# A 100 KHZ TO 6 GHZ FAST SCANNING RECEIVER FOR UNDER £1K?


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## ABSTRACT

The original design brief was to achieve a receiver capable of scanning a band from 100 kHz to 6 GHz in less than 1 second. The additional requirements were: an instantaneous bandwidth of up to 20 MHz; a final IF suitable for feeding a digital receiver with around 100 Msps sample rate; a minimum signal sensitivity of -107 dBm and; a dynamic range of at least 80 dB. This presented many design issues and the additional requirements of low power consumption, small size, modular construction and a production cost budget of under £1000 made this an even more challenging design. The paper covers the derivation of the requirement specification, choice of system architecture and frequency plan, specific design issues and the measured results.


## INTRODUCTION

The new design was required to replace an existing 3 GHz COTS scanning superhet receiver which was going out of production. It was evident that this rather dated design used a frequency plan which was bound to produce problems with spurs and was very slow to scan even the 3 GHz span. This suggested a "back-to-basics" study including zero IF, Low IF as well as conventional superhet architectures.

Other requirements included the need for a flexible design capable of enhancement and extension, particularly the frequency range and an instantaneous bandwidth of 20 MHz with a final IF suitable for a 100 Msps ADC.

## PERFORMANCE REQUIREMENTS

The overall receiver design system requirements were as follows:-

| System requirements | Value |
|---|---|
| **1) RF Frequency Range** | 100 kHz to 6 GHz |
| **2) Instantaneous RF bandwidth** | 20 MHz Flat to within +/-4dB |
| **3) Tuning resolution** | 1 MHz (2 MHz in 3.0 to 6.0 GHz Band) |
| **4) Scan rate** | 0 - 6 GHz in < 1s in 20 MHz steps (design aim) |
| **5) RF image band rejection** | -60dB up to 1GHz Image Freq<br>-50dB from 1 GHz to 2.4GHz Image Freq<br>-40dB above 2.4 GHz Image Freq |

| | | |
|---|---|---|
| 6) | **RF Rx. min. input level** | -107 dBm into 50R |
| 7) | **RF Rx. max. input level** | -37 dBm |
| 8) | **Dynamic Range** | 80 dB |
| 9) | **Receiver Noise Figure** | <=22dB |
| 10) | **Spurious Free Dynamic Range (SFDR)** | >=60dB |
| 11) | **Static Spur Level** | Maximum equiv. level –60dBc wrt Max Signal Level of -37dBm (i.e.<= –97 dBm)<br><br>Design aim <=-105dBm |
| 12) | **Overall System Phase Noise** | @ 10 kHz offset $\leq$ -90 dBc/Hz<br><br>@ 100 kHz offset $\leq$ -100 dBc/Hz<br><br>@ 1 MHz $\leq$ -110 dBc/Hz |

## CHOICE OF ARCHITECTURE

Space does not permit detailed discussion of the zero IF / low IF approaches but, despite their obvious attractions of simple architecture, low component count and low cost (hence their widespread use in the mobile industry) there are significant problems when trying to use over the sort of bandwidth we are dealing with here. These are, primarily, achieving adequate phase and amplitude balance over a wide band (for the low IF case) and LO breakthrough and 2$^{nd}$ Order "blocker" problems (for the Zero IF case).

This suggests the use of a conventional Superhet design, which was the basis of the original 3 GHz scanning receiver, as shown in Figure 1 below.

