SDR Experience: PNW Microwave Group

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1. Introduction

1.1. Basic SDR Hardware and Software

Some members of the PNW Microwave Group are building and operating SDR-based VHF/UHF and microwave stations. We use SDR devices for QSOs from 144 MHz to 24 GHz and 122 GHz, and as microwave test equipment in our home labs. This paper describes the SDR stations we use, illustrates some of the creative uses of unique SDR device properties, and suggests ways to use SDR devices in home RF laboratories. The emphasis is on our homebrew experiences. In the end, SDR-device-based stations are built and developed along the same lines as traditional non-SDR stations, with rig design options from a few unique SDR device features.

For our projects, our group has settled on the Analog Devices Active Learning Module (ADALM) Pluto[1] and Ettus USRP B200mini[2] SDR transceivers, two flexible and stable SDR hardware devices. Moreover, both devices provide an affordable and well supported RF development platform under a range of different software operating systems.

The main software applications that we use in our SDR projects are GNU Radio[3], SDR Console[4], and the Langstone Project[5]. These applications are free to download and offer a range of built-in SDR tools such as spectrograms, waterfall displays, modulators/demodulators, filters, PA/LNA controls as well as transmit-receive capabilities. In practice, these continuously updated, user-friendly software applications mesh well with our SDR devices and prove as simple to use as traditional analog radios and test instruments.

2. Foundation of an SDR Station

2.1. 70 MHz to 6 GHz VHF/UHF SDR Transceiver

Our ADALM Pluto- and Ettus B200mini-based SDR transceivers can operate stand alone and directly on the VHF and UHF bands, from 70 MHz to 6 GHz, without the need for additional amplifiers, etc. We use this SDR station configuration on the air for local QSOs.

Computer software controls the frequency selection, modulation/demodulation, rig control and display functions. Any frequency between 70 MHz and 6 GHz is independently selectable for the receive and transmit operation. The software offers common radio communications modulation: SSB, CW, FM, and digital modes. In operation, signals can be visualized as well as heard. A screenshot of SDR Console's main screen is shown in Figure 1, where some of these features are visible.

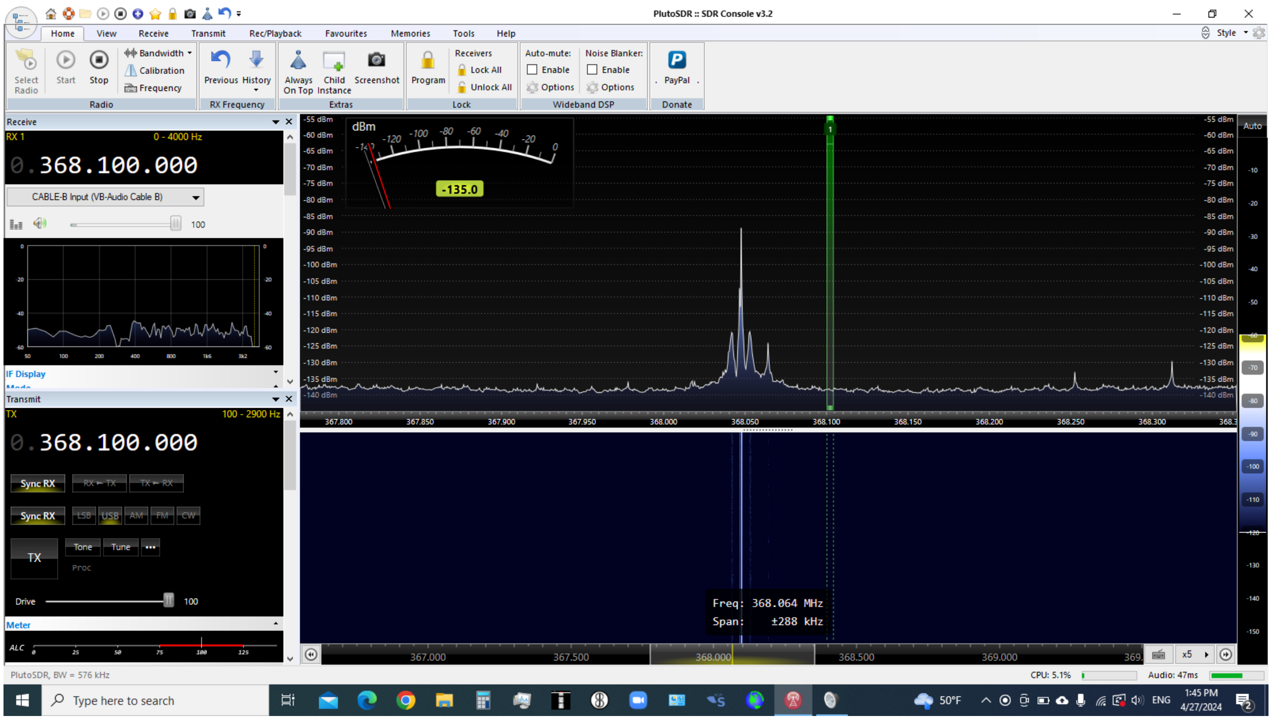


Figure 1. SDR Console screenshot.

Digital modulation additionally requires an accessory digital software modem (e.g. Fldigi, WSJT-X). The WSJT-X software includes a suite of weak-signal digital protocols aimed at implementing near-optimum coding modulation schemes. Initial development was oriented to use FSK for EME contacts in the VHF/UHF bands. We are testing FT8 modulation on short range QSO's throughout the VHF/UHF and microwave spectrum.

In our opinion, the Q65 digital mode offers potential for weak signal work with our equipment. Q65 allows the selection of sub-modes with wider TX/RX sequence lengths and tone spacing choices. This digital mode introduced a predefined message structure in a synchronized QSO exchange that facilitates data compression and the addition of forward error correction. This makes the protocol particularly robust on slow-varying signal conditions and in the decoding of signals close to the noise floor.

3. Further Development of the Basic SDR Station

3.1. Amplifiers, Filters, Frequency References

Improving radio performance beyond the basic level relies on the same traditional techniques common to high-performance analog radio systems. Receiver pre-amplifiers, transmit PAs, frequency references, relay control circuits, morse and beacon keyers, and RF filters are accessories that can be added to the basic SDR station in the ordinary way.

