The IQ+ Dual Channel Receiver

A Practical Implementation against Faraday Rotation

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Introduction

After playing for a long time with simple Software Defined Receivers for VHF based on the Softrock SDRs, with mixers, transverter kits and crystal local oscillators, in 2010 I took the challenge to produce a versatile, simple and easy to manage dual channel IQ receiver having *Linrad* as its core software. The goal was to build an Adaptive Polarization receiver for 144 MHz at our club station, HB9Q, and at the same time have a portable receiver that we can use in DXpeditions.

In previous years we finished the installation of a dual feed for 144 MHz in our 15.1 m dish. Our first system was based on the WSE boxes designed by Leif SM5BSZ with outstanding performance; but unfortunately these excellent receivers are big, heavy and need a dual power supply, making portable operation quite difficult.

My experience with Rx systems was not great, so to build a receiver was a completely new technical challenge for me. For that reason I made direct contact with SM5BSZ, who helped me from the beginning and motivated me several times when things were not going in the direction I expected. I am thankful for the tremendous help that Leif gave to my IQ+ project.

The most difficult part was to decide how to convert the 144 MHz signals into a usable spectrum for an adaptive polarization receiver. Questions like: shall I use the audio card as A/D, or would it be better to build an embedded A/D converter?

Because my small electronic lab has limited ability to make sophisticated printed circuit boards, I decided to involve another friend who would help me with the CAD design. George Boudreau (http://www.yoyodyneconsulting.ca) has a small independent design house in electronics, based in Toronto Canada, and dedicated specially to A/D audio converters and some SDR designs. George was responsible for translating my diagrams into usable PCB circuits.

My original idea was to produce four radios, two for HB9Q and two for me, but the great demand has transformed this IQ+ project into a much bigger operation, with 40 units sold and another 50 pre-orders on the waiting list. Hand assembly was taking me 22 hours for each receiver, with two new pre-orders arriving for every unit shipped! To meet this demand, I have been forced to change to more professional construction techniques.

But most important of all is that **the performance of the IQ+ exceeds all my expectations**, so now I am sharing with you that experience.

Signal Polarization on the EME Path

On lower bands like 50, 144 and 432 MHz, linear polarized antennas are the world standard. But even if we transmit in a standard polarization, in EME operation the polarization of the received signal will almost certainly be different. This polarization change can be a big problem for us, as it can lead to reduced signal strength, apparent ‘one-way propagation’ and even complete ‘lockout’ between two stations [1].

As is well known, the change in polarization is the sum of three different components. The fixed component is the predictable ‘spatial’ rotation due to the difference in longitude between two stations; but as the EME signal passes outward through the ionosphere and back inward again after reflection from the moon, Faraday rotation will cause two additional polarization changes that are much less predictable.

Faraday rotation is inversely proportional to the frequency squared. At lower frequencies the rotation is larger and also changes more rapidly with ionospheric conditions, which can make QSOs more difficult on 50 and 144 MHz. When operating 50 MHz EME for the first time from Namibia as V55EME, during a single 1-minute Rx period I would often hear a strong signal that would disappear in the next 30 seconds, come back strong and then start to disappear yet again – a real nightmare for the operator. On 432 MHz, the much slower rates of change bring a different kind of problem: if the ionosphere is relatively stable, polarization can become ‘stuck’ at an inconvenient angle for several hours.

Rotatable Antennas and Switchable Yagis

To defeat these problems of polarization, one solution has been to physically rotate the complete antenna array. This is easier to do with a small dish feed, or with a 432 MHz Yagi array [1], but almost impossible with the much larger Yagi arrays for 144MHz and 50 MHz because of the extremely unbalanced weight and wind loading. Optimum polarizations are different between Tx and Rx, and rotation of the whole large array can lose valuable time from every Tx and Rx period. Rotating the dish feed on 144 MHz was evaluated initially at HB9Q but we discarded even this simpler idea due the mechanical complexity.

That is why crossed Yagis have gained a lot of popularity on the lower EME bands. The number of 144 MHz stations with that capability has increased enormously during recent years. Having both polarizations on the same antenna axis and switching the feedlines (horizontal or vertical) is a tremendous step against Faraday and spatial rotation, but simple polarization switching can only help properly when the polarization mismatch is close to 90°. If the angle mismatch is 45°, the attenuation will be 3 dB with either polarization [1].