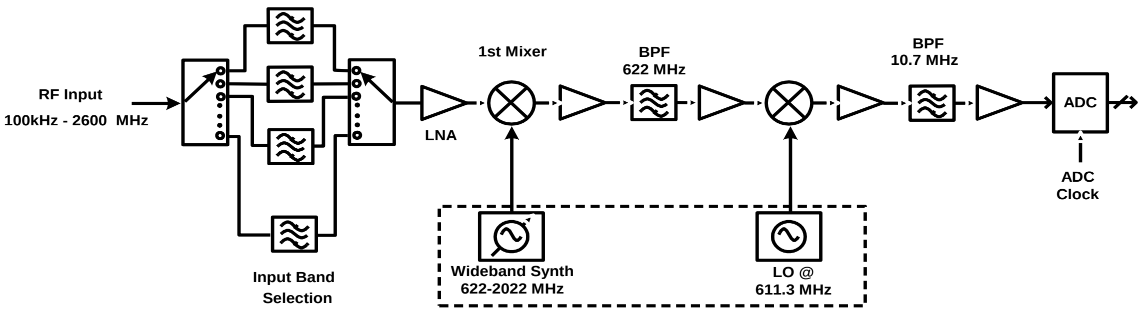



**Figure 1. Simplified Architecture of Existing 3 GHz Scanning Rx**

Although a well tried and tested approach, it does have some significant drawbacks for a wideband scanning receiver. The main problems are the difficulty in obtaining adequate image filtering (caused by the fairly low 1$^{st}$ IF) and the number of relatively high level spurs caused by the frequency plan.

An obvious, better place to look is in the wealth of expertise available in the Spectrum Analyser field. The requirement, after all, for scanning receivers and spectrum analysers is broadly similar, i.e. how to scan a broad band from 100 KHz to 6 GHz with high dynamic range and low spurs. A typical Swept Spectrum Analyser architecture is shown in Figure 2 below.

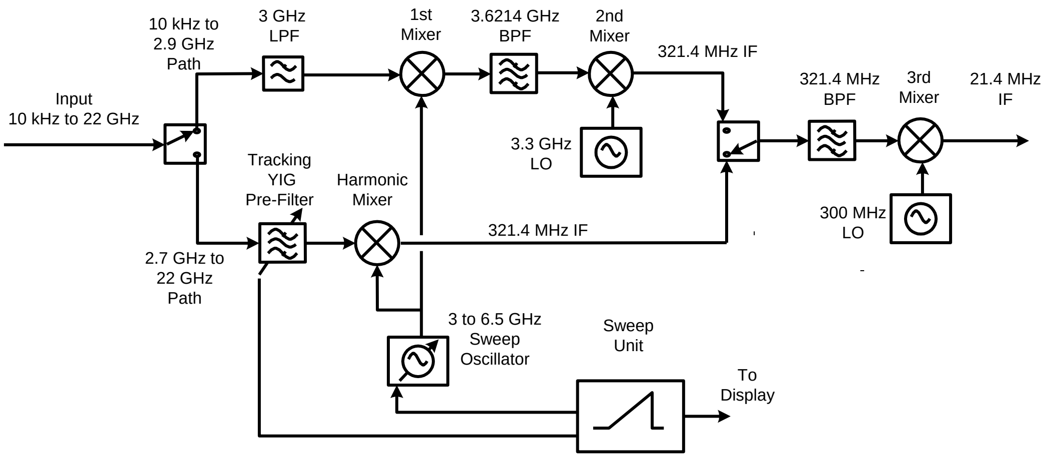



**Figure 2. A Typical Swept Spectrum Analyser Architecture**

The key difference from Figure 1 is that the lower frequencies (10 kHz to 2.9 GHz in this example) are actually up-converted to a high 1st IF before down-converting to the final IF using a more conventional two-stage superhet down-converter. This has the double advantage of making the higher frequency images easier to filter out and a frequency plan which has fewer problems with higher order mixer intermods. For frequencies above 2.7 GHz a straight two stage down-converter is used but requires the use of a tuneable pre-filter to reduce images and spurs. This is normally a tunable YIG filter which is relatively expensive and is certainly not a candidate for a receiver with a £1K budget.

Taking the up-converter method and extending it to cover the range 100kHz to 6 GHz seemed, therefore, to be the most promising approach. A simplified architecture is shown in Figure 3 below where there are three distinct paths. Firstly, unlike the conventional spectrum analyser approach shown in Figure 2 above, the lower frequencies from 100 kHz to 35 MHz have been fed directly to the ADC. The problem with up-conversion at such low RF frequencies is that the 1st LO frequency is very close to the 1st IF frequency causing problems with 1st Mixer LO breakthrough. The ADC sample rate was chosen to be 93.33 Msps (explained below) so that the signals for this band lie in the 1st Nyquist zone.