One of our 1296 MHz stations is a good example of an enhanced basic station for improved local terrestrial QSOs. (See Figure 2.) Transmit capability is enhanced with an external PA and LPF. The amplifier and LPF connect to the TX port of the antenna relay. The SDR device RX port connects directly to the RX port of the antenna relay. A low noise preamplifier could be inserted in the RX pathway. (As will be discussed below, our microwave 10 GHz stations all benefit from external low noise preamplifiers and PA enhancements.)

Another station enhancement is better frequency accuracy. We use an external reference to discipline the native internal SDR device clock almost 100% of the time. Our SDR devices offer a port for an external frequency reference. Frequency stability has also proved particularly important for reliable on-the-air digital mode communications. Data decoding improved when even minimal short term and long-term frequency drift are eliminated. Field conditions work against the thermal stability of the SDR device native crystal oscillators.

Our most simple and best solution to implement an accurate and stable frequency reference is to use the programable Leo Bodnar miniGPS Referenced Clock[6]. We have settled on the GPS-referenced Leo Bodnar unit due to its compact form factor, trouble free operation, and adjustable output frequency. (Figure 2 shows Mariana's 1296 MHz SDR transceiver system using a Leo Bodnar device as external reference for the Pluto SDR.) The adjustable frequency of the output reference signal is necessary to match the different external reference requirements of our devices. For example, the ADALM Pluto will accept any external reference in the 10 to 80 MHz frequency range. In contrast, the Ettus USRP B200mini will accept only a 10 MHz reference signal.

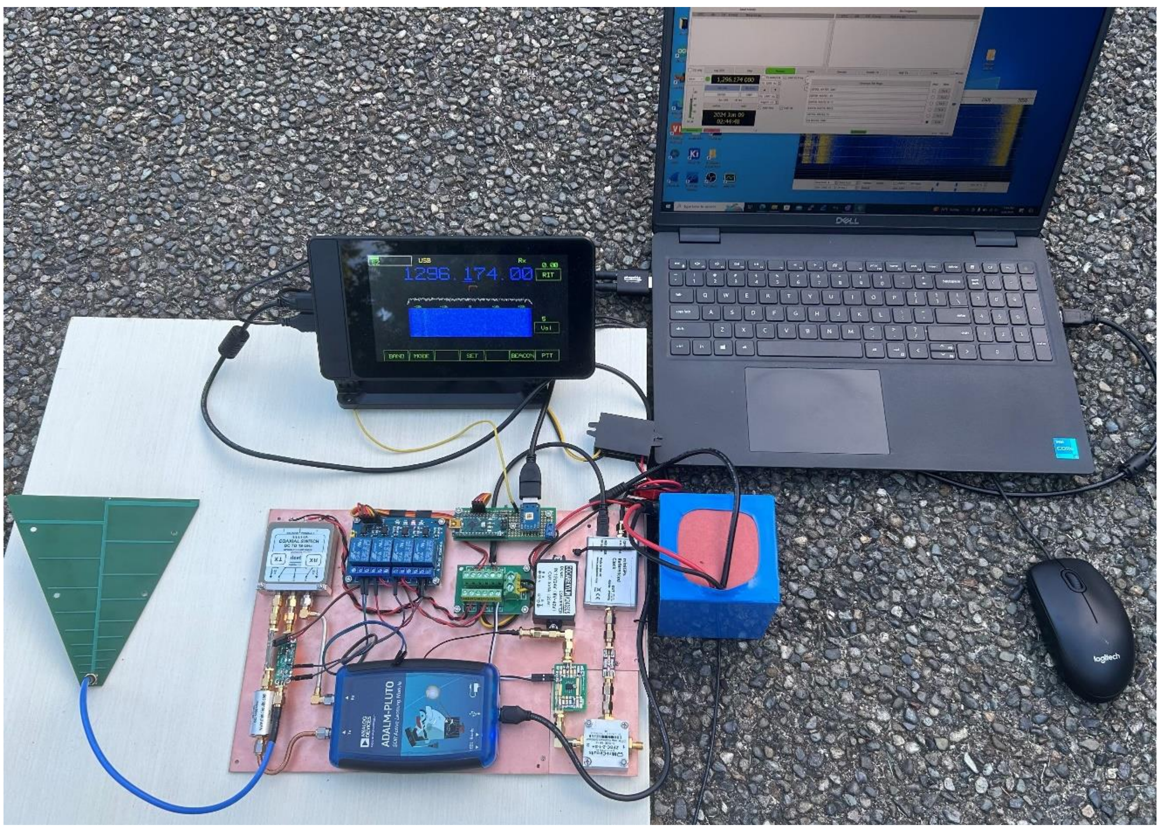


Figure 2. WA7EE's 1296 MHz SDR transceiver system.

4. Multiplying and Mixing to Microwaves & Beyond and Unique SDR Device Features

A fundamental signal frequency can be up-converted with an external mixer to a higher frequency. The native SDR device output levels of +5 dBm are sufficient to adequately drive most balanced mixers and many low-level amplifiers. Our SDR microwave and mmWave stations now use external mixers to upconvert the native SDR frequency range to microwave frequencies. In this way, our current microwave rigs are able to operate on 10, 24, and 122 GHz.

Some early microwave experiments used simple 2X or 3X frequency multiplication from UHF to 10 GHz for CW and FM operation. The results with SSB and digital modulation were disappointing. We rely on mixer-based up-conversion for our current multi-mode radios. With a mixer configuration, the complete functionalities of the SDR device (i.e., wide frequency coverage, flexible software control, and useful operating GUI), are all retained and translated to a higher frequency. Our SDR microwave mixer radios follow the classic microwave up-converting balanced diode mixer conversion scheme. Namely, an outboard oscillator is employed as LO, the SDR device works as the IF (i.e., Intermediate Frequency) device, receiving and transmitting on a frequency that is within its coverage range, and the mixer's RF port supports RF input and output at the desired higher microwave RF frequency.

Some of our transceivers use a single mixer, that is the IF path is relay switched in and out of the TX or RX circuits. We also build dual-mixer transceivers, with one mixer in each of the TX and RX paths, an approach that obviates the IF switching relay.