Options for Adaptive Polarization Reception

The only way to make an improvement for receiving will be to have separate receivers for vertical and horizontal polarization, and to make an optimally weighted vector sum of the signals coming simultaneously from both channels. The crossed Yagis will then have electronically rotatable linear polarization to any angle. The best approach for that was the Adaptive Polarization system developed by Leif SM5BSZ more than a decade ago, with his WSE converters and his fantastic software *Linrad* [2]. The IQ+ receiver is a consequence of that pioneering work by Leif.

An Adaptive Polarization antenna system requires two crossed antennas (or arrays) mounted at 90° to each other in either the ‘+’ or the ‘X’ configuration. Each polarization has its own preamplifier, feedline and receiver, and these two receiving channels must be as closely matched as possible in terms of NF, gain and phase shifts. Errors can be compensated by various means, both electrically and in software, but the basic aim should be to make the two receiving channels identical in every respect.

Then comes the two-channel A/D converter and DSP software. PC audio cards have long been popular with SDR users, especially as the performance of high-end models continues to improve and prices continue to fall. That last point is important because an Adaptive Polarization receiver requires two stereo audio cards (or more likely today, two USB audio interface units).

WSE and Linrad

Leif SM5SBZ proposed more than a decade ago his Adaptive Polarization system with two main components: the WSE hardware and *Linrad* software [2].

WSE units are state-of-the-art receivers assembled from four different units. The first three are a chain of dual-channel downconverters from 144 to 70 MHz, from 70 MHz to 10.7 MHz and then down to 2.5 MHz. The fourth unit is the dual-channel SDR which converts 2.5 MHz into two IQ pairs of baseband audio signals with a 90 kHz bandwidth. All four WSE units have very low phase noise local oscillators and an outstanding dynamic range. When properly calibrated and integrated with *Linrad*, they make a laboratory-standard signal processing system. Fifty WSE systems were produced and I think 30 active stations are using them. These units are not produced any more but diagrams and PCB CAD templates are published under the *Linrad* homepage [2].

Linrad doesn't need a presentation here. It is sophisticated software able to do a lot of things, and with the best noise blanker I ever heard. All these fantastic characteristics are not free – you will need some computer experience to run *Linrad* properly – but *Linrad* today is more accessible to the masses with less complex setup routines than previous versions many years ago. *Linrad* received another boost when *MAP65* (the wideband WSJT decoder by K1JT) was introduced a few years ago, because *MAP65* was originally designed to use the WSE hardware followed by *Linrad* as a DSP front-end.

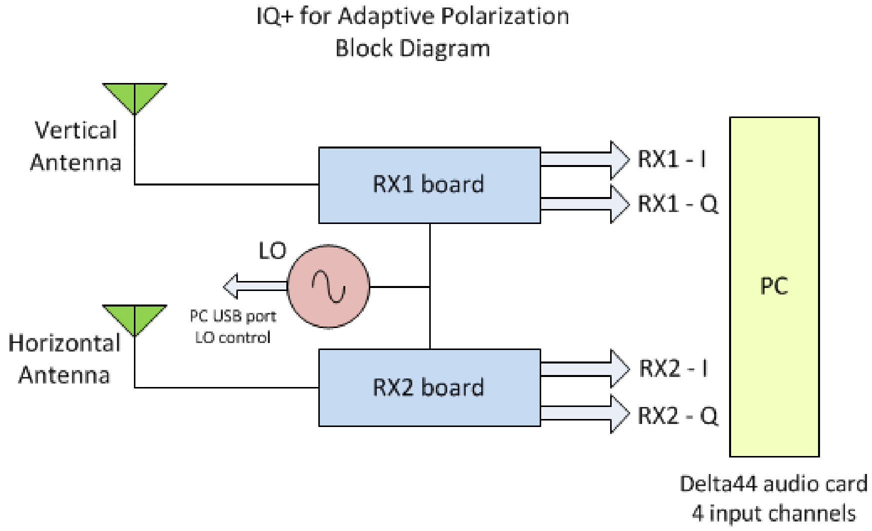
Another option for an Adaptive Polarization system is the famous Softrock SDR. More than 20,000 units have been sold, especially to the QRP and HF enthusiasts. For less than $30 per unit, this device has an outstanding performance in terms of cost/benefit ratio. For Adaptive Polarization you will need two of these receivers running at 28 MHz or 14 MHz as an IF, and two matched downconverters from your VHF band. In addition, all modules must share the same LO signals for each conversion to achieve phase tracking between the two channels. Integrating all these modules correctly will demand some electronic expertise. The results will be better than fixed linear polarization, but not as good as the WSE hardware.

