Low Cost Hydrogen Line Radio Telescope using the RTL SDR - Phase 3

Abstract

This paper describes the phase 3 upgrade, further improving the receiver. A dual channel switched receiver based on the pseudo-correlation continuous comparison receiver(1,2) *is described that seeks to minimise the effects of gain variations. Early results show excellent repeatable performance.*

Introduction

In the basic receiver paper(3), it was noticed that receiver gain (60dB RF and 49dB for the RTL SDR) drifted between measurements affecting both FFT average and ratio/temperature determination. In this upgrade a switched correlation receiver approach is adopted to minimise the effect of gain drift. Receiver units were boxed in aluminium to further reduce external interference. Two parallel channels, as well as requiring more hardware, unfortunately require two SDR dongles and computers capable of synchronised recording. Ideally the dongles should be matched, but innate frequency tuning accuracy can be compensated.

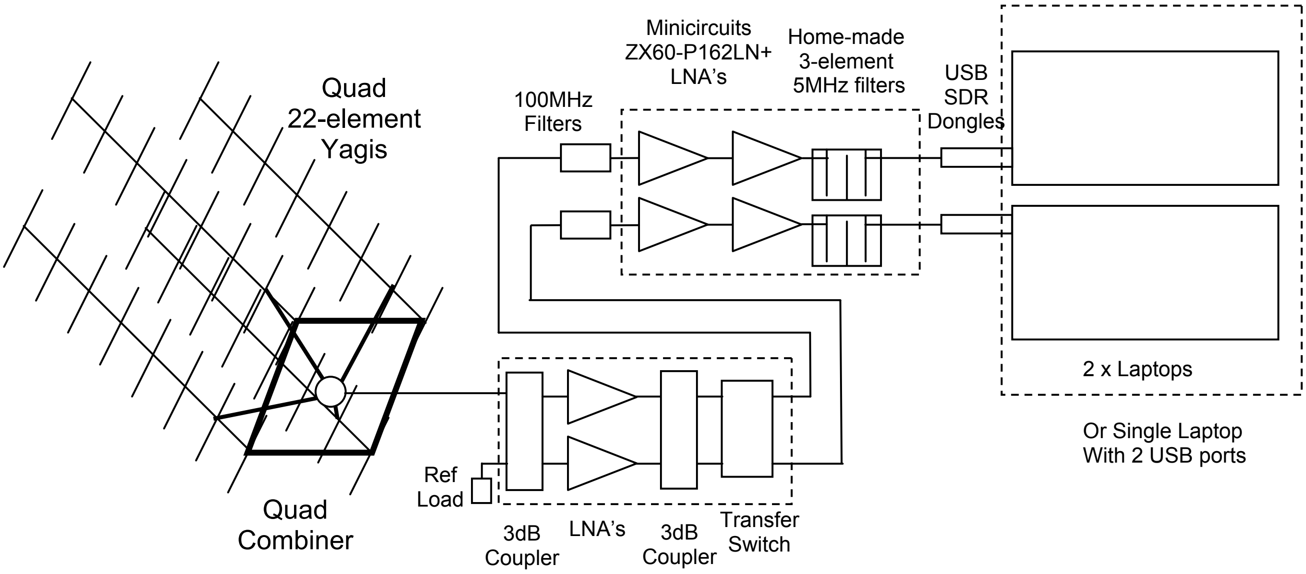

Figure 1. Simple Radio Telescope Upgrade 3

Figure 1 shows the upgrade schematic. The receiver is now boxed in three units, the switched preamplifier closely attached to the antenna and the remaining twin channels, placed remotely near the SDR/Laptop processors. If the PC/Laptop computer has two separate USB ports then it is possible to run two SDR dongles on one computer, otherwise two synchronised computers are necessary. Synchronising software is identical for either option (see Appendix 2).