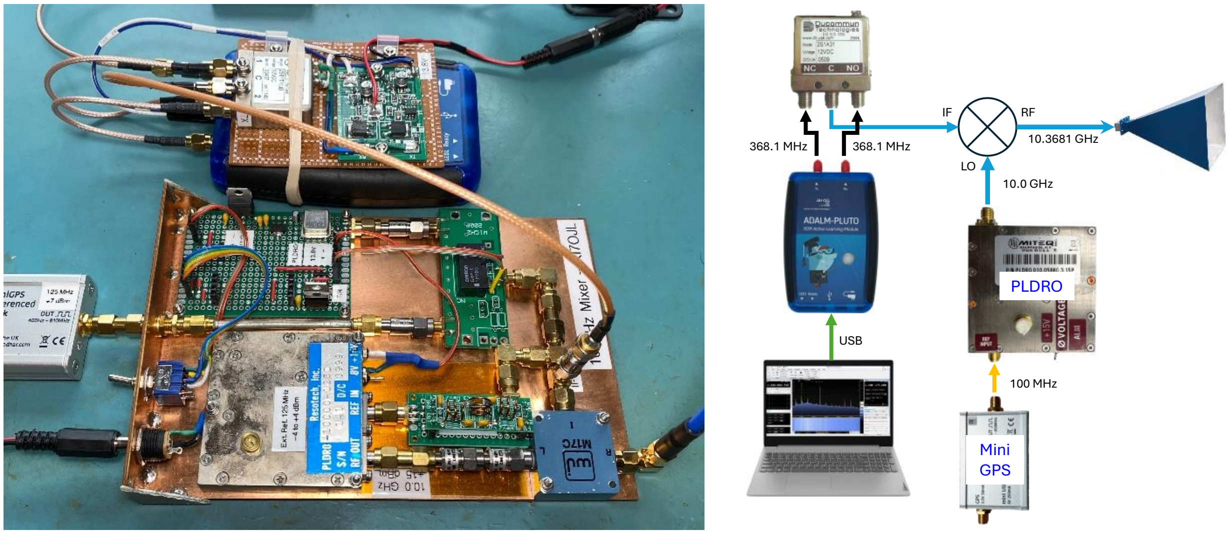
4.1. Choice of IF Frequency

IF flexibility allows the builder a wider choice of available mixing components (mixers and LOs) to satisfy the mixer equation[9]. One feature of using a SDR device as IF is that any IF frequency in the SDR device native frequency range can be used for this purpose. That is, the IF for up-conversion is not required to be in one of the traditional IF frequency bands of 144, 432, and 1296 MHz. Our group ends up relying on these flexible IF choices for many of our homebrew rigs with surplus/available mixers and LOs.

4.2. Description of Microwave Stations

Figure 3 shows Pablo's single-mixer 10-GHz transceiver, which uses an available 10-GHz PLDRO as LO. When mixed at an IF of 368.1 MHz the result is 10.3681 GHz RF transceiver operation. The PLDRO is referenced by a GPS-disciplined 125 MHz signal from a Leo Bodnar miniGPS. This is a simple rig with no power amplifier or LNA. As shown in the schematic, the mixer's RF port is directly connected to the antenna. At the same time, the TX and RX ports of the Pluto SDR device used as IF are connected to a TX/RX switch whose common output is connected to the mixer's IF port.

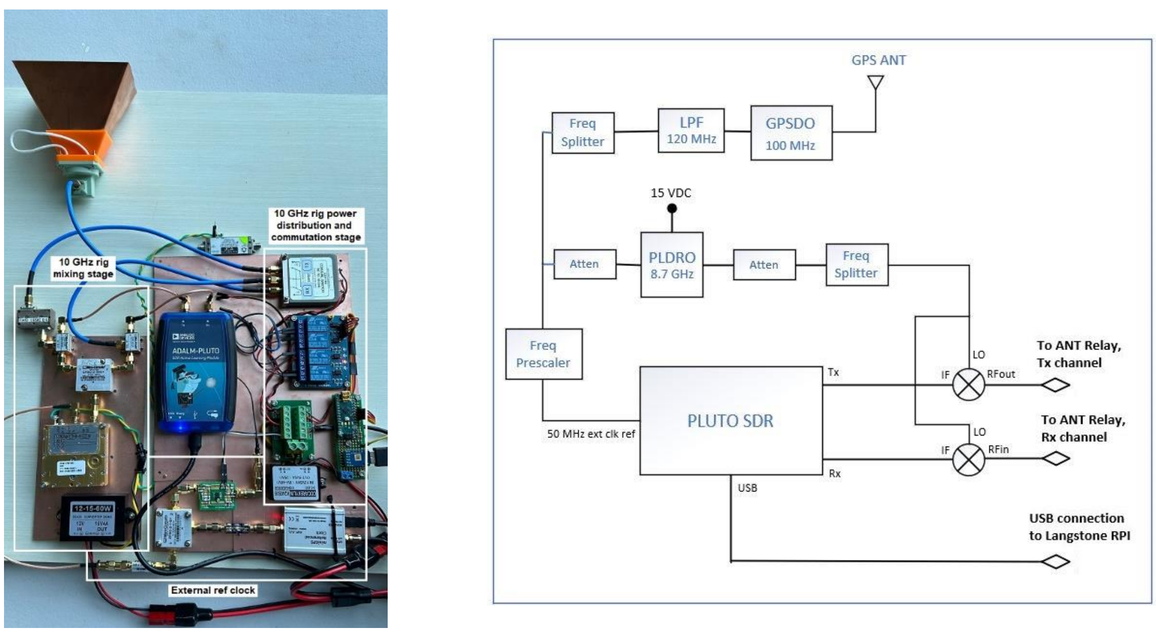
WA7EE's 10 GHz rig, shown in Figures 4 and 6, utilizes a dual mixer architecture. A PLDRO acts as the 8700 MHz LO for both the TX and RX mixers, with a +15dBm output that is sufficient to drive the two mixers adequately. An alternative to the PLDRO was to use a second Pluto SDR. However, the Pluto frequency range and power levels would have required using harmonics or a frequency multiplier, additional power amplification, and filtering. The PLDRO offered a simpler, integrated solution with comparable or better performance.



(a) (b)

Figure 3. KI7OJL's 10 GHz single-mixer SDR transceiver system: (a) system photo; (b) schematics.