The second path takes a signal band of 30 MHz to 1900 MHz and, using a High-Side LO, up-converts to the 1st IF of 2120 MHz. This is rather lower than the 3.6 GHz IF suggested in Figure 2 above and was chosen because of the ready availability of low cost SAW filters at these frequencies. One of the biggest cost drivers is the filter requirements (discussed further below) and SAW filters can provide excellent performance in terms of bandwidth, insertion loss, flatness and image rejection, provided the frequency plan can be adapted to use them.

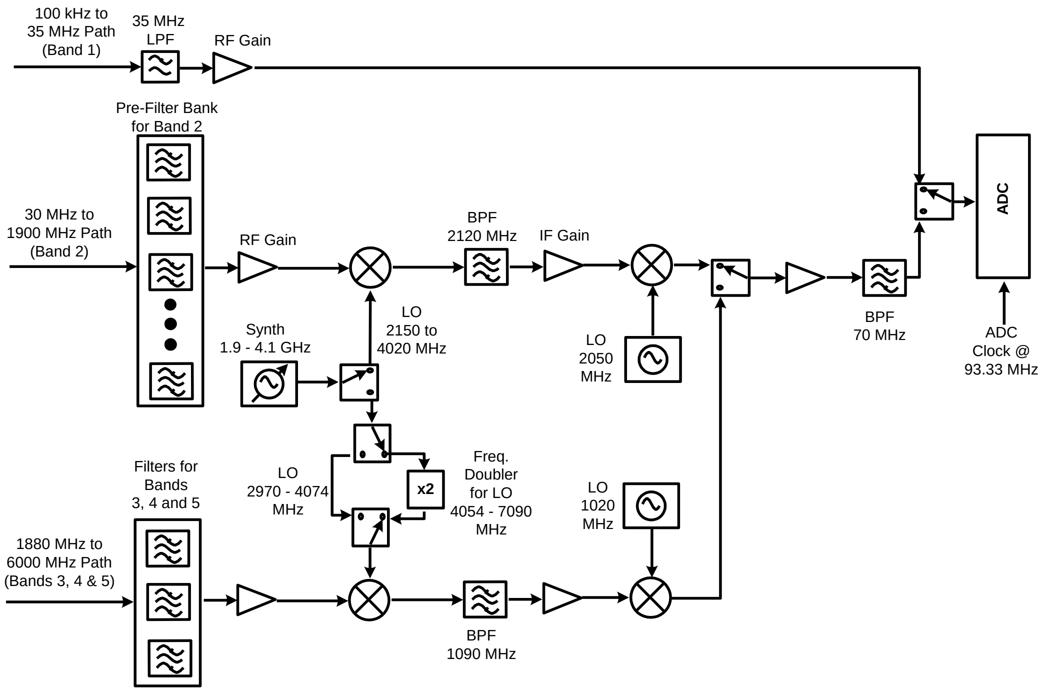



**Figure 3. Architecture for 6 GHz Receiver with Selectable Pre-Filtering**

As noted above, the use of a tuneable YIG pre-filter would be prohibitively expensive but a certain level of pre-filtering is necessary, both to attenuate image frequencies and those frequencies which would allow mixer intermod products to fall into the 1st IF band. A switchable filter bank was used and, because this is a critical part of the design and a potential cost driver, it will be described in more detail below.

As may be seen from the overall frequency plan of Figure 4 below, image frequencies (Green), are generally well separated from the wanted RF bands (Blue) and allows more relaxed filter requirements. Also, the LO bands (Red) do not overlap the 1st IF frequencies.