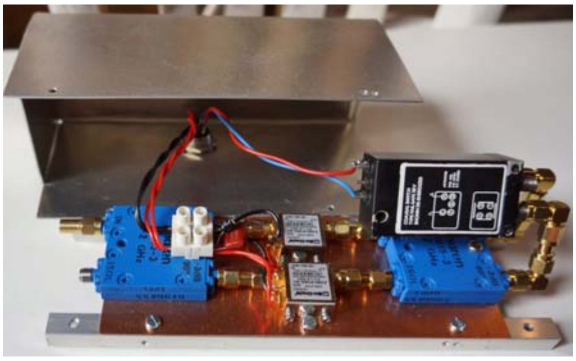

Figure 2a Preamplifier/Switch Unit

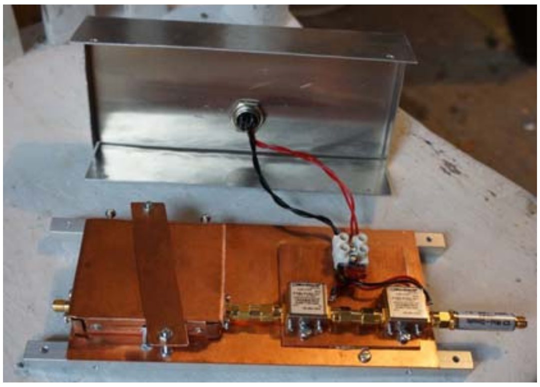

Figure 2b Post-amplifier/Filter Unit

Receiver Description

The receiver architecture follows the basic form of the earlier receivers and similarly applies the ratiometric Dicke-Fix(5) processing described previously.

The preamplifier/correlation receiver (Figure 2a) is now comprised of two 3dB couplers from Anaren (1-2GHz type: 10015-3) and two low noise amplifiers (Minicircuits ZX60-P162LN+) with a transfer switch (Sivers type PM7553) at the output. The couplers may be 90º or 180º types (see Appendix). The first coupler splits the input signals equally between the two similar amplifiers, whilst the output coupler recombines the amplified signals and splits them to the output ports such that the amplified input signals are isolated and exit different ports. Effectively, both input signals pass through both amplifiers and so are equally affected by any amplifier gain changes so that any subsequent comparison preserves that of the two inputs. Detailed analysis is given below.

The correlation receiver outputs are amplified and filtered in the secondary twin channel units shown in Figures 1 and 2b, that feed a corresponding pair of RTL2832U SDR dongles. Operation of the transfer switch re-directs the preamplifier output signals to the opposite amplifier chain and SDR dongle. This enables compensation of the two channel amplifier/dongle gain differences.

In addition, it may be necessary to adjust spectrum measurements or dongle frequency settings to match different SDR frequency measurement accuracies.

Receiver Operation Analysis

Figure 3 shows a basic schematic of the total receiver system.

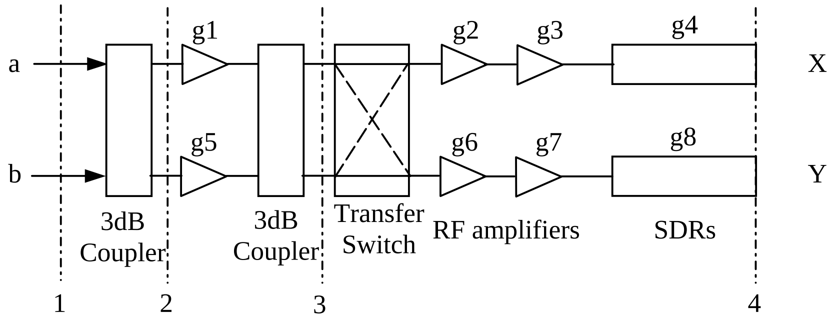

Figure 3 Twin Channel Switched Receiver Chain

The top channel is denoted ‘X’ with a generalised input signal ‘a’ and the lower, second channel ‘Y’ with an input signal ‘b’. 180º couplers are assumed so that the voltage outputs of the input coupler, at position ‘2’ after the first coupler in Figure 3, are $\frac{a}{\sqrt{2}}+\frac{b}{\sqrt{2}}$ in channel ‘X’ and $\frac{a}{\sqrt{2}}-\frac{b}{\sqrt{2}}$ in Channel ‘Y’, as shown in Table 1.