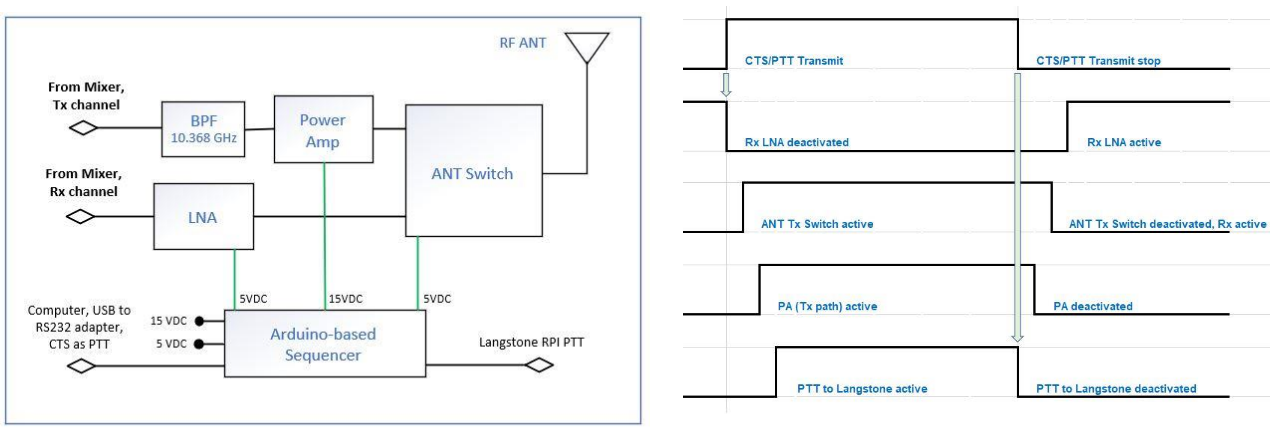
Similarly to the implementation in KI7OJL's 10 GHz rig, a Leo Bodnar GPSDO unit set at a frequency of 100 MHz provides the external clock reference for the PLDRO. Through a splitter and pre-scaler, the GPSDO output is reduced to 50 MHz to serve as the external clock reference for the Pluto SDR.



(a) (b)

Figure 4. WA7EE's 10 GHz transceiver: (a) rig details; (b) diagram of mixing stage.

The software functionality of WA7EE's rig is based on the Langstone Project. Together with the Pluto SDR, it implements an all-mode narrow-band transceiver. This particular rig version, aimed toward operation in the field, uses a touchscreen user interface running off a Raspberry Pi 4. At home for testing, a laptop with a larger screen is used. (See Figure 6.) Directions to build a Langstone Transceiver are available through the project’s website[5]. These instructions are rather straightforward and require no programming skills — copying the software to an SD card for the Raspberry Pi and connecting ancillary hardware devices for the transceiver operation (a 7" touchscreen, a USB Audio dongle with Mic input/Headphone output, and a USB mouse) should suffice to get the transceiver up and running.



(a) (b)

Figure 5. WA7EE’s 10 GHz transceiver: (a) diagram of commutation stage; (b) timing diagram.

The Langstone design allows for a PTT input to reach the Raspberry Pi through one of its GPIO pins. An Arduino-based sequencer (see Figure 5) handles the timing and sequence of relay activation, preventing the PTT signal from reaching the Raspberry Pi too early — and so preventing Langstone to command the Pluto to transmit until the PA and antenna are active on the TX path.

When operating digital modes, the current implementation of Langstone, requires an additional device (laptop or Raspberry Pi) to run WSJT-x on. The resolution of the standard 7” Raspberry Pi touchscreen that Langstone uses is not enough to fit the WSJT-X GUI. And since Langstone has been designed as a standalone project, it cannot run on the same laptop or Raspberry Pi where WSJT-x runs. For the moment being, WA7EE’s rig uses a separate laptop to run WSJT-x, with a USB audio adapter to exchange audio with Langstone, and a USB to RS232 adapter to pass the PTT command from WSJT-x to Langstone, too.

Pablo's dual-mixer 10 GHz rig, shown in Figure 7, similarly as his single-mixer system, uses a 10.0 GHz PLDRO as LO, but in this case the LO signal is split and fed into the two mixers, serving the RX and TX signal paths, respectively. The IF device RX and TX ports are each connected to the IF port of the corresponding mixer. The RF output from the TX mixer goes through a 1/2W power amplifier, and into the TX port of the antenna switch, while the RF output from the RX mixer goes directly to the RX port of the antenna switch. Sequencing the PA and antenna switch is handled by the SDR Console software, which controls them via a USB dual-relay.

When working in digital modes, SDR Console is PTT-controlled by WSJT-X via the CAT ("Computer Aided Transceiver") protocol. In this case, two virtual cables are also required to route the RX audio from SDR Console to WSJT-X, and the TX audio in the opposite direction.