Another more complex option is to build your own receivers based on special down-converters equipped with dual channels, like KL7UW did, but I think this option is more complex and will cost more [3].

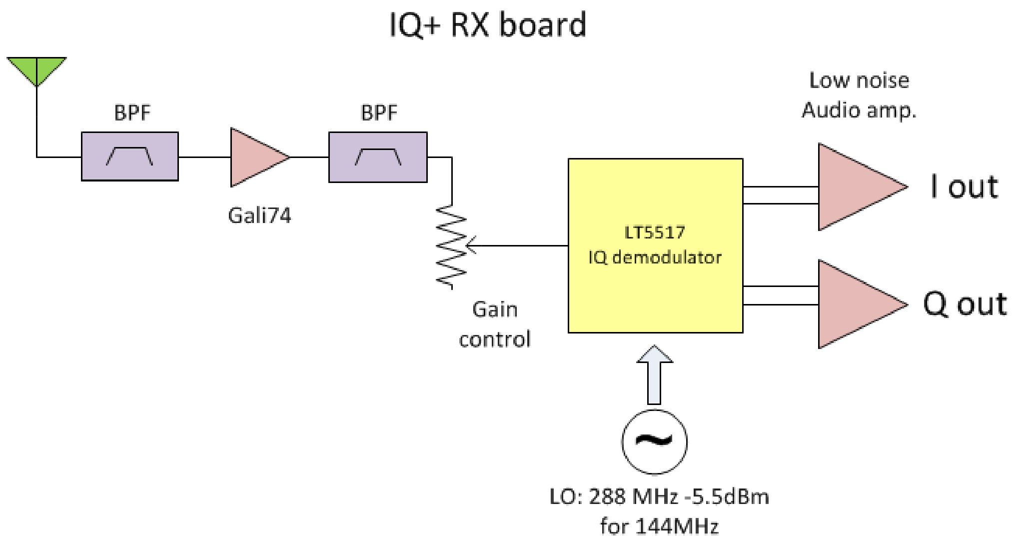
The IQ+ Dual Channel Receiver

The IQ+ is a very small dual channel receiver with direct conversion from signal frequency to the audio baseband. The base model 'IQ+ V' is for 144 MHz, and for other bands the 'IQ+ VL' (50 MHz) and 'IQ+ U' (432 MHz) will be available in due course. Presently the IQ+ is the only available 'ready to use' dual channel radio for Adaptive Polarization.