Channel	1	2	3	4
X	a	$\frac{a}{\sqrt{2}}+\frac{b}{\sqrt{2}}$	$\left(\frac{a+b}{2}\right)g1+\left(\frac{a-b}{2}\right)g2$	$\left(\left(\frac{a+b}{2}\right)g1+\left(\frac{a-b}{2}\right)g5\right)g2g3g4$
Y	b	$\frac{a}{\sqrt{2}}-\frac{b}{\sqrt{2}}$	$\left(\frac{a+b}{2}\right)g1-\left(\frac{a-b}{2}\right)g2$	$\left(\left(\frac{a+b}{2}\right)g1-\left(\frac{a-b}{2}\right)g5\right)g6g7g8$
X_{Sw}	a	$\frac{a}{\sqrt{2}}+\frac{b}{\sqrt{2}}$	$\left(\frac{a+b}{2}\right)g1+\left(\frac{a-b}{2}\right)g2$	$\left(\left(\frac{a+b}{2}\right)g1-\left(\frac{a-b}{2}\right)g5\right)g2g3g4$
Y_{Sw}	b	$\frac{a}{\sqrt{2}}-\frac{b}{\sqrt{2}}$	$\left(\frac{a+b}{2}\right)g1-\left(\frac{a-b}{2}\right)g2$	$\left(\left(\frac{a+b}{2}\right)g1+\left(\frac{a-b}{2}\right)g5\right)g6g7g8$

Table 1 Channel voltages - 180º Couplers

In Table 1, X and Y are the channel outputs with the transfer switch in the straight through position. X_{Sw} and Y_{Sw} are the outputs when the transfer switch is in the crossover position. The amplifier gains g_n are voltage gains and g_n^2 are the corresponding power gains. For proper combination at the output coupler it is essential to ensure that the through phase of both channels is near identical.

Channel	Power
X	$\left(\frac{a^2}{4}(g1+g5)^2+\frac{b^2}{4}(g1-g5)^2\right)g2^2 g3^2 g4^2$
Y	$\left(\frac{a^2}{4}(g1-g5)^2+\frac{b^2}{4}(g1+g5)^2\right)g6^2 g7^2 g8^2$
X_{Sw}	$\left(\frac{a^2}{4}(g1-g5)^2+\frac{b^2}{4}(g1+g5)^2\right)g2^2 g3^2 g4^2$
Y_{Sw}	$\left(\frac{a^2}{4}(g1+g5)^2+\frac{b^2}{4}(g1-g5)^2\right)g6^2 g7^2 g8^2$

Table 2 Power Output

Table two shows that if the gains g_1 and g_5 are not equal then there is signal leakage between the outputs and therefore the ratio measurement will be distorted. However, further analysis shows that if the gain difference is less than about 1dB the error/leakage term can be ignored.

The two measurement ratios are,

$$R1=\frac{Y_{Sw}}{Y}\approx\frac{a^2}{b^2}\frac{(g1+g5)^2 g6^2 g7^2 g8^2}{(g1+g5)^2 g6^2 g7^2 g8^2}$$

$$R2=\frac{X}{X_{Sw}}\approx\frac{a^2}{b^2}\frac{(g1+g5)^2 g2^2 g3^2 g4^2}{(g1+g5)^2 g2^2 g3^2 g4^2}$$

Taking the square root of the product of these ratios, we get,

$$R=\sqrt{R1R2}=\frac{a^2}{b^2}$$

Demonstrating that this result produces a virtually gain-invariant measure of the input powers or temperature.

For completeness it can be shown that the error in *R*, *dR* due to non-equal preamp section gains is,

$$dR=c^2\,\frac{1-R^2}{1+Rc^2},\;\; where,\; c=\frac{1-g5/g1}{1+g5/g1}$$

For all values of *R*, between 0 and 1, the error in *R* is less than 0.012 if, 1.25>*g5/g1*>0.8, implying the preamplifier gains need to match to better than about 2dB.

Receiver Operation – Software Control

With the transfer switch in the straight-through position and the antenna directed at the wanted source, both SDRs are initiated simultaneously to record digitised data for a set time. Similarly, with the transfer switch in the crossover position, simultaneous operation of the SDRs for the same duration, generates a second pair of data files.

To achieve simultaneous recording, two terminal windows, one for each SDR, run a copy of the control software that is set with the desired recording parameters.