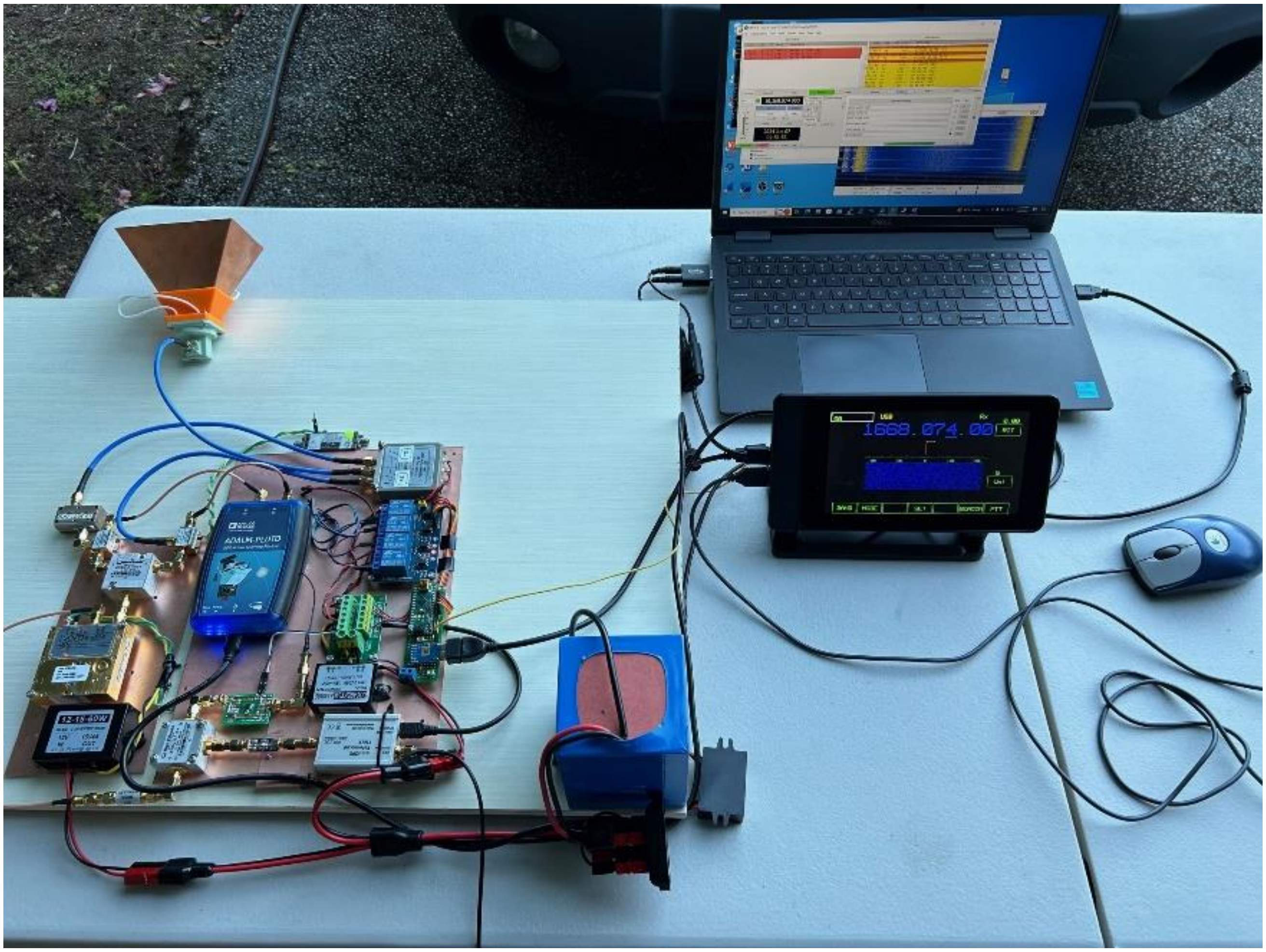
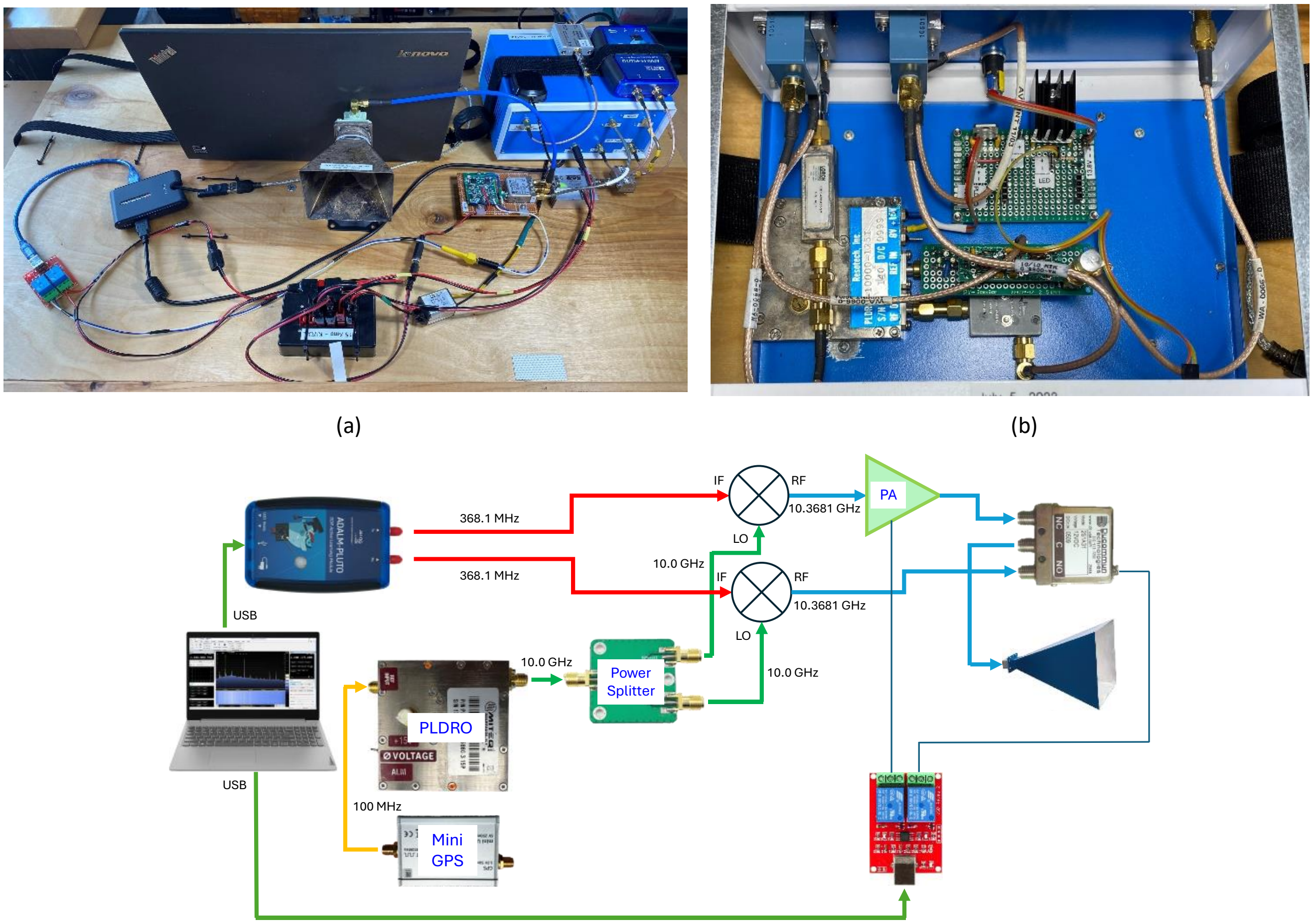


Figure 6. WA7EE's 10 GHz dual-mixer SDR transceiver system.

