A high performance 2m down converter for foxhunting

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Introduction

Foxhunting has enjoyed nearly 3 decades of activity in the Melbourne area. A trend towards increased use of lower power transmitters and increased distances along with more challenging terrain has required much better sensitivity of receiving systems. At the same an increase in the power and number of close adjacent band users (particularly paging transmitters) has put an ultimate limit to the amount of gain that can be used ahead of most receivers for foxhunting use before problems set in due to intermodulation.

This article describes a converter that provides a high intermodulation intercept without significantly compromising the sensitivity and noise figure required for detection of very weak signals.

Additionally the converter features a synthesised local oscillator that can be remotely controlled via the output port. A fixed output frequency allows the converter to directly feed a high selectivity IF filter.

Key Requirements

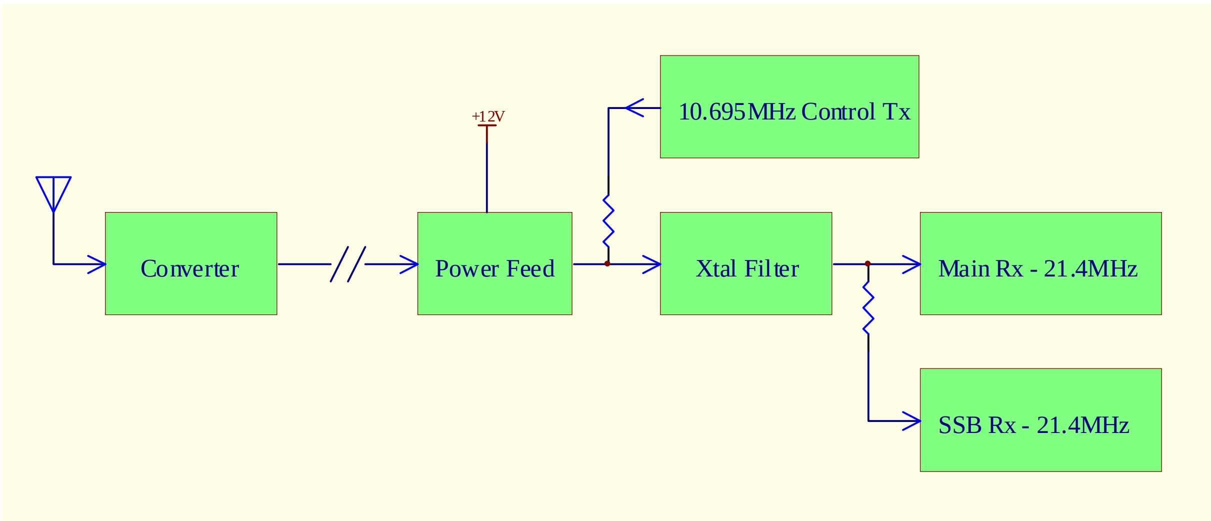
The converter has a number of key design requirements.

- High IP3 and dynamic range.
- Good sensitivity. (Low system noise figure)
- No overload, even within a few metres of a transmitter!
- Compact design to allow “on antenna” mounting.
- Consistent performance over whole 2m band.
- Fixed IF frequency – (On-board PLL tunes 144-148MHz.)
- Single coax feed for all power and signalling.
- High side injection. (Low side would put the 1st IF image in the top end of the FM broadcast band.)
- Control of operating parameters via 10.695MHz FSK link
- SMD construction for predictable results.
- Fully self contained and shielded. Case also used as heatsink.

One significant item missing above list is "low power consumption". As the setup is powered from a vehicle supply this limiting power consumption is NOT a requirement and actually has been exploited to help achieve the required performance parameters.

System Block Diagram

The block diagram below shows main functional blocks of the system. The system is designed so that there can be more than one converter, but the 2m converter has by far the most stringent requirements. Although converters for other bands and full descriptions of the other functional blocks in the system are beyond the scope of this paper, a brief description of the other blocks is given below.



The power feed block serves to decouple the power feed from the IF and control signals. It also must provide a significant amount filtering to ensure that noise from the 12V vehicle supply does not degrade system performance.

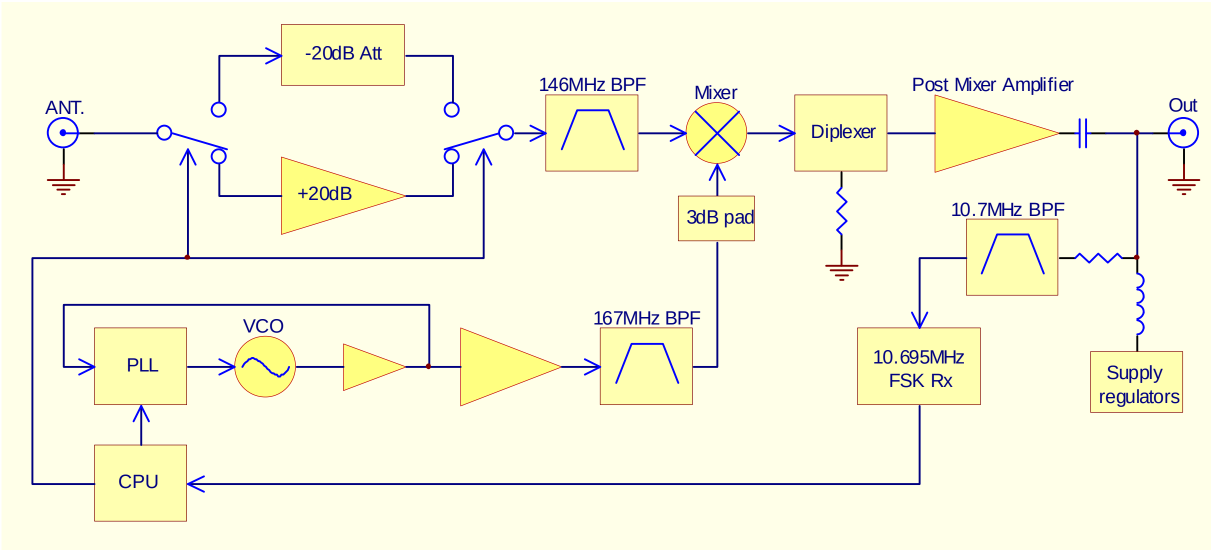
The 10.695MHz Control Transmitter is basically a DDS based modem that is controlled by the serial output of a microcontroller. It serves to set the converter operation frequency and attenuator settings. 2nd harmonic has to be well filtered to ensure DDS noise sidebands don't make their way into the 21.4MHz IF (this proved to be more of an issue than first thought). The converter itself does not send back any control or status information.