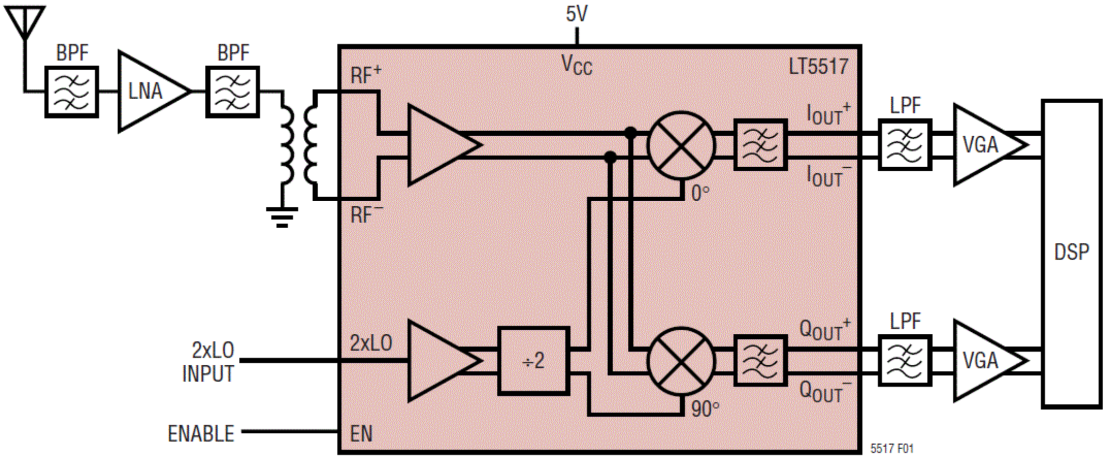
The IQ+ is essentially two identical receivers, RX1 and RX2 for horizontal and vertical polarization respectively, integrated onto a single PC board [4]. The receivers have independent antenna inputs, and are fed with the same LO frequency (from a separate board) to provide controlled gain and phase characteristics. After the down-conversion, each receiver channel produces an IQ pair of audio outputs. These are connected to the stereo inputs of two PC audio interfaces such as the Delta44 or later models which act as the A/D converters. Software for the IQ+ will be discussed in a later section.



The next block diagram show the main structure of a single receiver channel on the IQ+ board. The core is the LT5517 IQ demodulator from Linear Technology. There are some applications examples on the web, but all the designs I studied didn't consider the presence of an external preamplifier. Most implementations also had an inadequate distribution of the noise increment between stages. This is the reason why I introduced a gain control after the internal amplifier, to regulate the noise contribution without destroying the dynamic range. The GALI74 was selected for the input LNA because it has a very good OIP3 (+38 dBm) and around 25 dB gain on 144 MHz. With that performance there is enough scope to attenuate the gain before the IQ demodulator without seriously affecting the dynamic range of the whole receiver.



The central core of each receiver is the LT5517 IQ demodulator from Linear Technologies. I and Q mixers, LO divider and quadrature generator and post-conversion lowpass filters are all integrated in this small chip, just 4x4mm.



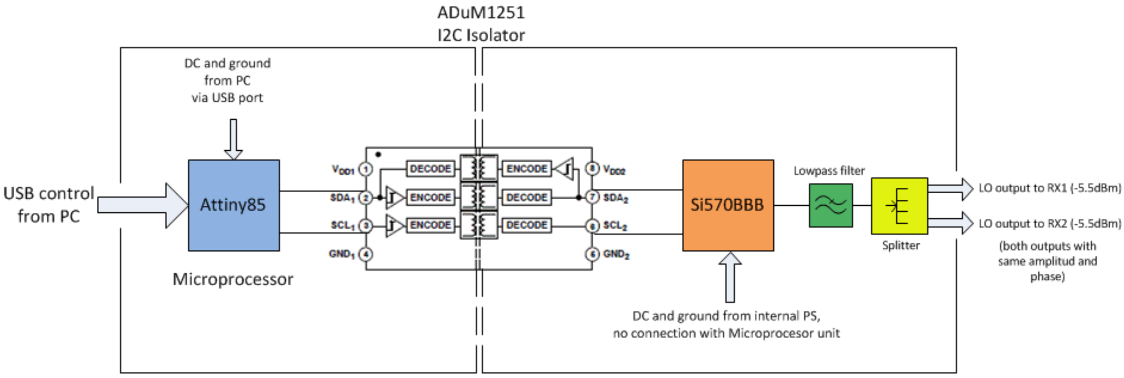
The main characteristics for the LT5517 are:

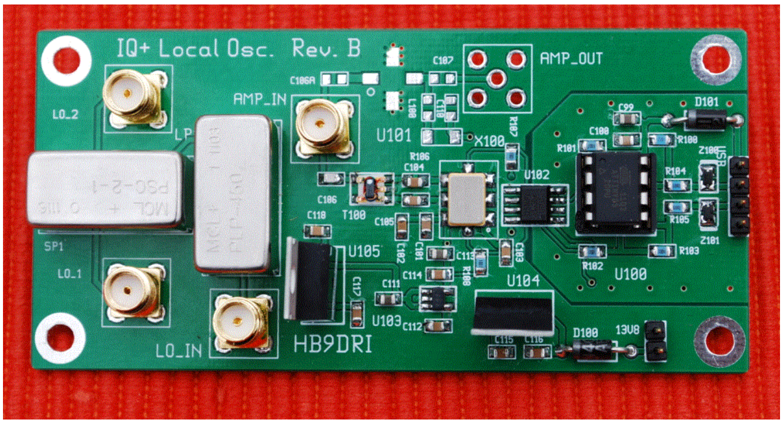
- RF Input Frequency Range: 40 MHz to 900 MHz (I have tested the LT5517 from 3.5 MHz to 1.3 GHz and works)
- High IIP3: 21 dBm at 800MHz
- High IIP2: 58 dBm at 800MHz
- I/Q Gain Mismatch: 0.3 dB max
- I/Q Phase Mismatch: 0.7°
- Noise Figure: 12.4 dB at 800 MHz
- Conversion Gain: 3.3 dB at 800 MHz
- Baseband Bandwidth: 130 MHz
- LO Input: at 2x f, single ended, 50 Ω matched
- Shutdown Mode
- Package: 16-Lead QFN (4mm X 4mm) with exposed pad

The next block diagram and photograph show the LO and the innovative solution to isolate DC and ground loops from the USB port to the IQ+. With this isolation we avoid artefacts, spurs and any electrical noise normally present on the noisy USB port. The oscillator part is done with the Si570BBB operating in grade A (up to 945 MHz). The RF output from the Si570 is injected to a Mini Circuits low-pass filter, cutting down the forest of harmonics normally produced by this chip's square wave output.

I decided to use the Si570 because of the possibility to change the frequency in an easy way, down to 1 Hz steps if needed. This gives the possibility to move the centre frequency within the 2 MHz band, which will help especially when the weak signals are too close to a birdie or artefact. Just moving your centre frequency a few kilohertz can allow you to place the desired signal in a clean area of spectrum. But this frequency agility also has some compromises in terms of phase noise; if you have strong signals in your passband near your DX frequency, probably the strong signals will overtake the weak signals. In that situation it would be better to have and LO with the lowest possible phase noise; but fortunately this rarely occurs in EME and I have not seen any adverse effect with the Si570 LO on air.

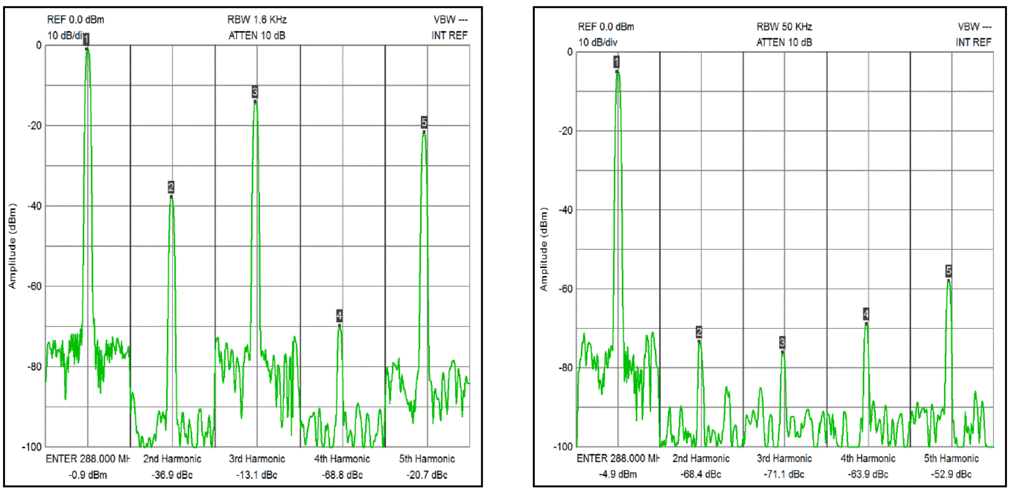
To keep same amplitude and phase, the clean signal is divided into two outputs with the same amplitude and phase via a 2-way 0° splitter. With an insertion loss of 3.4 dB in each port the amplitude unbalance is only 0.01 dB and the phase unbalance is only 0.07° (all measurements at 288 MHz).