Frequency stability is essential when operating in digital modes. For this reason, a GPS-disciplined reference for the Pluto SDR device is also necessary in this case. Pluto SDR version Rev D accepts an external reference signal. A separate reference device can be used for this purpose, or the same signal used to reference the PLDRO can be split and pre-scaled to reference both, the PLDRO and Pluto. We all follow this latter approach in some of our rigs.

John's 10-GHz rig, shown in Figure 8, is a further example of a transceiver that uses separate mixers for the TX and RX paths. The IF path relay is eliminated. Both mixer LO ports are driven via a RF splitter by the same LO signal. The LO in this rig is a 13.6 GHz DRO, high side mixed, with SDR device IF of 3.23 GHz, which the mixers convert to 10.3681 GHz RF. The transceiver works just fine despite tuning backwards. For the digital modes the modulation should be on the LSB and not on the USB. The IF frequency subtracts rather than adds to the LO frequency. His rig also features both a PA and LNA integrated into the TX and RX paths, respectively.

Many commercial and homebrew up-converting transverters will work with SDR devices configured as single frequency transceivers. In our only 24 GHz SDR transceiver shown in Figure 9, (we are not a big presence on 24 GHz), the SDR device is configured as a VHF transceiver, transmitting and receiving at an IF of 144.1 MHz. The SDR device is the IF to a venerable barefoot Kuhne MKU 24 G SHM transverter and crystal LO. Totally conventional and totally old school.



(a) (b) (c)

Figure 7. KI7OJL's 10 GHz dual-mixer SDR transceiver system: (a) system photo; (b) dual-mixer box; (c) schematics.

4.3. Split RX and TX IF Frequencies

The SDR device can transmit and receive signals on different frequencies! That means, the frequency of the RX channel does not depend on the frequency of the TX channel. The RX and TX channels can be separated.

This feature is exploited to form a transceiver with a dish-mounted 10 GHz transceiver. (See Figure 10.) The receiver uses a satellite TV receiver and LNA IC tuned for 10 GHz and down converted to an IF of 618 MHz. The transmitter path includes a mixer device, a 14.4 GHz DRO as LO, and a 4.03 GHz transmit IF signal to up-convert to 10 GHz. The receiver path of the SDR device is therefore tuned for 618 MHz IF and the transmitter path of the SDR device is tuned for 4.03 GHz IF. The receiver and transmitter modules are paired to become a compact 10 GHz transceiver mounted at the feed point of an offset dish antenna. The transmitter IF frequency is subtracted from the LO frequency by the mixer, and the satellite TV receiver IC adds the IF to the receiver LO frequency. The tuning frequency discrepancy between the TX and RX channels is easily handled by the GNU Radio software with the result that the completed transceiver tunes normally.)

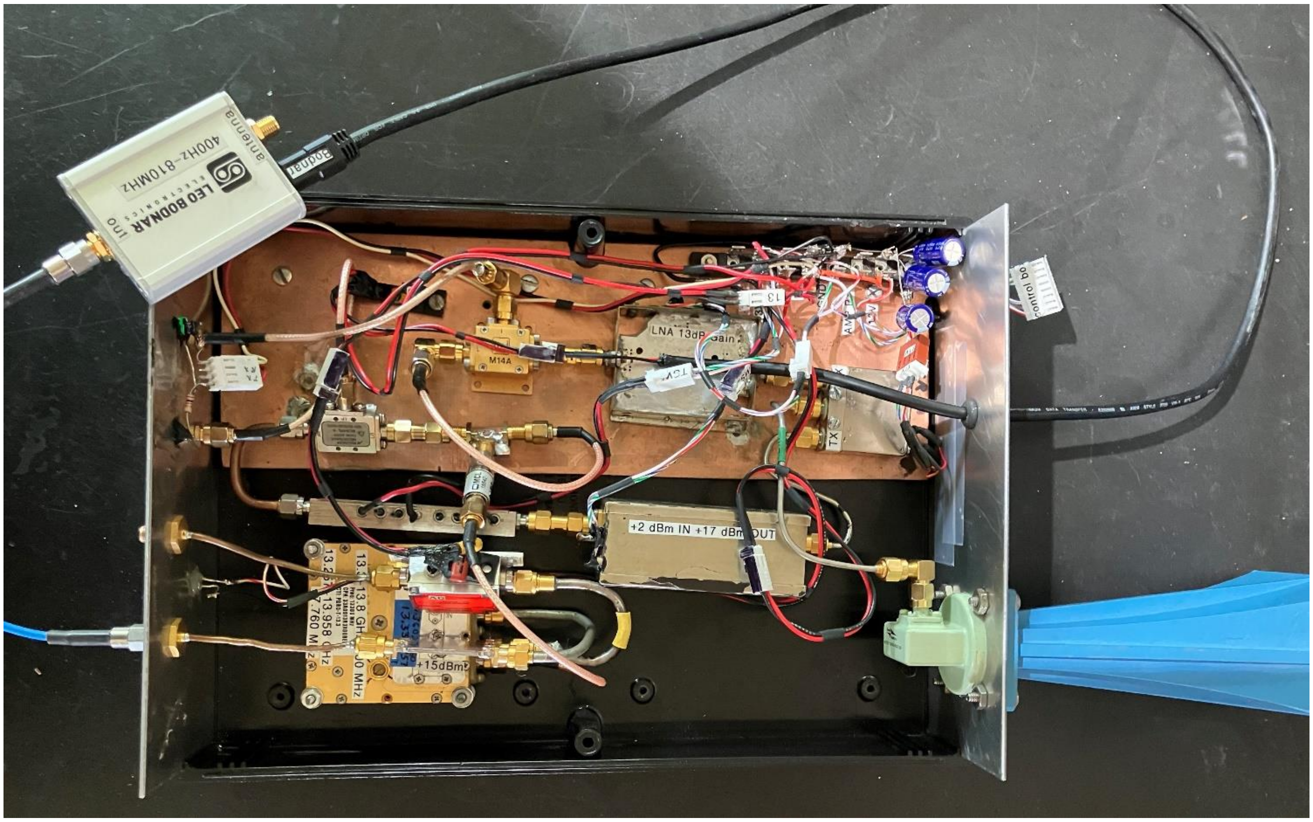


Figure 8. W7FU's 10 GHz SDR transceiver system.