The Crystal Filter determines the ultimate high signal level adjacent channel selectivity of the system. The filter presently used is a 21.4MHz 8 pole filter with 15KHz bandwidth. The filter is matched to 50 ohms via a low loss L/C network.

The main receiver is a specially modified MK4 sniffer DF unit operating at 21.4MHz. The SSB receiver is presently based on a Yaesu FT817 and basically "sniffs" signal at 21.4MHz to provide an audio monitor. A better IF processing setup is planned.

Converter block diagram

The diagram below shows the major functional blocks:



The converter is a relatively straightforward single conversion design. A significant difference from more traditional converters used for foxhunting is that the local oscillator is tuneable rather than at a fixed frequency.

To gain maximum sensitivity and best noise figure there is almost a complete lack of filtering before the 20dB LNA. While many may see this as a backward step, it will be shown later that as long as enough current is provided by this stage, the system IP3 is actually limited by later stages. Some rolloff of out of band signals does occur, but to a much lesser extent than many other receiver designs. There is no need to trade off supply current against IP3 so basically the LNA runs as much current as it can without impacting its noise figure.

The function of the band pass filter following the LNA in this design is mainly to provide image rejection.

The 10.695MHz FSK Rx Modem is preceded by a 10.7MHz filter that is about 280kHz wide. The filter's main purpose is to isolate the modem from the converter's 21.4MHz IF frequency.

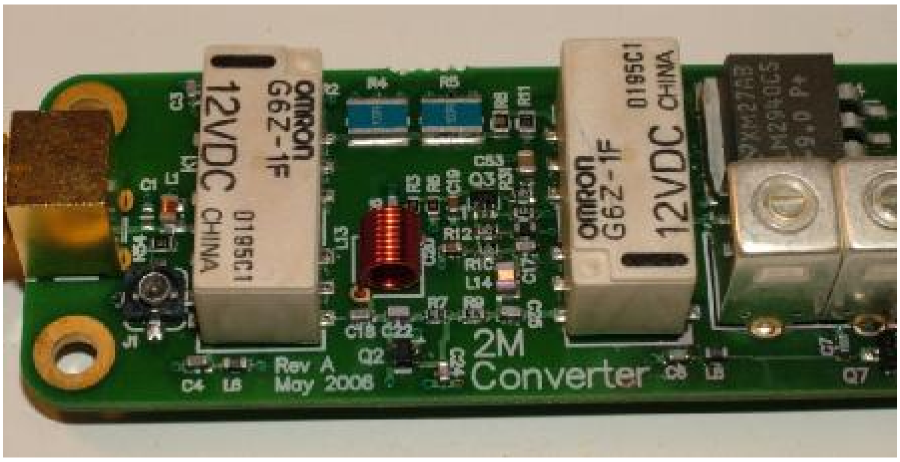
The completed module.

The completed module PCB has a size of 200 x 28mm and is designed to be mounted in a milled Aluminium case which also doubles as a heat spreader. This is necessary as the amplifiers around the mixer effectively dissipate nearly a watt in heat. A thermally conductive pad under the board assists in the heat flow between the board and the box. The module becomes too hot to touch if operated outside the box and becomes "lukewarm" when installed in the case. As the case is normally mounted on top of a moving vehicle where there is plenty of "forced air" cooling, additional heatsinking is not normally required.

In order to try to make the module as small as possible and to have a predictable design through use of accurate computer simulation, construction of the converter is all surface mount except for helical filters and connectors. At VHF and higher frequencies, parasitic effects are easy to accurately model with surface mount components. This is a requirement to confidently predict the final performance of the design.

Front End Requirements

A reasonable amount of effort has gone into the design of the first stage of the converter. The input stage is effectively divided into two parts, a 20dB LNA and a 20dB attenuator. Relay switching by quality RF relays ensures minimal loss with virtually no IP3 impairment.