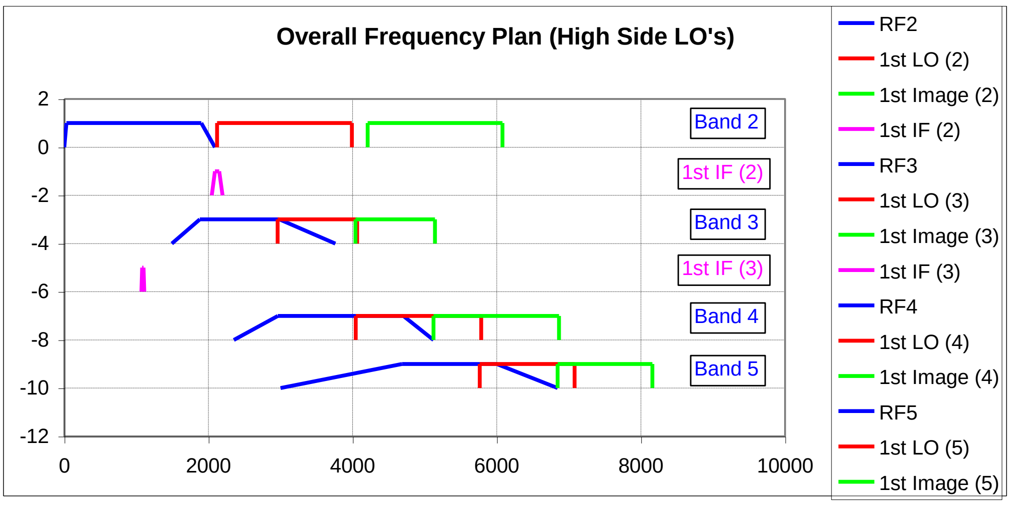
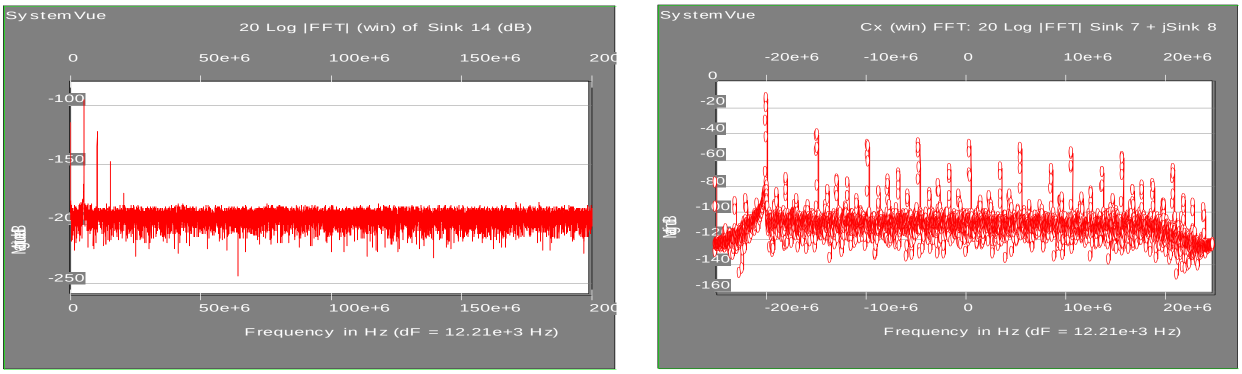