Typical control software commands to run two SDRs (-d 0 and –d 1) on a single computer for MS WINDOWS are,

```
>RN_RTLAT "./rtl_sdr dat0.bin –f 1420e6 –d 0 –g 49 –n 100e6" 256 14 24 00

>RN_RTLAT "./rtl_sdr dat1.bin –f 1420e6 –d 1 –g 49 –n 100e6" 256 14 24 00
```

These are run in two Command windows set to the working directory, which also contains the Osmocom rtl_sdr tools.

These commands start recording data from both SDRs at 14hr 24m 0s using the Osmocom rtl_sdr program. In this example, on collection of 100 million samples, the data is analysed in 256 point blocks using a FFT algorithm and outputs averaged spectrum text files dat0.txt and dat1.txt.
Operating the transfer switch and resetting the software commands as required, a second set of files dat3.txt and dat4.txt can be generated.
Inputting these four data text files into Excel or mathcad software the temperature ratio graphs can be produced indicating H-Line characteristics.

Receiver Test Measurements

The antenna measurements recorded and presented in this section used a single 22-element Yagi tuned to 1420MHz. The aim of the measurements was to confirm any improved receiver stability and to calibrate the ratio plots.

Two sets of measurements were made. The first set involved no antenna and the antenna port was left open-circuit, simulating a zero antenna temperature ($T_{ant} = 0$). Note that the open circuit input could also change the low-noise amplifier noise figure and so may not provide an accurate measure of the system noise temperature, but will give a rough guide.

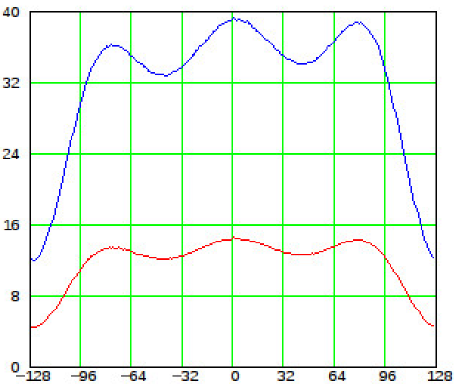

Figure 5a Channel X Spectra

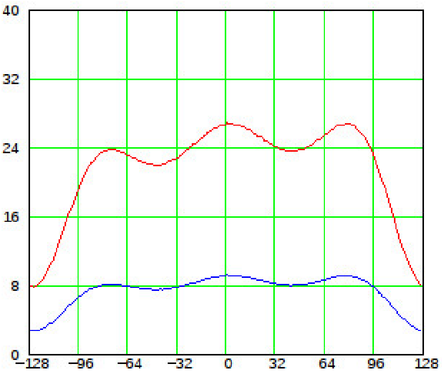

Figure 5b Channel Y Spectra

Figure 5 shows the spectrum plots for the two transfer switch states (Red - switch state 1; Blue – switch state 2). It is immediately evident that there is a significant gain difference between the two channels of some 4dB, and the band profiles do not track exactly.

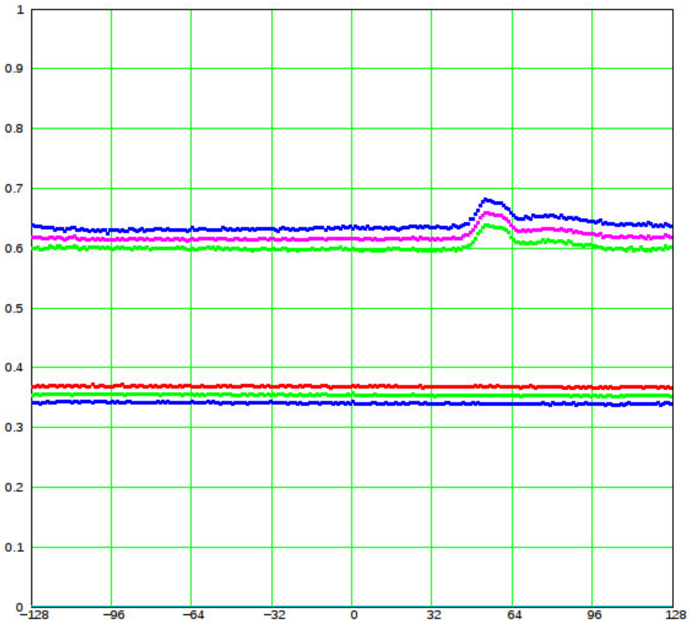

Figure 6 Spectrum Ratios: lower plots – open-circuit input; upper plots – antenna input

The reference/cold ratio appears to be approximately 4.5dB – this can be more accurately determined by forming the ratio as shown in the lower half of Figure 6 (Red – R1, Y channel ratio; Blue – R2, X channel ratio; Green plot – R, the square root of the product of the two channel ratios).