4.4. 122 GHz Operation is an Exception

Our 122 GHz radios (see Figure 11) use only the receive mode of the SDR device. The transmit function is not used. The 122 GHz station is built using the Silicon Radar TRA_120_002 IC transceiver system. The FM and FSK transmitter consists of a 10 MHz frequency disciplined 1.9 GHz PLL LO that is multiplied directly to 122 GHz. The receiver is an integrated mixer and preamplifier that mixes with the multiplied LO for a 144.4 MHz receiver IF. Unlike the previously described SDR projects, the SDR device in this rig only acts as a receiver at the 144.4 MHz IF frequency. The 122 GHz transceiver is always transmitting and receives in a duplex mode.

5. SDR: Test Instruments for the Home Laboratory

We also use our SDR devices as test instruments for bench testing and equipment building/trouble shooting purposes. The SDR device receiver and transmit capabilities can be configured via software to function as a spectrum analyzer (SDR receive only) or a signal generator (SDR transmit only). The native frequency range of the basic SDR device test system can be extended to higher frequencies using a mixer, as well.

Figure 9. W7FU's 24 GHz SDR transceiver system.

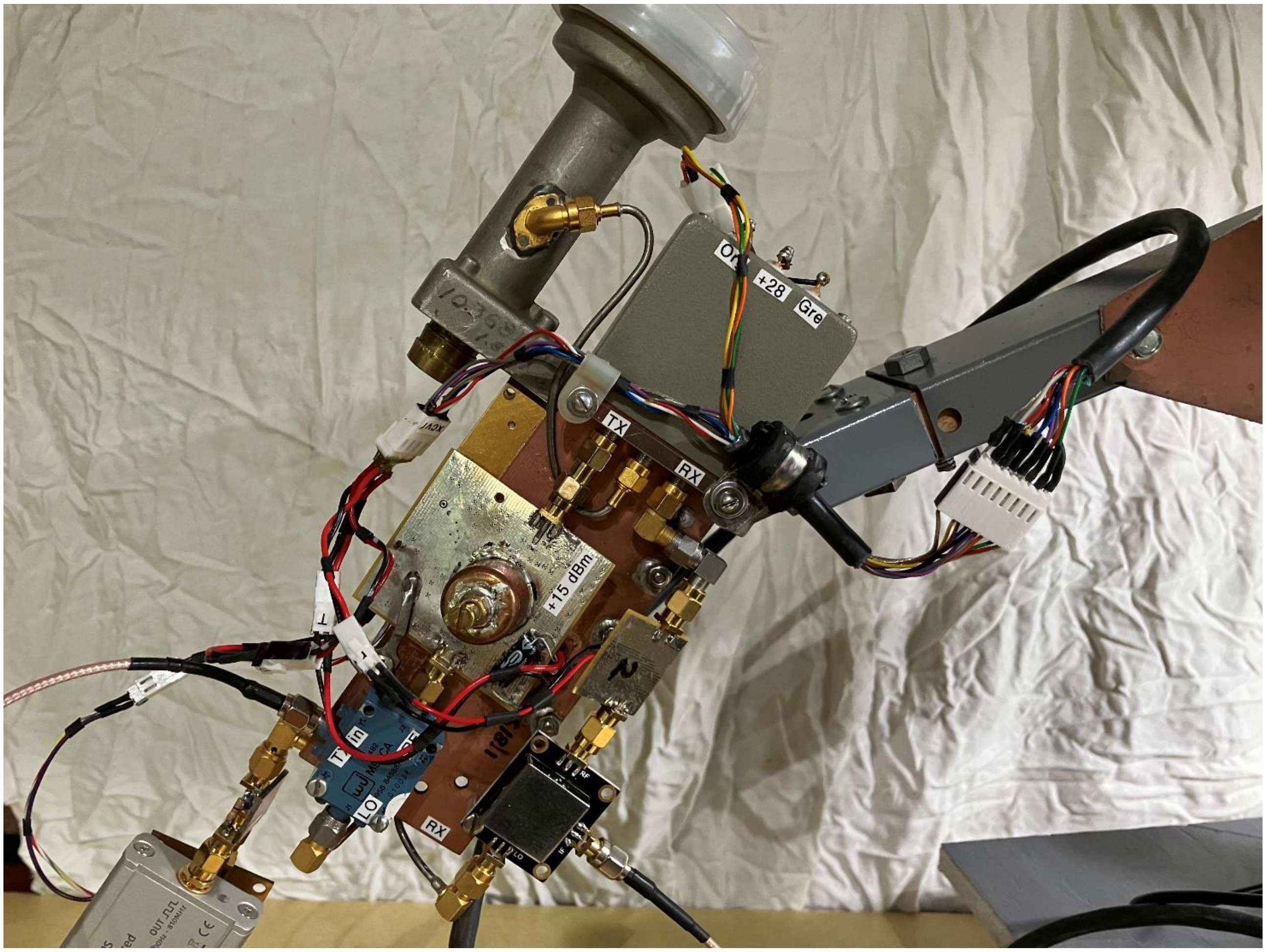


Figure 10. W7FU's Split-frequency 10 GHz SDR transceiver system.

5.1. Spectrum Analyzer

The SDR device receive software can be set to scan large or small frequency segments for spectrum analysis. Large frequency segment scans, up to 25 MHz, are useful to identify unknown signals including RF spurs. Narrow segment scans are best for equipment tuning and modulation analysis.

The utility of the SDR spectrum analyzer benefits from the useful software GUI features: a graduated FFT amplitude display with calibrated linear/log readings, frequency readout, peak hold, trace averaging, and trace persistence functions.

With this tool we obtain useful measurements of oscillator outputs (fundamentals, harmonics, spurs), rig outputs, and filter characteristics. That said, amplitude measurements are relative and not absolute. The SDR hardware is not calibrated in absolute terms. The device gain is not perfectly constant over the spectrum. Point by point amplitude measurement accuracy can be improved by comparing a test signal of known amplitude with the analyzed signal of the unknown amplitude.