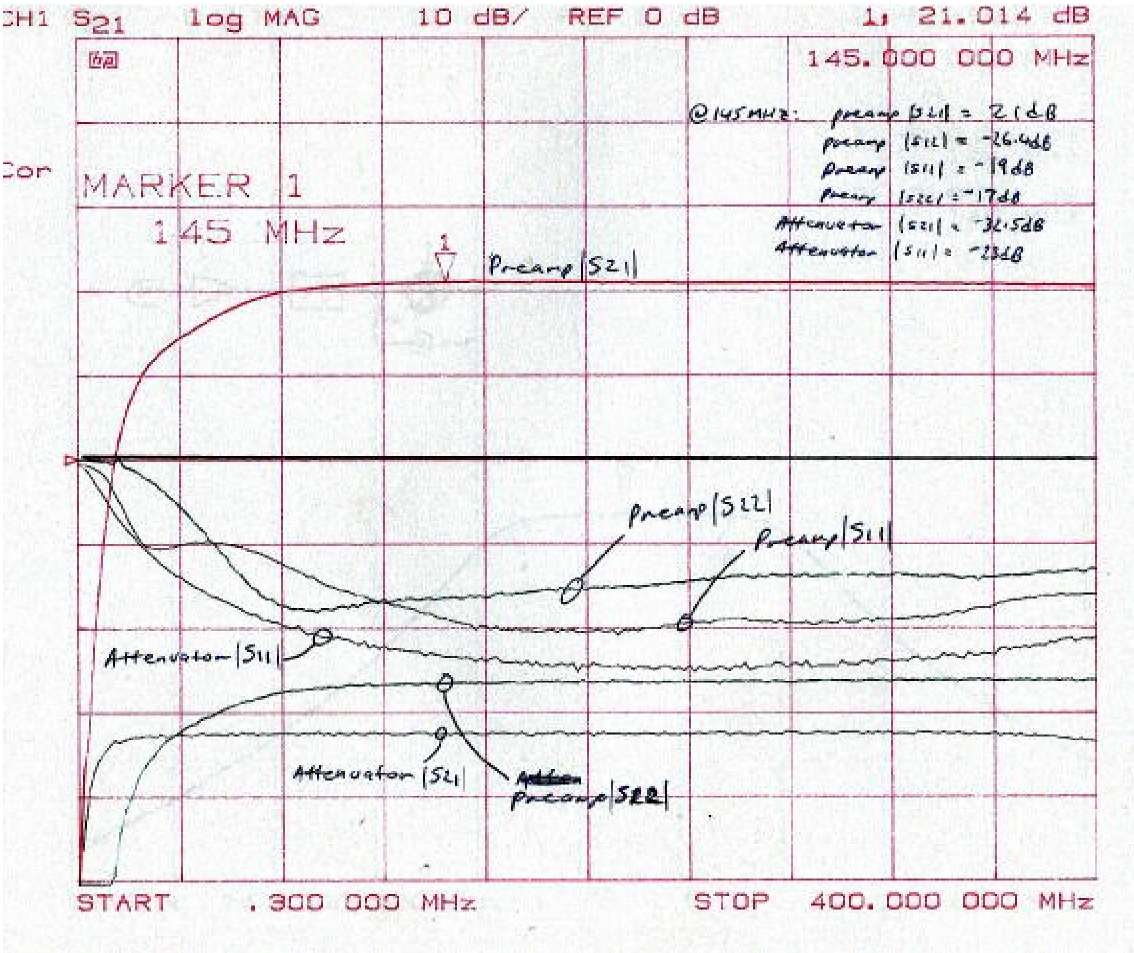
To ensure best handling of strong signals and maximum IP3 the LNA runs at around 60mA at 5V and is based on the Avago ATF54143 enhancement mode microwave GaAsFET. Negative feedback along with some source degeneration is used to provide unconditional stability (K>1) and good return loss for both input and output and to make sure gain is flat and predictable across the band. However the use of feedback to provide this does come at the expense of some impairment of noise figure. For a full description of this arrangement see Avago application note AN5057.

The 20dB attenuator stage is a simple 50 ohm PI type arrangement that is capable of handling up to 2 watts. (Yes, because I can I have gone for overkill...)

Front end performance

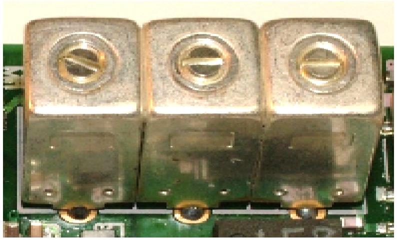
The graph below shows the performance of the stage when the LNA is switched in. Major performance highlights are:

- |S21|=21dB (forward gain)
- |S12|=-26dB (reverse isolation)
- |S11|=-19dB (Input return loss)
- |S22|=-17dB (Output return loss)
- Flat response from 100-400MHz.

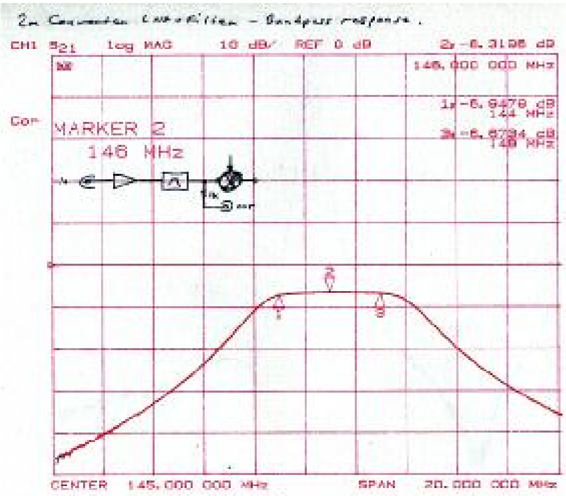


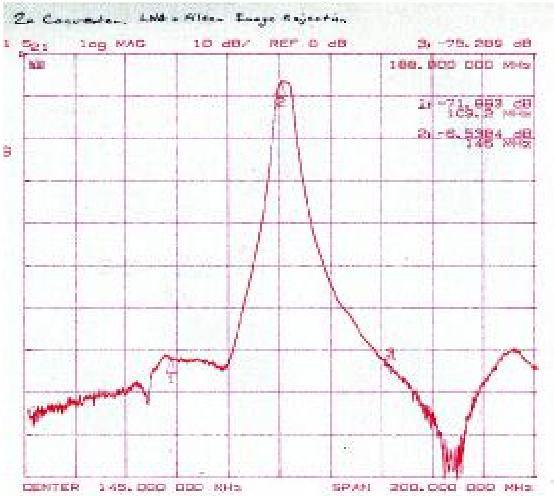
Note that the above graph shows the attenuator providing 32.5dB. This was later revised to give just on 19dB of attenuation as there was a system requirement to give as close as possible a 40dB change between LNA and attenuator options.