Referring to the lower plots in Figure 6 corresponding to the receiver with an open-circuit at the normal antenna input; the red line is the spectrum ratio from channel X and the blue the ratio of the channel Y measurements (Figure 5). The green line corresponds to the square-root of the product of the X and Y channel measurements.
We can re-calibrate the ratio ordinate by noting that, when $T_{ant} = 0$, from Figure 6, R = 0.35
With these substitutions in the ratio equation $R = .\frac{T_{ant} + T_{sys}}{T_{ref} + T_{sys}}$, together with T_{ref} = 290ºK, we find,

T_{sys} = 156ºK (equivalent to 1.9dB noise figure).
This seems rather high, since the RF amplifiers used have a quoted noise figure of 0.6dB, equivalent to 43ºK. The 3dB coupler may have a loss of around 0.5dB (~35)ºK.
The assumption that with an open or short circuit amplifier input, it still maintains its quoted noise figure may be suspect. There is also the possibility that coupler isolation could affect the measurement accuracy.
Figure 6 can now be calibrated, since R=0.35 is equivalent to 156ºK and from the ratio definition above, ratio R = 1, corresponds to a temperature of 290ºK (T_{ref}) then, for any other value of R,

$$T_{ant} = 446R - 156$$

The upper plots in Figure 6 were measured with the Yagi connected to the preamplifier input (Blue – R1, Y channel ratio; Green – R2, X channel ratio; Magenta plot – R, the square root of the product of the two channel ratios).
The ratio corresponding to the magenta plot baseline is approximately 0.615 and the ratio at the hydrogen line peak is 0.66. Using the equation above, the antenna temperatures are calculated as 118.3ºK and 138.3ºK, respectively. The first is a measure of the antenna sidelobe power and resistive losses. The difference 20ºK is the indicated hydrogen line temperature. The antenna beamwidth is about 26º and, assuming the hydrogen source is mainly constrained to a band 5º centred on zero galactic latitude, then the measure power represents about a fifth of the true hydrogen temperature, now indicating 100ºK which is near to that expected.
Assuming the antenna achieves its designed gain (24dB) and the antenna + system temperature is as calculated above (156+118.3 = 274.3 ≅ 24dB) making the G/T of the system is 0dB.

Conclusions

Gain measurements show that in the correlation receiver section, the amplifiers in both channels match well in both gain and phase. Isolation is better than 20dB. Tests similarly combining the twin amplifier channels with 3dB couplers were inconclusive and appeared not to completely separate the input signals. However the present receiver architecture did demonstrate better stability between measurements than the simpler earlier versions.
More information is available at http://www.y1pwe.co.uk/RAProgs/index.html

References

1. Harris et al, “Design Considerations for Correlation Radiometers”, http://www.astro.umd.edu/~harris/kaband/gbt_memo254.pdf
2. Mennella et al, “Advanced pseudo-correlation radiometers for the Planck-LFI instrument”, http://www.deepspace.ucsb.edu/wp-content/uploads/2013/02/Advanced-Pseudo-Correlation-Radiometers-for-the-Planck-LFI-Instrument-Proceedings-20031.pdf
3. http://www.y1pwe.co.uk/RAProgs/HLRrtl.pdf
4. http://www.y1pwe.co.uk/RAProgs/HLRrtl2U.pdf
5. http://www.y1pwe.co.uk/RAProgs/Ratiometric Dicke Radiometer.doc
6. http://sdr.osmocom.org/trac/wiki/rtl-sdr
7. http://www.y1pwe.co.uk/RAProgs/dos/AMP_STS.EXE
8. http://www.y1pwe.co.uk/RAProgs/linux/amp_sts64.exe
9. http://www.y1pwe.co.uk/RAProgs/linux/amp_stats
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11. http://www.y1pwe.co.uk/RAProgs/linux/bin_txt64.exe

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25. http://www.y1pwe.co.uk/RAProgs/dos/RN_RTLAT.EXE
26. http://www.y1pwe.co.uk/RAProgs/linux/r64_rtl_at.exe
27. http://www.y1pwe.co.uk/RAProgs/linux/run_rtl_at

Appendix

1. RF Gain Variation Tolerance Analysis

Two gain varying processes can be considered.
The first involves gain variation during the measurement dwell period, and the second, gain variation between measurement periods.