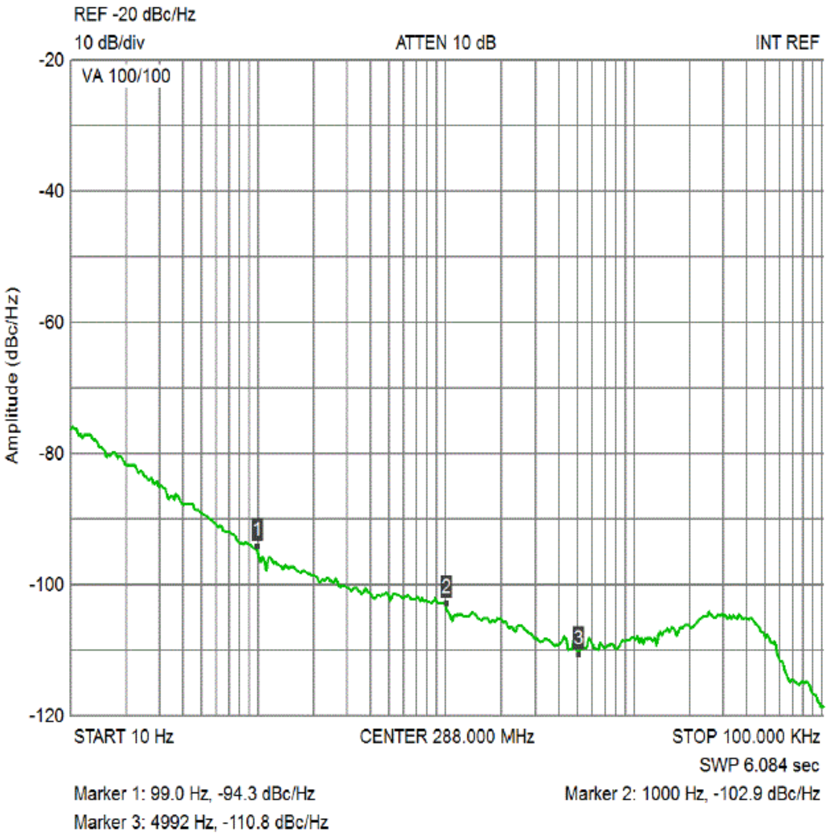
The IQ+ LO board

The output of the Si570 is a square wave so a low-pass filter is essential, as shown below. After the filter the harmonic levels are adequate.



Si570 harmonic levels, before and after the low pass filter

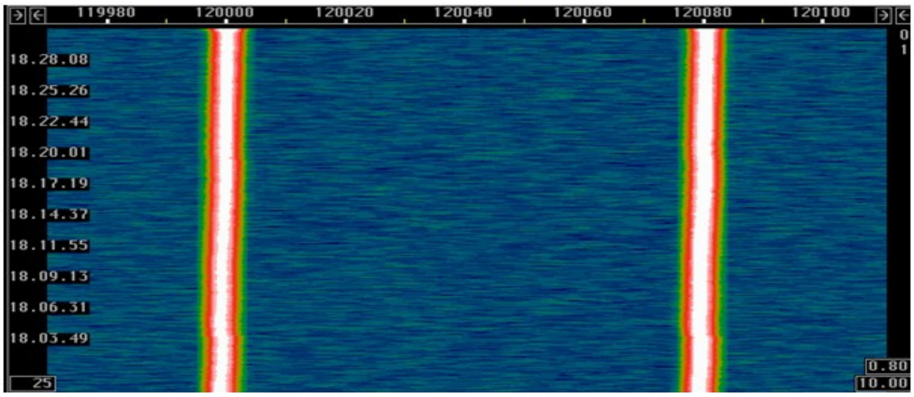
The next graphic shows the phase noise plot at the LO input frequency at 288 MHz. This is not in the same league as a WSE receiver but again it is adequate.



I received some requests to lock the LO frequency to an external reference like 10 MHz. After several tests I concluded that the IQ+ LO is stable enough to work without any external reference oscillator. You only need to lock your LO with an external reference if your LO drifts too much, and this is not the case for the IQ+.