Image Filter



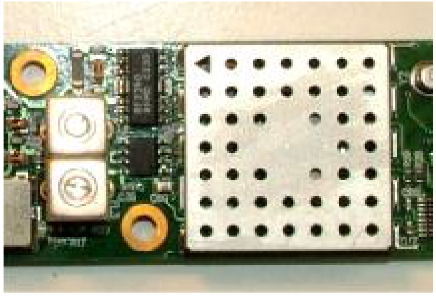
The image filter is based on a Temwell VHF Helical filter. This filter provides about 70dB of image rejection on the high side. Low side injection would have provided better filtering but would have put the image within the top of the FM broadcast band (101.2-105.2MHz). High side injection puts the image between 186.8 and 200.8MHz. While this is normally used for TV broadcasting, it was seen as less of a problem in the Melbourne area. The use of a beam antenna before the converter also provides some (albeit small) additional image filtering.





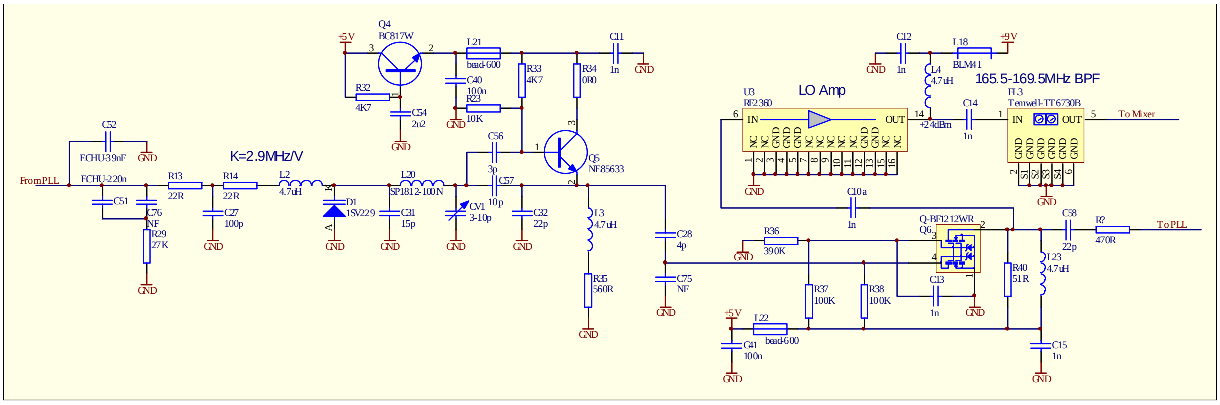
The pass band response covers the entire 2m band with less than 1dB ripple. Rejection in the 148-150MHz pager segment is minimal. Maximising IP3 is ultimately responsible for rejection of the problematic signals within this segment. No filter can provide significant rejection of this close adjacent band without either taking up a lot of additional space and/or significantly compromising in-band performance.

Local Oscillator



The local oscillator has a significant impact on the operation of the converter. Rejection of adjacent channels and bands is determined to a large degree by the phase noise and sideband spur performance of the local oscillator. Strong signals from adjacent channels can be reciprocal mixed to become in band noise. The use of high Q components in the oscillator tank as well as minimising the varactor tuning range can help to reduce phase and modulation noise. A “capacitance multiplier” (Q4 in the circuit below) also serves to provide a very well filtered and low noise supply feed to the oscillator.

The VCO here is a work in progress and the component values shown do not reveal the best performance possible. Such an analysis is beyond the scope of this paper. However the topology used allows significant freedom in optimising the parameters needed to obtain very good phase noise. Figures exceeding -118dBc/Hz at 10kHz offset have been possible at UHF frequencies and hence this should be able to be easily exceeded at VHF.



A major note is the use of Polyphenylene Sulphide (PPS) plastic film capacitors from Panasonic in the PLL loop filter. While these capacitors are rather expensive in small quantities they provide superior performance to ceramic and other plastic film capacitors and eliminate the “ping” (reference sideband ringing) that occurs due to leakage and “curing” as the oscillator changes frequency or starts up. It is vitally important that leakage is minimised as even a few tens of nanoamps of leakage can contribute significantly to the levels of oscillator reference sidebands.

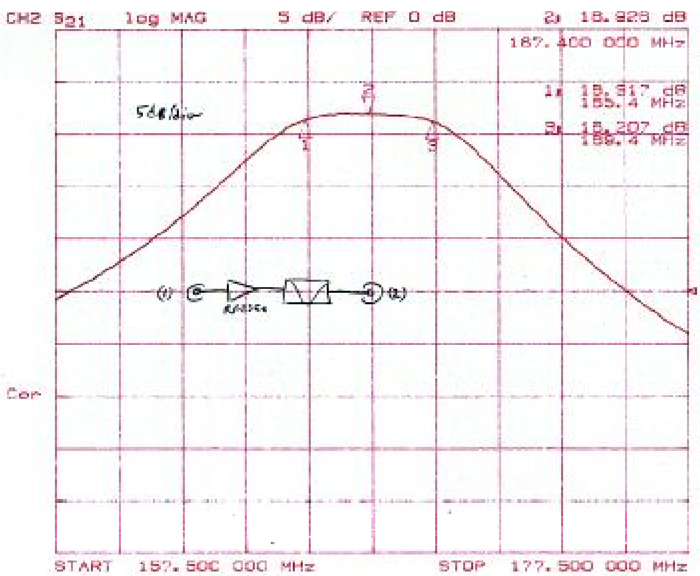
Microphonics (FM modulation due to mechanical shock) can be a problem with VCOs. The main VCO inductor uses a Coilcraft surface mount part which has resin joining the coil turns. While this is mainly to aid vacuum pickup for automated loading it has the side benefit of significantly reducing inductance change due to mechanical vibration.