Case 1 Single channel switched between the antenna and a reference load(3,4).

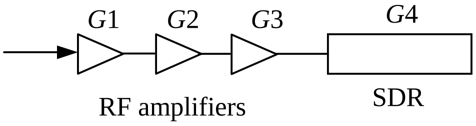

Figure A1 Single Channel Receiver chain

The power gain variation with time can be assumed to be a general function of the form, $G(t)$ ($= G1G2G3G4$).
When switched to the antenna, the output data is proportional to, $(T_{ant} + T_{sys})G(t)$, where, T_{ant} is the antenna + sky temperature, T_{sys} is the receiver system noise temperature and T_{ref} is the reference load temperature.
Along the data record, blocks ‘n’ spectra are derived using the digital Fast Fourier algorithm and averaged.

The antenna data average can be written, $\overline{G_{nA}(t)}(T_{ant} + T_{sys})$

Switched to the reference load, the reference load data average is, $\overline{G_{nR}(t)}(T_{ref} + T_{sys})$

The processed ratio(5) is,

$$R_{proc} = \frac{\overline{G_{nA}(t)}}{\overline{G_{nR}(t)}} \cdot \frac{T_{ant} + T_{sys}}{T_{ref} + T_{sys}} = \left(1 + \frac{\delta G}{\overline{G_{nR}(t)}}\right) . R_{true}$$

where δG is the mean gain change between antenna and reference measurements ($= \overline{G_{nR}} - \overline{G_{nA}}$).

With a knowledge of the reference load and system temperatures, this data ratio allows estimation of the sky noise or target temperature.

For four cascaded amplifiers, the gain variation is approximately, $\frac{\delta G}{G_n(t)} \approx \frac{\delta G_1}{G_1}+\frac{\delta G_2}{G_2}+\frac{\delta G_3}{G_3}+\frac{\delta G_4}{G_4}$

Showing a proportional measurement error dependant on the sum of the gain variations of each gain stage.

Case 2 Twin Channels with post-preamplifier switching

To assess the effect of gain changes between switch states, we rewrite the ratio equations, identifying the switched gains, ie,

$$R1 = \frac{Y_{Sw}}{Y} \approx \frac{a^2}{b^2}\frac{(g1_s + g5_s)^2 g6_s{}^2 g7_s{}^2 g8_s{}^2}{(g1+g5)^2 g6^2 g7^2 g8^2}$$

$$R2 = \frac{X}{X_{Sw}} \approx \frac{a^2}{b^2}\frac{(g1+g5)^2 g2^2 g3^2 g4^2}{(g1_s + g5_s)^2 g2_s{}^2 g_s3^2 g4_s{}^2}$$

Replacing $g2_s{}^2$ by $\overline{G2}\left(1+\frac{\delta G2}{\overline{G2}}\right)$ and similarly for the other switched position gain terms and substituting for these, the wanted ratio R becomes,

$$R = \sqrt{R1R2} \approx \frac{a^2}{b^2}\left(1+\frac{\delta G6}{2\overline{G6}}+\frac{\delta G7}{2\overline{G7}}+\frac{\delta G8}{2\overline{G8}}-\frac{\delta G2}{2\overline{G2}}-\frac{\delta G3}{2\overline{G3}}-\frac{\delta G4}{2\overline{G4}}\right)$$

*G*1 and *G*5 (power gains) are not represented as these cancel perfectly on multiplication. The variance terms are halved due to the square root function. With temperature consistent mean gain fluctuations, it is feasible that some gain variation can now cancel leading to a more stable value of the ratio *R*.
It is possible to incorporate the amplifiers g_2, g_3, and g_6, g_7 within the preamplifier couplers if size and weight allow. This has the advantage that temperature gain drift of these amplifiers is now cancelled and only the SDR error terms of amplifiers g_4 and g_8 remain.