The LO will have a heavy drift following a cold start, but the IQ+ V (144 MHz) and the IQ+ VL (50 MHz) need only 10 minutes to reach maximum stability, while the IQ+ U (432 MHz) will need 30 minutes. After that warmup period the LO is very stable.

In the next figure you can see 100 Hz of BW and two carriers, at 144,120.00 kHz and 144,120.08 kHz respectively. Both carriers are locked with same 10MHz external reference so any sideways drift is due to the LO in the IQ+. The image represents 25 minutes of a waterfall display, so the short-term LO drift is less than 0.1 Hz/min. Long term stability was not tested but you can see more details about the stability of the Si570 at reference [4].



Regarding sensitivity, it is important to remark that the IQ+ is designed to work with an external preamplifier, which means that it would not be correct to compare the IQ+ with other radios that have been designed to work in the much more noisy RF spectrum below 30 MHz. The following measurements have been made, first with no preamplifier, and again with an external preamp (25 dB gain, 0.3 dB NF).

- Input IP3 +7 dBm (no preamp), –18 dBm with external preamp
- Dynamic Range 110 dB (no preamp), 93 dB with external preamp
- NF 9 dB (no preamp), 0.39 dB with external preamp (calculated)
- Sensitivity @ 500Hz BW:
  Noise floor IQ+ -146.7 dBm
  Noise floor with external preamp –121.7 dBm
- A/D saturation:
  At IQ+ input –118 dBc/Hz
  At external preamp input –93 dBc/Hz
- LO Level –5.6 dBm for IQ+ VL and V; –10.0 dBm for IQ+ U
- LO Phase Noise:
  –110.8 dBc/Hz @ 5 kHz (288 MHz)
  –107.0 dBc/Hz @ 5 kHz (864 MHz)
- LO Stability : ± 20 ppm from –40 to +85°C
- Phase Unbalance Port1 - Port2
  0.05° @ 100 MHz
  0.01° @ 288 MHz
  0.35° @ 864 MHz
- Amplitude Unbalance Port1 - Port2 :
  0.00 dB @ 100 MHz
  0.03 dB @ 288 MHz
  0.03 dB @ 864 MHz

Software for the IQ+

The IQ+ is compatible with a range of software under Linux, Windows and MAC. The software must carry out two major functions: LO control and acting as the front-end for data processing.

Linrad is the default software for LO control. Some other control programs have 'diversity' functionality but they are oriented mostly for the HF bands. The LO in IQ+ is based on the free USB AVR Code by Tom Baier (DG8SAQ) who used it in his own Si570 board. The IQ+ LO use the firmware from PE0FKO v 15.14 and to configure the firmware there is a Windows configuration tool *CFGSR*. The *CFGSR* tool will allow you to configure most parameters on your Si570BBB chip but we don't recommend to play with this tool if you don't have the proper know-how. Unexpected behaviour or even damage to the chip could happen with improper operation.

For data processing the IQ+ is compatible with both *Linrad* and *MAP65*, and these are the only two programs capable of Adaptive Polarization. For CW *Linrad* has an extraordinary set of filters and noise blankers, and can also be used to send data to *MAP65* for the WSJT modes. The original version of MAP65 requires *Linrad* as a front-end, but the new *MAP65 Version 2* [5] has the option to interface directly to the IQ+ and offers decoding of all WSJT signals in a 90 kHz window, with individually optimized polarization for each signal. Initial comparisons demonstrate that this works really well, but for those who demand a more sophisticated noise blanker the recommendation will be to use *Linrad* as a front end and then send the data to *MAP65 v2*.

Improvements in IQ+ Rev.B

Starting from about the time of this EME Conference, the IQ+ boards will be assembled using automatic machinery in a professional factory in the USA. The boards will be tested and the complete radios assembled in Switzerland. This move should reduce my work input from about 22 hours per radio to only 3 hours, and after the existing pre-orders have been filled I hope to be able to ship the IQ+ within 72 hours [6].

Organizing this has not been easy, but because the PCBs needed to be done again I decided to add some improvements based on the feedback from the first users. For that reason the Rev.A is retired and all future radios will be Rev.B with the following improvements.