Local Oscillator Amplifier

The mixer requires 17dBm (50mW) of local oscillator injection. A two section Helical Filter provides significant rejection at LO +/- IF frequency. This stops any IF sideband noise from directly entering the IF. A 3dB pad is used on the output of the helical filter to provide improved mixer LO port termination. Due to the additional loss of these two networks, the amplifier needs to provide about +23dBm (200mW) of output power.

An RF2360 cable TV amplifier chip capable of up to +26dBm output with a noise figure of under 2dB provides this function.

The amplifier runs off a 9V supply.

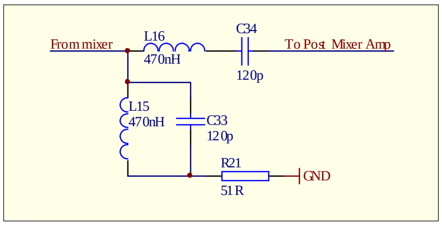


The LO output filter provides effectively flat injection power across the 4MHz tuning bandwidth.

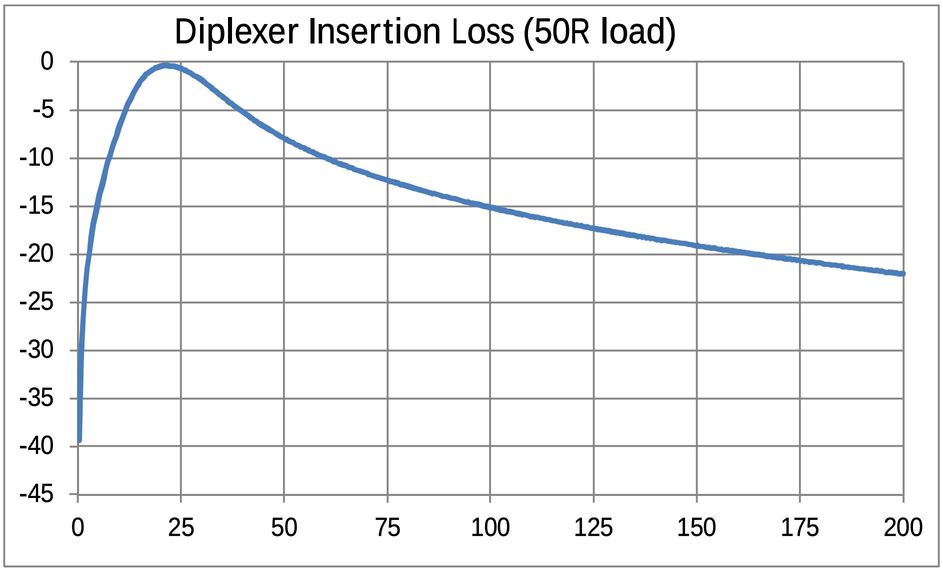
Mixer

The mixer is based on a Mini-Circuits HJK-3H FET ring mixer. This device provides a very modest IP3 rating (IIP3=+34dBm) with an LO injection level of only +17dBm. Compression point (IP1) is +19dBm and conversion loss is typically 8dB. This is a narrowband VHF device which happens to just nicely cover the 2m band.

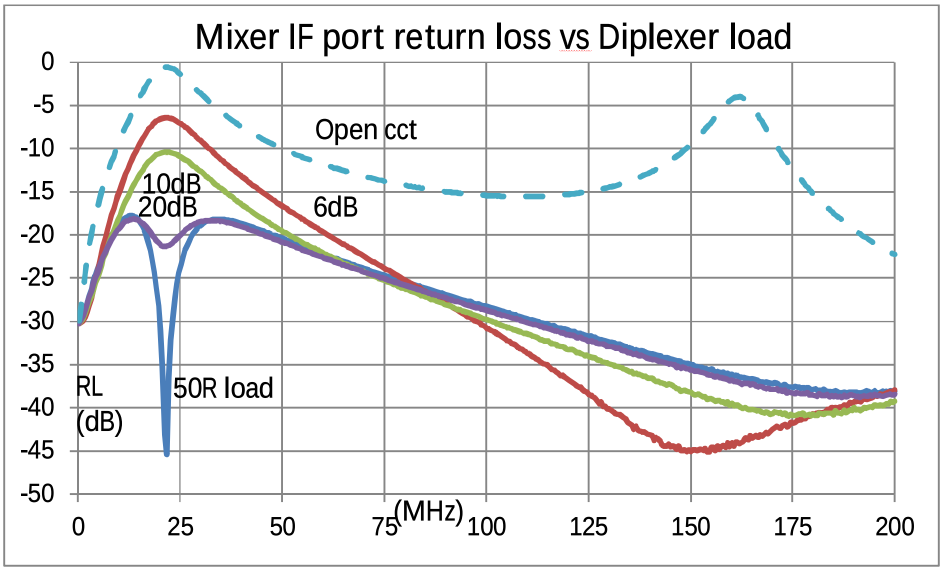
IF Port Diplexer



For best IP3 performance the mixer IF port must be terminated at all its operation frequencies with 50 ohms. A diplexer on the output serves this function by passing the IF frequency with minimal loss and passively terminating all other frequencies.