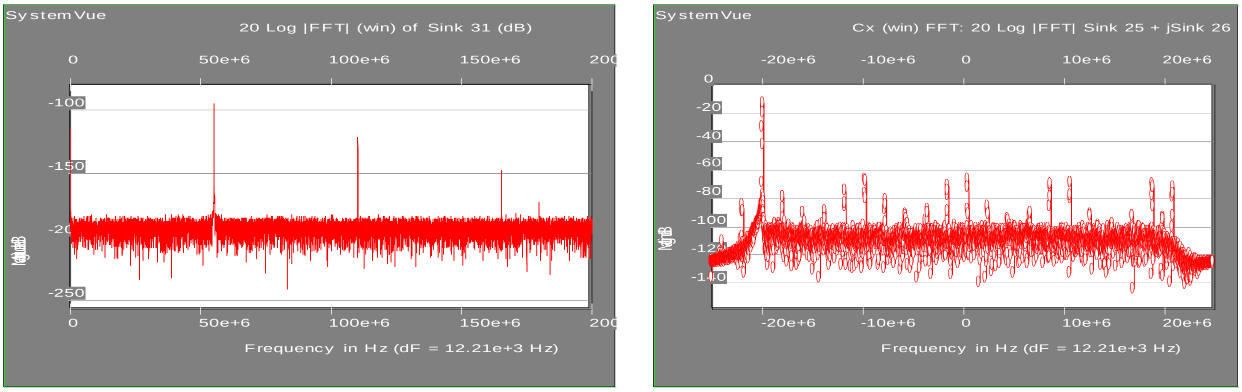

**Figure 4. Simlified Overall Frequency Plan for Bands 2 through 5**

After suitable 1st IF gain and filtering at 2120 MHz, a second stage of down-conversion is used to a fixed IF of 70 MHz. This choice of IF was again conditioned by the ready availability of SAW filters with a 20 MHz flat passband and excellent rejection at the sampling image frequencies. Choosing a sampling rate of 4/3 times 70 MHz ensures that the final IF falls centrally in the 2nd Nyquist zone.




(a) ADC Input, 1st Nyquist, with Harmonic Distortion (b) Digitised Base band I&Q after DDC

**Figure 5. Effect of Input Harmonic Distortion for 1st Nyquist Case**




(a) ADC Input, 2nd Nyquist, with Harmonic Distortion (b) Digitised Base band I&Q after DDC

**Figure 6. Effect of Input Harmonic Distortion for 2nd Nyquist Case**

The above simulation attempts to explain the reasons for preferring the 2nd Nyquist zone. Figure 5(a) shows a signal at the lower edge of the 1st Nyquist zone which has significant harmonic distortion. This can easily be generated in the later stages of a receiver where signal levels are high and filtering is minimal. As would be expected, this distortion lies in-band and will transfer to the digitised base-band, as shown in Figure 5(b). For the 2nd Nyquist case, shown in Figure 6 (a) and (b), any such distortion products will lie outside the anti-alias filter band and will not transfer to the I&Q baseband.

The third signal path shown in Figure 3, has a different 1st IF. The reason is that signals close to the Path 2 IF of 2120 MHz are liable to break through the 1st mixer and enter the IF causing false detection. For this reason, a lower IF of 1090 MHz was chosen for these frequencies.

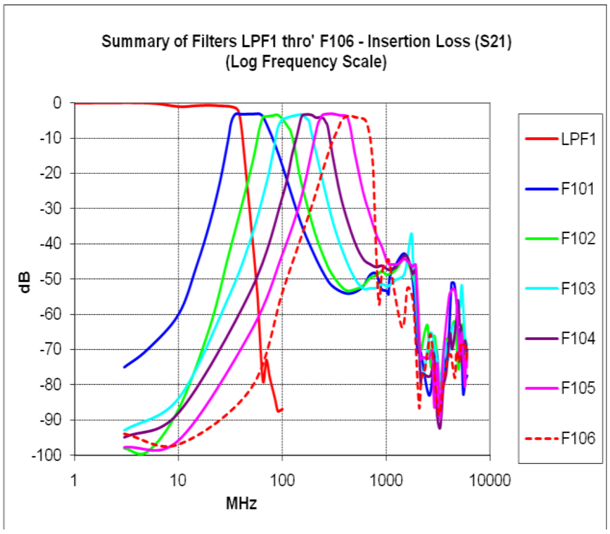
A further important part of the design is the Synthesiser. Fortunately, this system does not require the ultimate in phase noise performance so that it has been possible to make use of one of Synergy Microwave's low cost, wide tuning range synthesisers (LFSW190410-100) which covers a band 1.9 to 4.1 GHz in 1 MHz steps. By judicious frequency planning and a frequency doubler for the higher LO frequencies, the full 30MHz to 6GHz RF band can be tuned using a single synthesiser.