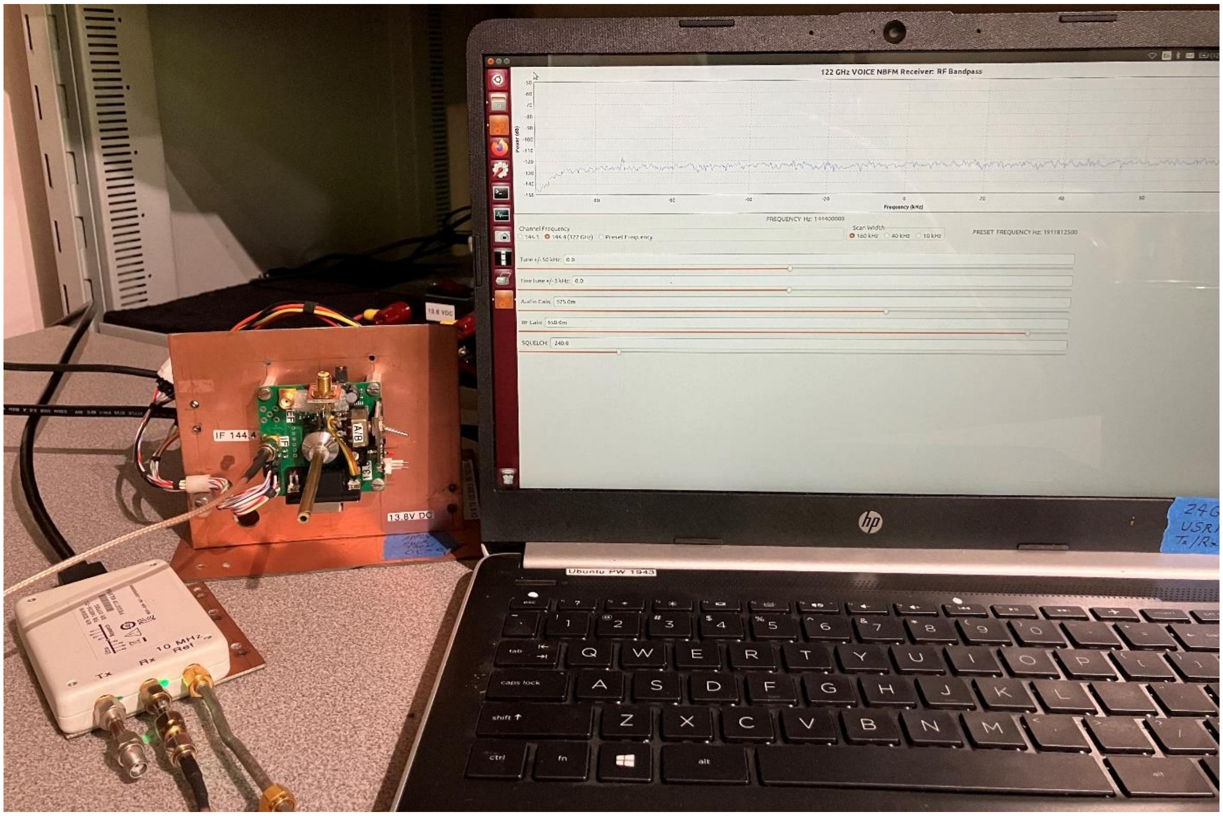


Figure 11. W7FU's 122 GHz SDR transceiver system.

5.2. Signal Source and Signal Generator

The SDR device transmit function can be configured as a signal source and used as a signal generator for testing purposes. For example, we use the signal source to tune receivers and receiver preamplifiers, RF filters, and with return loss bridges and the like. To generate a test signal, the software is set to transmit a constant carrier (usually FM mode without modulation) at the desired frequency and output level. The signal source frequency can be set to any frequency in the native frequency range of the SDR device. In some test situations, we add an external attenuator or external amplifier to tailor the signal output to the needed level.

5.3. Extending the Frequency Range

Spectrum measurements at frequencies beyond the native range of the SDR device, require an external mixer and LO. All the functionality of the spectrum analyzer is retained when used with a mixer. The frequency conversion approach is the same described above for a microwave transceiver system.

An upconverted, non-harmonic, signal is most useful to tune 10 GHz RF multi-cavity filters, pipe cap filters, amplifier blocks, and return loss bridges. It is not always necessary to up-convert the signal source for testing microwave equipment. Testing of sensitive microwave receivers, for example, only require low signal levels. Harmonic signals from the SDR device are usually of sufficient amplitude. Our SDRs provide detectable harmonic signals through 76 GHz.

Our attempts to configure the separate transmit and receive channels of our SDR devices to function as a swept scaler network analyzer (combine the spectrum analyzer and signal source) failed. The poor transmit and receiver port isolation (PCB RF leakage) is the culprit. An approach for point-to-point network analysis is to use a signal generator as an external signal source, and the SDR device as the spectrum analyzer. We use homebrew synthesizers built around the ADF4351[7] and ADF5355 ICs[8]. Frequency discipline with an external reference permits precise signal frequency calibration of these synthesizers.

6. Conclusion

Construction of a station with an SDR device relies on the traditional first principles of radio architecture. The SDR devices permit an alternate approach to implement radio transceivers with some advantages. In the end, there is nothing magic about using SDR devices for VHF through microwave stations.

Operationally, we find the complexity of a computer and software interface is offset by the frequency flexibility of the hardware design and the multitude of software features that permit enhanced operational performance. A downside of this type of station is the difficulty of maintaining a computer in the field (i.e., excessive daylight brightness and eventual rain are problems to be overcome). We have each built small computer enclosures from various materials to help keep the computers dry and the screens visible. None are perfect. The test instrument potential with this equipment is adequate for most of our amateur home projects.

7. On-the-Air Cautionary Notes

The core of the SDR device, the transceiver RFIC, is designed to be broadband and offer minimal losses. In other words, the input and output ports are unfiltered. Receiver reciprocal mixing and a high receiver noise floor is an issue at VHF/UHF frequencies, particularly in situations where we share the same RF dense mountain top location with nearby FM and TV antennas. A high pass receiver filter prevents severe reciprocal mixing. For less RF dense environments, high Q antennas, such as a high gain Yagi antenna, or a mixing converter at microwave frequencies adequately suppress these out-of-band signals.

The SDR device transmitter is rich in harmonic signals. Amplified harmonics are a significant regulatory issue. Output low pass filters are a necessary component in any advanced VHF/UHF transceiver enhanced with external PAs and especially when broadband amplifiers are used. Simple pipe cap bandpass filters provide adequate filtering for our mixer-based microwave stations.

References

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