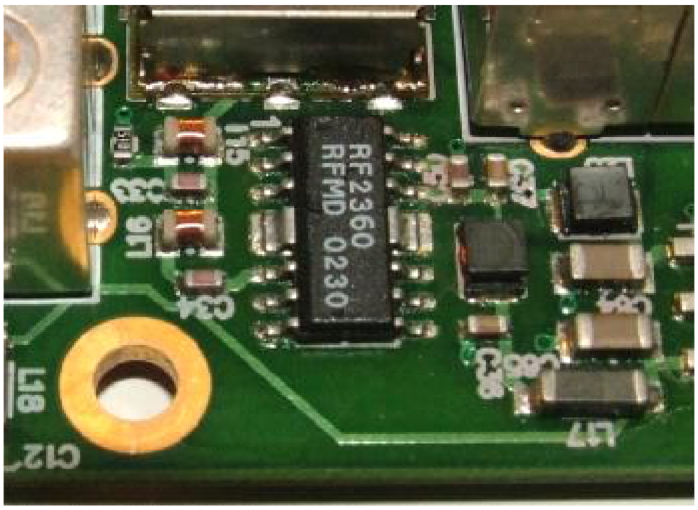


The diplexer should preferably provide some attenuation of the LO and RF signals to avoid the post-mixer amplifier from having to deal with these signals at high level.



Another issue that was found was that the load presented to the IF port was somewhat dependant on how good the return loss was on the diplexer output. The graph shows that the amplifier only needs to provide a half reasonable return loss at 140MHz+ to give good results.

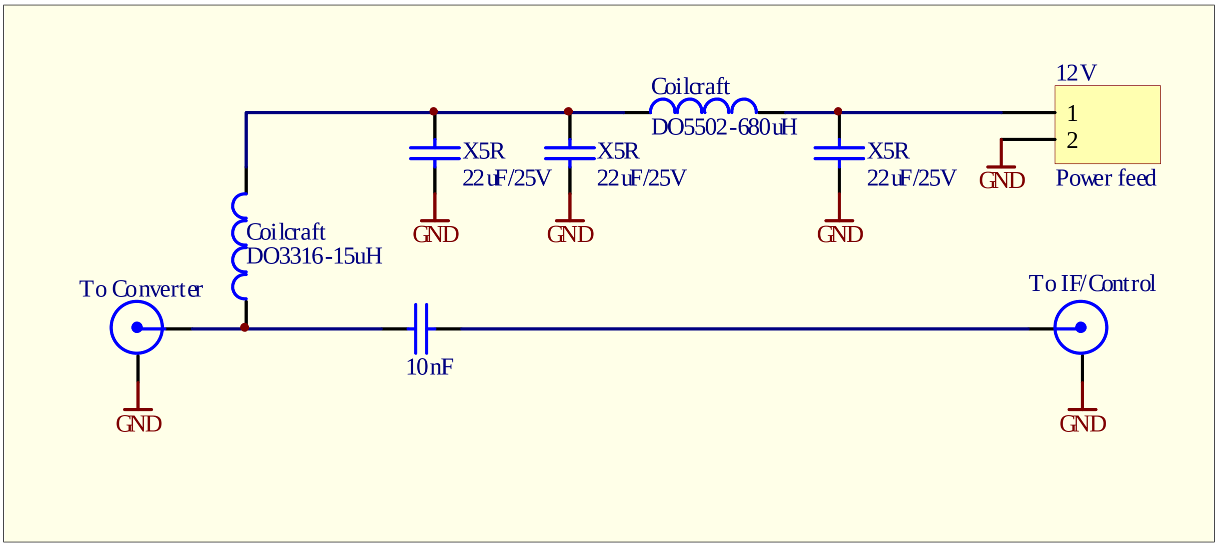
Post Mixer Amplifier



The post mixer amplifier is based on a RF2360 CATV amplifier similar to that used as the LO buffer. Internal feedback allows this part to have a particularly wide frequency range with good input and output return loss that extends down to 5MHz with a 1.5dB noise figure. At 20dB its gain is a little high for this function but the high OIP3 (+35dBm) helps to maintain reasonable intermodulation performance. The high compression point is necessary to maintain good dynamic performance due to the extra associated gain. The stage draws around 120mA at 9V.

Another key requirement is that this stage needs to provide a reasonable match to the mixer diplexer at RF and LO as well as IF frequencies. It also needs to provide some isolation from anomalies that may occur in the cabling that feeds the rest of the system.