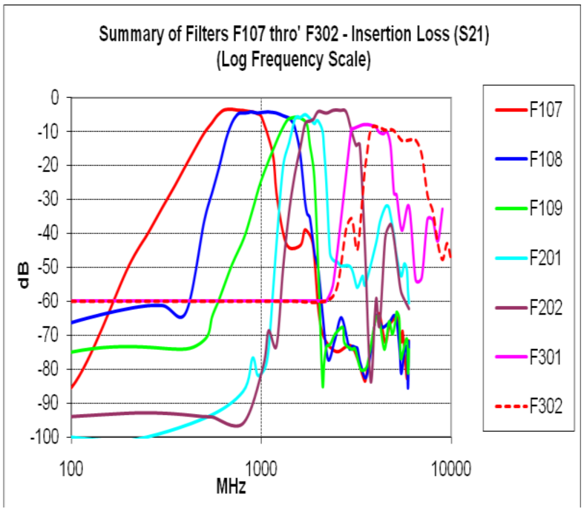
## FILTER BANK DESIGN

Although there are many other design issues which could be covered, the single most difficult challenge was undoubtedly, the switched filter bank. Overall, a bank of 14 low-pass or band-pass filters were required to ensure the overall receiver spur and image performance. Many design approaches were considered and rejected either on the grounds of size, cost or performance. Although lumped element LC filters were considered feasible up to around 1GHz, above this component parasitics led, in particular, to poor passband loss and roll-off. Outsourcing the design was, again, found to be an expensive option given the receiver cost budget..

Finally, a solution was found which made use of Mini-Circuits large range of low-pass and high-pass ceramic filters. By judicious modification of the frequency plan, it was found that ceramic filters were available to cover the whole band for filters above about 400 MHz. With small size also being a requirement, the track-layer substrate was chosen to be Rogers RO4993C, 8mil (0.2mm) thick, which allowed very thin, 0.4mm coplanar waveguide tracks to be used. This is an excellent match to the pin size of many of the latest surface mount RF devices including, for example, the Hittite HMC252 SP6T switches. Although this allowed the size to be kept very small, such a small substrate thickness also increased pad capacitance for the devices with larger pads (including many of the Mini-Circuits ceramic filters. This had to be carefully controlled by using ground-plane cut-outs in the 4-layer board to reduce pad capacitance where required.

Overall, the filter bank performance was found to be an extremely good match to the performance predicted by Genesys. The measured results, including all connector, launch and switch-tree losses are shown in Figure 7 below. The insertion loss typically varies from around 3dB at lower frequencies to around 10dB at 6 GHz. Given that pass-band loss was not a critical factor (there is a front-end LNA) this performance was found to be very satisfactory.



