 shows the 25 MHz signal on the spectrum analyzer. This signal is precisely 25 MHz, suitable for disciplining the LNB to have a good tune at 10.4895 GHz. A deviation over 10 Hz is not allowed for a narrow band signal of only 3 KHz wide.

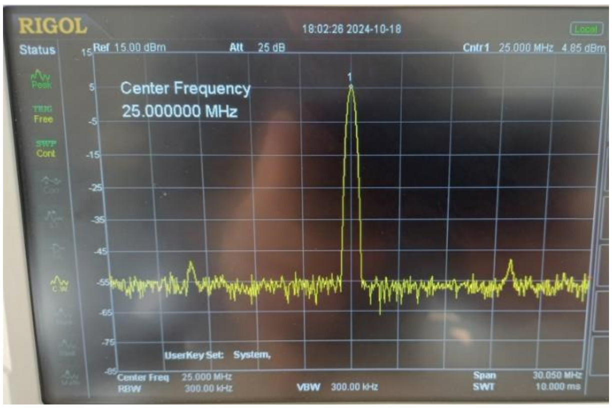

Figure 9. The reference sinusoidal signal applied to the LNB-LO input

The frequency shift is under 0.001 Hz at 25 MHz. At 10 GHz, it is under 1 Hz. Marker "1" revealed the center frequency and the magnitude of the 25 MHz signal (4.85 dBm). Figure 10 shows two inputs, one for the LNB-LO and the other for the LNB-RX. The dish is 0.65 meters in diameter and has a gain of 35 dB at 10 GHz. At 2.4 GHz the dish has only 22 dB. Those gains refer to the antenna element located at the focus point of the reflector. At 2.4 GHz, the Helix antenna has a simulated gain of 10 dBi, contributing to the radiator's overall gain. The total gain of the reflector plus Helix is up to 30 dBi anyway, which is enough at a transmitter power of 2 to 4 W (33 – 36 dBm). The gain of the dish has been evaluated with Equation 5:

$$Gain_{dB} = 10\log_{10} 6\left(\frac{D}{\lambda}\right)^2 \qquad (5).$$

Where D is the diameter of the dish reflector.

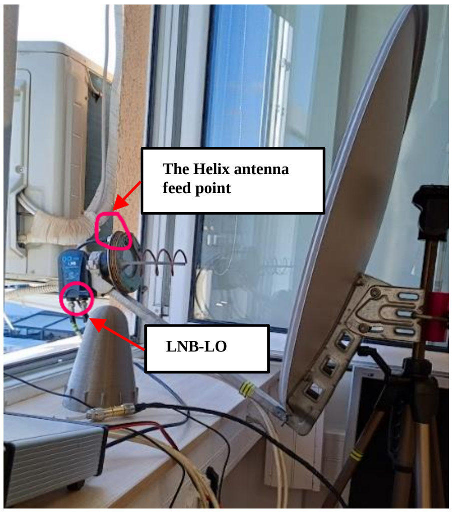

Figure 10. The LNB with the Helix antenna and the parabolic reflector.

The owner recommends using a dish at least 0.8 meters in diameter to work through the QO-100 satellite. The Helix antenna will compensate for the satellite's power deficit compared with the standard microstrip patch, which exhibits at least 3 dB gain below the Helix.

Figure 11. The UI interface on Raspberry PI 4 with the SDR attached

Suppose the patch antenna is used instead of the Helix antenna. In that case, the dish reflector should be larger in normal circumstances (when the aerial works in the same condition of power and weather conditions). Figure 11 shows the Raspberry PI's display with the graphical interface active. The user can touch the virtual button to operate the SDR as if it were a real front panel of a UHF transceiver. The mouse scroll button can change the frequency digit, marked by a small dash. The receiver works in SSB mode and selects the upper band of the signal. A simple spectrum and a waterfall signal representation are visible on the screen. In the middle, the PSK signal is transmitted continuously by the satellite transponder with telemetry data. The signal report is S4, which is -83 dBm.

Table 4. The QO-100 transponder band plan for narrow-band signals

Up-link Start [MHz]	**Up-link End [MHz]**	**Down-link Start [GHz]**	**Down-link End [GHz]**	**BW [KHz]**	**Modulation SSB/CW/FT8/PSK/8APSK max. 2.7 KHz bandwidth**
-	-	10.4895	10.489505	5	Lower Beacon
2400.005	2400.04	10.489505	10.489540	35	CW
2400.04	2400.08	10.48954	10.48958	40	FT8
2400.08	2400.15	10.48958	10.48965	70	PSK
2400.15	2400.245	10.48965	10.489745	95	SSB
-	-	10.489745	10.489755	10	CW
2400.255	2400.35	10.489755	10.48985	95	SSB
2400.35	2400.3575	10.48985	10.489858	7.5	-
2400.3575	2400.365	10.489858	10.489865	7.5	Emergency band
2400.365	2400.49	10.489865	10.48999	125	CW/SSB/PSK/DPSK/FT8
-	-	10.48999	10.489997	7	Multimedia beacon – 8APSK
-	-	10.489997	10.490	3	Upper Beacon

The PSK beacon signal is transmitted between 10489.745 MHz. After the first down-conversion, the LNB gets the *IF1*, selecting the difference between the first and the VCO signal (see Figure 5) as follows: $IF1 = 10489.745 - 9750.5\ MHz = 739.245\ MHz$. The second conversion gets the *IF2*, which is: $IF2 = 739.245 - 306.5\ MHz = 432.745\ MHz$. The IF2 is applied to the SDR input and displayed on the spectrum (see Figure 11). On the band plan spectrum from Table 4, a frequency band has been reserved for narrow-band digital modes with very low data rates. Here, one can transmit short messages with information. Those messages can contain temperature, location, weather, and signal reports followed by the sender's license callsign.

V. CONCLUSIONS

This paper proposes some modifications to use the SDR Adalm-Pluto together with the Raspberry PI 4 to design and implement a full-duplex ground station for the QO-100 satellite. A ground station is a complex system that involves many devices, such as transceivers, SDRs, and up-and-down converters. Usually, all those are under the control of a PC. Instead of the PC, a Raspberry PI can do this task if an SDR and a display with a touch screen help it. In full duplex mode, the operator can transmit and monitor its signal at the end of the downlink side as if he is the recipient of the transmitted message. This is possible due to the satellite transponder retransmitting the received signal on another frequency band toward the Earth. The technique helps prevent the satellite's receiver from overdriving or making some measurements regarding atmospheric conditions. The Adalm-Pluto is a native full-duplex transmission device; nevertheless, it is not used as it is in this respect. The signals received from satellites are weak and could be easily covered by noise from the transmitter path during full-duplex mode. So, a good separation demands two SDRs, but only one has been available for the experiment. This problem has been solved by using a radio transceiver for uplink and an SDR to monitor the downlink channel. In the paper, some other issues related to frequency stability have been addressed and solved with the help of a GPSDO reference. Unfortunately, the SDR Adalm Pluto has not been designed to process narrow-band signals in microwave bands. Its TCXO reference of 25 MHz is not suited for the task. To overcome this issue, the TCXO of the Adalm Pluto has been replaced with a better one. The proposed ground station can be handy for experiments. In this regard, any comparison between the antennas could be envisaged. Another point is the usage of digital modes to transmit short messages in PSK, 8APSK, or FT8 modes. Notwithstanding, the second transponder, with its broad band's modes like image transmission [8], should be investigated shortly.

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