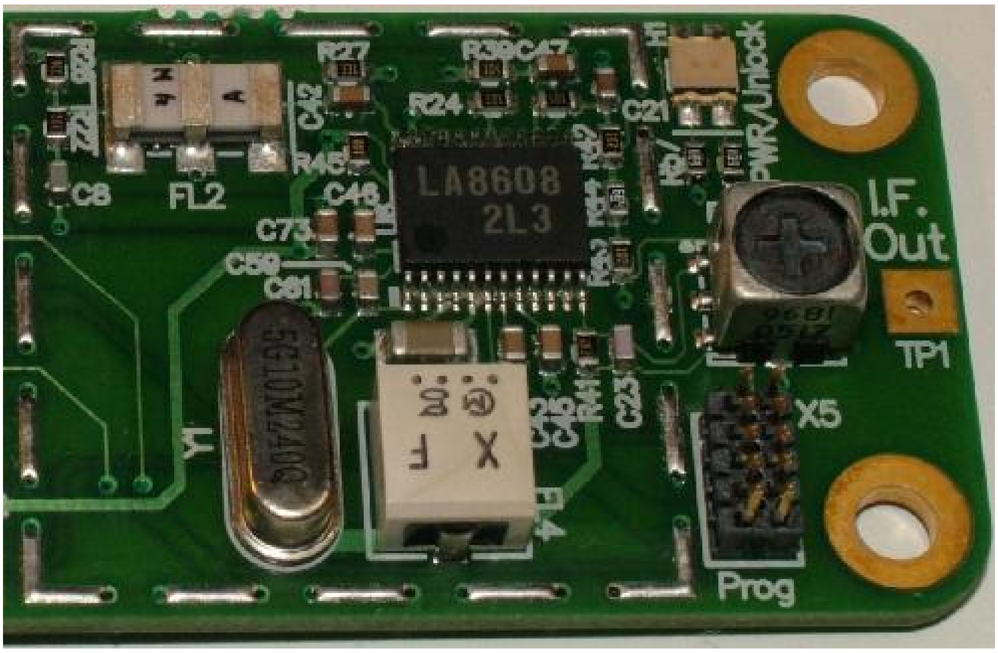
Power Feed



The powerfeed shown above is actually that used at vehicle supply end but the network used to provide the converter supply is very similar. The main purpose of this network is to decouple DC and RF paths with minimal impact to each other and allow a single coax feed for power and RF feeds. Murata X5R ceramic capacitors provide very high capacitance density that relatively stable with voltage and temperature and provides bypassing with very low ESR.

Feed Inductor performance is rather critical as most inductors undergo a reduction of inductance with increasing current. With smaller inductors this can be significant and starts to occur well before the inductors “rated” current. Comparison of inductance and self resonance parameters against current with a network analyser is beyond the scope of this paper but can give some rather surprising results.

Signalling Modem

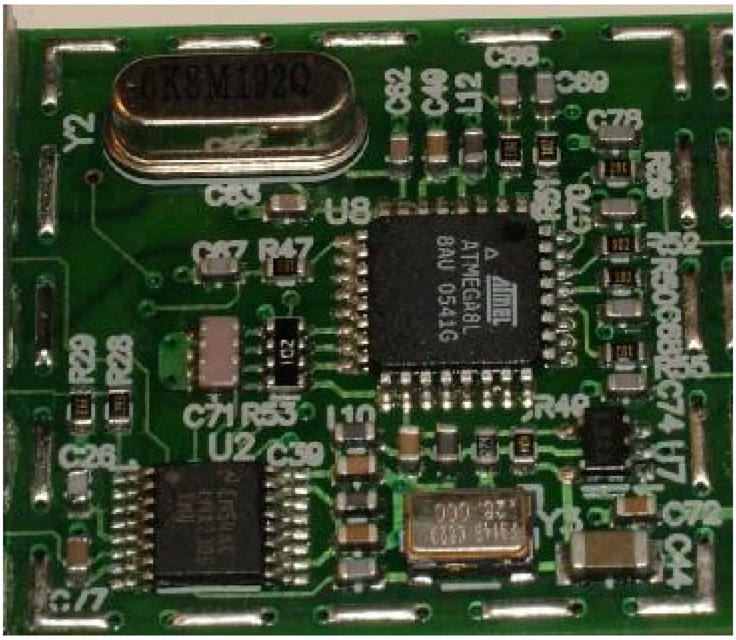


This section takes the 10.695MHz FSK signalling from the downstairs DDS modem and converts it to asynchronous data for the on board microprocessor. The purpose of this stage is to provide remote control of the converter.

The stage is based on a conventional narrowband FM IF part. An on part comparator takes the demodulated FM and squares up its output to feed the CPU RxD line directly. Some hysteresis is used on the comparator to maintain clean edges.

More recently the above stage has been disabled and replaced by a 900MHz single chip transceiver. This has been found to be a more reliable way of passing control data and allows more flexibility with other converters and parts of the system as it allows for bidirectional control. It also eliminates a problem with a low level 2nd harmonic of 10.695MHz getting into the IF chain. The new stage simply plugs onto the programming header at the bottom right and communicates through its SPI bus.

Processor and PLL



The main control centre for the converter is based around an AVR Mega-8L microcontroller. The reason for choosing this part is one of stock on hand, programming tools and familiarity. There is nothing special about its function in this application and almost any similar part could have been used.

This part has been found to have some issues with conducted noise from harmonics of its internal clock and most lines are filtered to minimise this conducted interference. The stage also allows for complete shielding to minimise radiated noise but so far its use has found to be unnecessary.

The area also contains a National Semiconductor LMX2306 integer PLL used to lock the on-board VCO/local oscillator. The raster is set at 5kHz and the PLL uses a pre aligned 26MHz ±1ppm TCXO as its reference.

Cascade Analysis

Stage	Gain	Cumul Gain	NF	Cumul NF	IIP3	Cumul I3
Atten switch	-0.10	-0.10	0.10	0.10	99.00	99.00
ATF54143 LNA	20.50	20.40	1.30	1.40	14.80	14.90
Temwell RF Filter	-2.90	17.50	2.90	1.43	99.00	14.90
HJK-3H Mixer	-8.13	9.37	9.50	1.85	34.10	12.66
Diplexer	-0.37	9.00	0.37	1.88	99.00	12.66
Post mixer amp	20.00	29.00	1.50	2.02	17.20	6.87
Powerfeed	-0.20	28.80	0.20	2.02	99.00	6.87
		28.80		**2.02**		**6.87**

The cascade analysis reveals that the dynamic performance is limited mainly by the post mixer amplifier stage and not by the LNA or mixer. Most of this is due to the excessive gain of the stage due to the use of an “off the shelf” part. A lower gain part with the same OIP3 (Output intercept) supply voltage and current would give a significantly improved IP3 result. Unfortunately parts with these parameters are rather hard to find and often have significantly higher noise figures than the part used. Originally a slightly lower gain part (RF2320) was designed in but there were problems found with stability with the part at around 2.5GHz where S11 would have a tendency to go positive. The higher gain and more stable RF2360 was substituted due to footprint and supply voltage compatibility at the expense of a 2dB reduction in IP3.