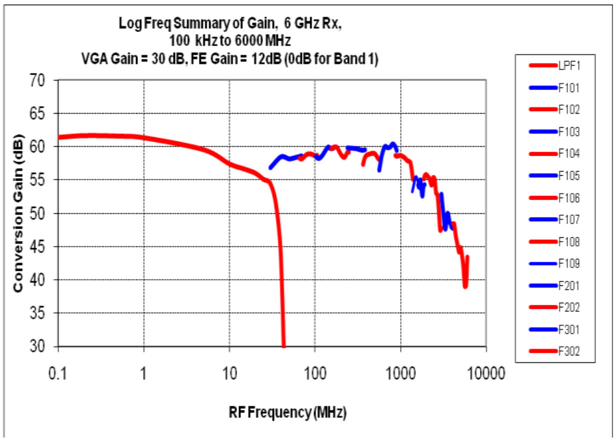

(a) Filter Bank DC to 580 MHz

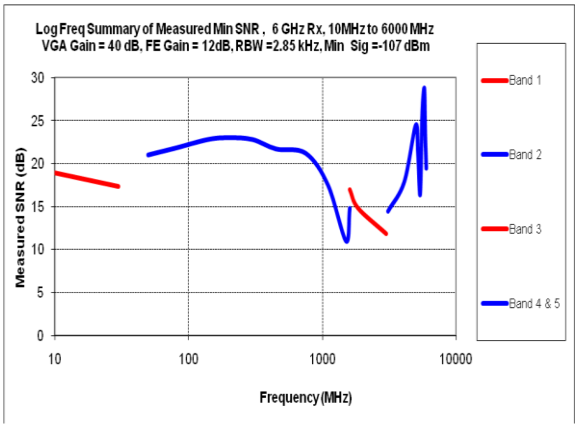
(b) Filter Bank 560MHz to 6 GHz

**Figure 7. Overall Switched Filter Bank Measured Response**

## OVERALL PERFORMANCE

Although it is not possible in a short paper to present more than a few of the results, the following may be of interest. Figure 8(a) below shows the measured conversion gain of the receiver with a fixed VGA (Variable Gain Amplifier) gain. In practice, system calibration and gain flattening (by varying VGA gain) will be applied by the system processor so that absolute gain roll-off with frequency is not a problem as long as the Noise Figure and minimum SNR is adequate.




**(a) Measured Receiver Conversion Gain** **(b) Measured Minimum SNR**

**Figure 8. Overall Receiver Measured Gain and Minimum SNR**

Again, as may be seen from Figure 8(b), the minimum SNR is well above the 10dB threshold at all frequencies (although there is some doubt about the accuracy of the high frequency figures). This ensures reliable detection of the minimum signal level of -107 dBm in a (nominal ) 3 kHz RBW (resolution bandwidth).

Although a few troublesome static spurs were found to exist, (spurs not dependent on the RF input and caused by local oscillators interaction), these have been largely eliminated or reduced well below the -107 dBm threshold by off-tuning each LO. This moves spurs out of band whilst maintaining the final IF frequency of 70 MHz.

## PHYSICAL CONSTRUCTION

The following pictures give an idea of the overall physical construction of the receiver. It consists of 4 units namely: Antenna Switch Unit; Filter Board; Synth Unit and Main Rx Board.

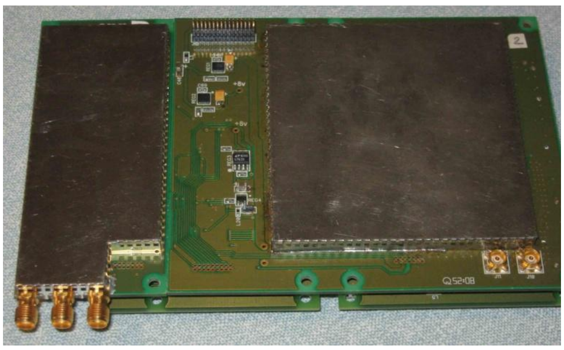


**Figure 9. Assembled Rx, Antenna Switch Matrix and Main Rx Board Side**

Figure 9 is a view of the top side of the assembled receiver, showing the Antenna Switch Matrix and Main Rx. Board. The Filter Board and Synth Unit are on the under-side, joined via MMBX coaxial connectors and Samtec multi-pin headers. This makes a very compact, flexible design and allows units to be independently tested, replaced or upgraded.

Figure 10 is a side view, showing more clearly the board interconnections and the various coaxial inputs and outputs.