The most important change will be the internal preamplifier. Rev.A used the GALI74 MMIC with 25 dB gain and, as mentioned earlier, this excess of gain forced me to install a variable attenuator between the last BPF and the LT5517 to distribute the noise levels properly; but this technique also reduce the final IIP3 of the radio by several dB with a corresponding impact on the dynamic range and 1 dB compression point. At present I have prototypes under test and at the EME Conference I will present the definitive design for the internal preamp. Initial calculation shows that the IIP3 can be increased by at least 10 dB while also reducing the NF by about 1dB, together giving an increase of 5 to 10 dB or more in the SFDR (spurious free dynamic range).

An important improvement on the Rev.B Local Oscillator board will be an auto-reset on the USB port when you switch the radio on or off. (With Rev.A if you switch off and then on again the LO re-starts on a default frequency instead of your desired frequency. The work-around is to unplug the USB port and re-plug again.)

Several Rev.A users reported that the central “zero IF” birdie was too big, creating about 500 Hz of unusable spectrum unless the LO frequency was manually changed. This central birdie cannot be eliminated but it can be reduced drastically. The Rev.B boards have some modifications on the ground system and DC decoupling (audio stage) and now the unusable spectrum will be 100 Hz or less, depending on your ground system and the grounding of the audio card or USB adapter in the PC. I observed that some audio cards like EMU1616m PCIe have a lower central birdie than the MAYA44, DMX6Fire or Delta44.

Last but not least, the Rev.B dual receiver card will improve the low-pass filtering between the output of the LT5517 and the opamp audio stage. Additional improvements have been made to the low-pass characteristics of the audio stage itself, to further protect the audio card from aliases.

All of these changes will be introduced in the next version, IQ+ Rev.B, which should be available from September 2012 [6].

Installing the IQ+ System

A proper installation is necessary to avoid performance degradation of the IQ+.

The most important is to use a clean, linear DC power supply. Any switching power supply will be sure to introduce birdies and artefacts that appear on the waterfall. The best power supply for the IQ+ is the standard ‘old style’ linear regulated power supply with a mains transformer inside.

Another important point is about your ground systems. I have helped several IQ+ Rev.A users via remote control over the Internet and have demonstrated poor ground systems with a lot of ground loops. It is mandatory to ground your IQ+ to the PC chassis and the PC needs to have a proper ground in your mains supply. Do not directly ground the shields of your audio cables at the output of the IQ+ or you will have strong AC returns to the audio stage. At the four audio outputs of the IQ+, the shields for the audio cables are connected to the groundplane of the board through on-board resistors – these were 25 Ω in Rev.A and have been increased to 100 Ω in Rev.B.

Another point is where you place the IQ+. It needs to be in an area of free air flow, out of direct sunlight and not near any fan, mains power supplies or power amplifier.

The last important point is about your external preamplifiers. The IQ+ **requires** preamplifiers with at least 24 dB gain. The optimal values are 26 dB for 144 MHz and 35 dB for 432 MHz. As a simple test, switching on and off your preamps needs to show a difference in noise levels of at about 16 dB. The minimum acceptable change to avoid degradation of system NF is 14 dB, and the maximum allowable to avoid degradation of the IIP3 is 20 dB.

If your antenna system is located in a very RF polluted area, you will also need to install an external bandpass filter. I had this situation at HB9Q: a microwave data link just 300 metres from our antenna introduces a lot of noise and interference every time the Moon azimuth passes through this direction. We introduced a 500 kHz wide BPF in each RX channel between the LNAs and the IQ+ and the problem was solved. There are several commercial options but you can also find several EME stations on the Internet with good design that are easy to build.

And Finally…

I like to do what I'm doing and my job doesn't finish when I send an IQ+ to its new owner. Every IQ+ user can request my assistance via the Internet, even if this takes a lot of time. For 'online' support I use the *TeamViewer* software, a fantastic tool which allows me to connect to your PC and then diagnose and configure your IQ+ setup in minutes. Several IQ+ users have already benefited from my personal assistance. If you have a problem with *Linrad*, *MAP65* etc (and even if you don't have an IQ+), just send me an email and I'll see what can I do to help.

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