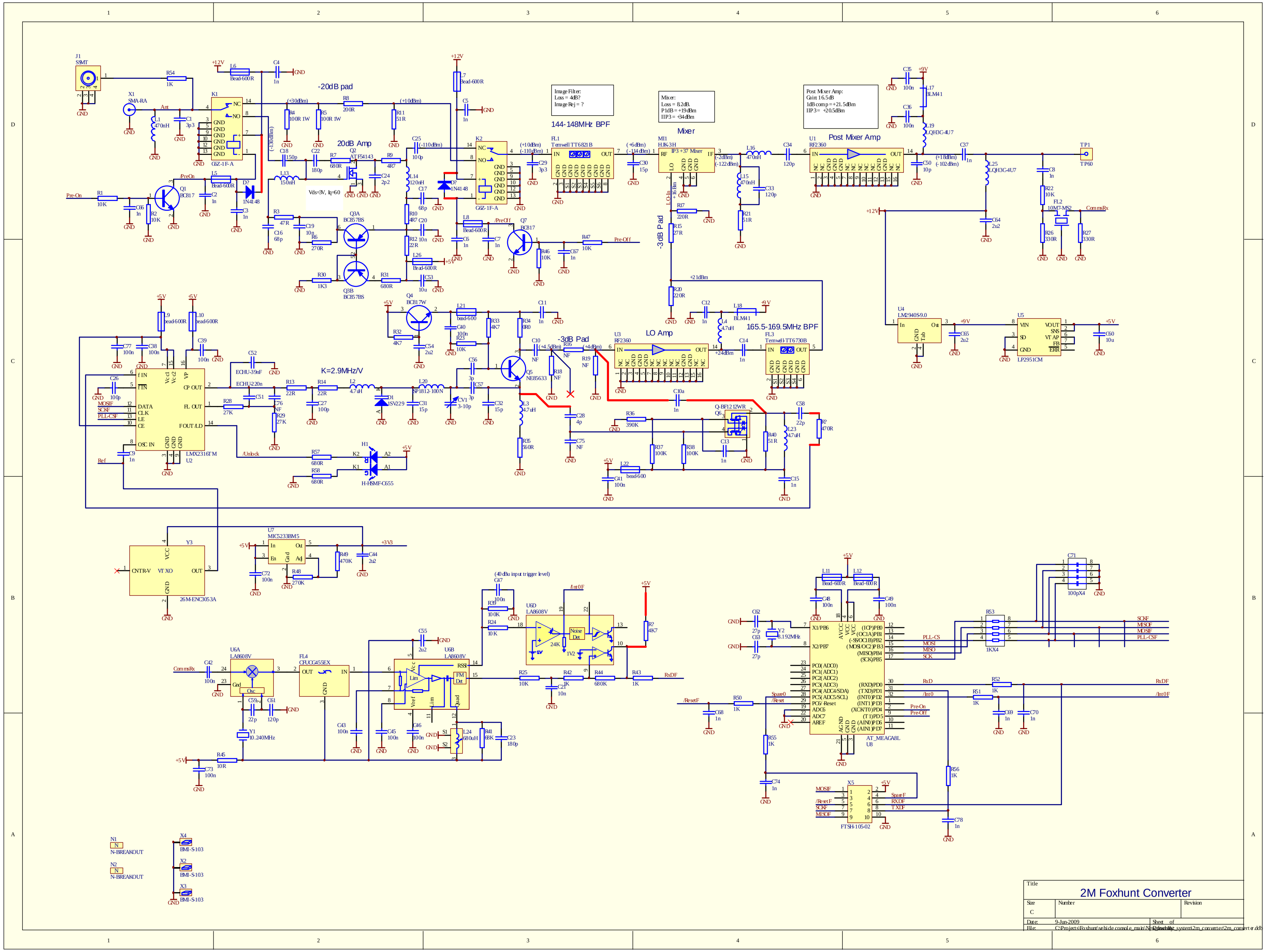
Tested Performance

- 1st IF Image rejection: 76dB
- IF rejection (21.4MHz): 87dB
- Conversion Gain: 29.3dB
- System noise figure: 2.7dB
- SINAD sensitivity: -124.5dBm (4kHz FM B/W)
- Current draw: 400mA at 12V

Results are fairly close to those predicted in the cascade analysis. While the noise figure is slightly higher than predicted and may not look that impressive on its own it must be kept in mind that this is a system noise figure which includes contribution of all stages and not just the LNA. By far the most important parameter is the input IP3 which has been predicted at just under +7dBm. This is quite an encouraging result when compared with many other receiving systems that give similar sensitivity at the expense of a significantly lower (and usually negative) IP3 result, especially when an external LNA is used to improve sensitivity.

Conclusion and future development

A synthesised high performance 2m downconverter has been presented. While some aspects are still a work in progress and could be further improved, the converter has been used successfully and has proved to be a significant improvement on the previous scanner and preamp based receiving setup. Simpler converters are planned for other bands (80m through 23cm) where IP3 requirements are not as stringent as they are on the 2m band in Melbourne.


-20dB pad
20dB Amp
Image Filter:
Loss = 4dB?
Image Rej = ?
144-148MHz BPF
Mixer:
Loss = 8.2dB
P1dB = +19dBm
IIP3 = +34dBm
Mixer
Post Mixer Amp:
Gain 16.5dB
1dB comp = +21.5dBm
IIP3 = +20.5dBm
Post Mixer Amp
-3dB Pad
LO Amp
165.5-169.5MHz BPF
K=2.9MHz/V
(40dBu input trigger level)
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