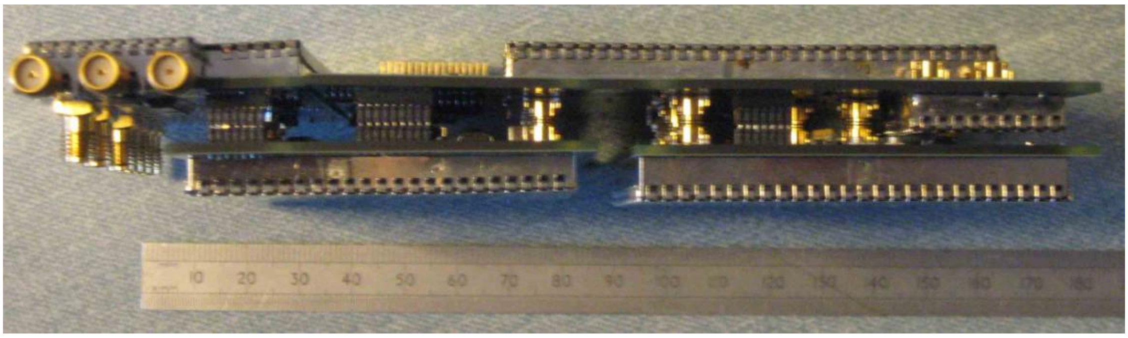


Figure 10. Side View showing MMBX coax and Samtec header Interconnections

Finally, Figure 11 is a view of the Filter Board (screen lid removed) showing the very compact, low cost design – 14 separate switched filters on a board 103mm x 65mm x 7mm.

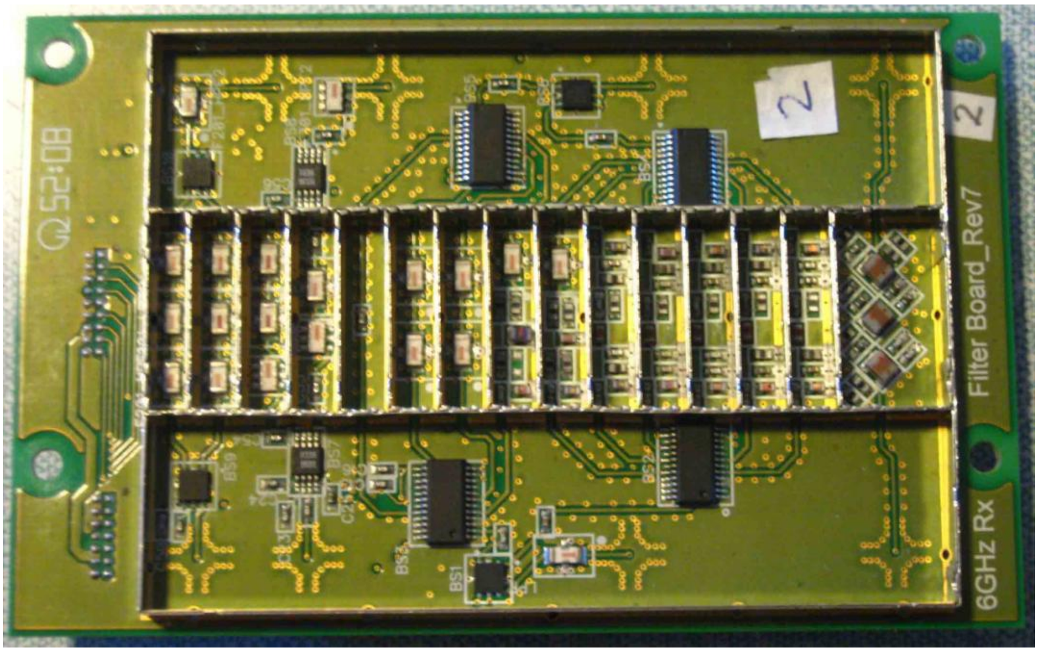



Figure 11. View of 6 GHz Switched Filter Bank – Screen Lid Removed

## CONCLUSIONS

The overall performance objectives were met comfortably in all respects, with the possible exception of static spurs. These have, however, been reduced to below the specified level by the method of off-tuning the 1st and 2nd LO's described above.

The overall size of 165mm x 103mm x 25mm (6.5" x 4" x 1") and the power consumption of approx 7 Watts at +9v allowed the end customer to stay well within his size and power constraints. The scan time from 100 kHz to 6 GHz in 20 MHz steps was well under 1second.

Finally, the production cost target of sub £1000 was, originally, met comfortably although recent weakening of Sterling has affected this somewhat due to components priced in USD.