2. Correlation Receiver RF Analysis 90° 3dB Couplers

Figure A1 shows the correlation receiver with 90° 3dB couplers and the corresponding stage signal voltages. The complex maths symbol ‘j’ represents 90° phase shift and ‘j$^{2’}$ 180° or signal negation (since, $j^2 = -1$).

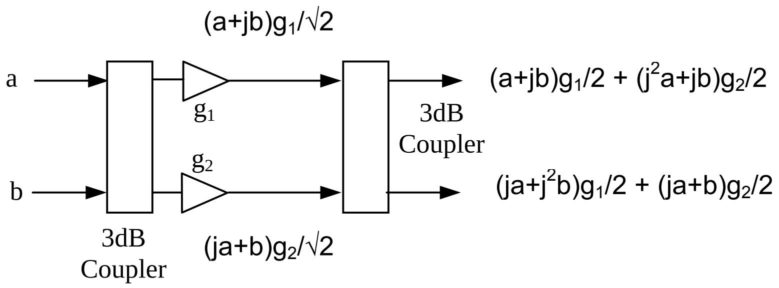

Figure A2 Correlation Receiver using 90° 3dB Couplers

The output signal components simplify to $a(g_1-g_2)/2 + jb(g_1+g_2)/2$, and $ja(g_1+g_2)/2 + b(g_2-g_1)/2$.
This shows that the signal ‘a’ appears at the lower output port amplified by the sum of the two amplifier gains with a 90° phase shift and the ‘b’ signal exits the upper output port similarly phase shifted.
As for the 180° coupler version analysed in the main body, there are similar error components should the amplifier gains be unequal.

2. Software Tools

For MS Windows/DOS – 32bit, (64bit) and Linux versions in [] brackets.

Program	**Function**	**Command Line (Win32)**
AMP_STS.EXE(7) (amp_sts64.exe(8)) [amp_stats(9)]	Takes rtl_sdr.exe(6) binary file and outputs a text file of the SDR ADC data distribution.	AMP_STS <infile> <outfile>
BIN_TXT.EXE(10) (bin_txt64.exe(11)) [bin_txt(12)]	Takes rtl_sdr.exe(6) binary file and outputs a text file of the SDR ADC data.	BIN_TXT <infile> <outfile> <number of 8192 sample data blocks>
RAFFT.EXE(13) (r64fft.exe(14)) [rafft(15)]	Takes rtl_sdr.exe(6) binary file applies the FFT algorithm to data blocks, and averages these over the input data length and outputs a text file	RAFFT <infile> <outfile> <Number of FFT points>
RAFFT2.EXE(16) r64fft2.exe(17)) [rafft2(18)]	As above but data offset to reduce the zero frequency spike.	RAFFT2 <infile> <outfile> <Number of FFT points>
RN_PRGAT.EXE(19) (r64_prg_at.exe(20)) [run_prg_at(21)]	Uses PC clock to run any program at a set time, on one or more PCs simultaneously.	RN_PRGAT <"prog.exe"><hr min sec>
RUN_RTL.EXE(22) (r64_rtl.exe(23)) [run_rtl(24)]	Runs the rtl_sdr(6) program and generates a bin file which is then processed with the FFT algorithm to output spectrum averaged text file.	RUN_RTL <"rtl_sdr data.bin + command line">< Number of FFT points>
RN_RTLAT.EXE(25) (r64_rtl_at.exe(26)) [run_rtl_at(27)]	Uses PC clock to run the rtl_sdr(6) program at a set time, generates a bin file which is then processed with the FFT algorithm to output spectrum averaged text file.	RN_RTLAT <"rtl_sdr data.bin + command line">< Number of FFT points><hr min sec>

Example 1: Running the MS Windows 32 Tools

1. Copy 'command.com' from 'Windows/system32' directory, RAFFT2.exe from the link – Reference (16) and your Osmocom 'rtl_sdr' recorded .bin files to your working directory.
2. Open 'command.com', change the directory to your working directory if required and type in:-
   RAFFT2 <infile> <outfile> 256
   where, 'infile' is your recorded .bin file 'outfile' is any name you choose and could end in .txt as it is a text file. The final command line entry '256' is the number of FFT points you choose. This must be a power of 2.
3. Open it in 'notepad', 'select all', 'copy' and 'paste' in 'Excel' and follow Excel instructions to produce a graphic display.