A Simple 122GHz Transverter

Fig 1 Finished system

An easier way onto the 2.4 mm-wave band.

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September 2019

Introduction

The 2.4mm Amateur band at 122.25 to 123 GHz seems out of reach to many ham operators. This is because the equipment is very complex and requires a lot of experience to build, It requires hard to find and often very expensive components and the test equipment is as rare as Unobtainium.

Why try ?....the challenge of it !! The 2.4mm band is actually a dumb place to try to achieve long distance communications. This is because of very high atmospheric absorption losses from oxygen and water vapor, hence the attraction to use the 122GHz band to try to break the laws of physics, or at least try to bend them. We want cold, still, low pressure, low humidity air, We don't want atmospheric pressure highs with thermal ducting and other high altitude atmospheric propagation enhancers as with VHF in Summer. 122Ghz is more like light than R.F. It's a Winter band.

Most current 122GHz equipment is based on high order frequency multipliers which are low in efficiency, very low in power output and the receivers rarely (if ever) have pre-amplification which means the receive sensitivities are not good. Generating any detectable signal at all on 122GHz is a considerable challenge.

This article presents a simpler, more compact and lower cost way to get operational on the band using an off the shelf, fully integrated transceiver chip originally designed for proximity measurement and Radar applications. The chip technology comes from a company in Germany, Silicon Radar. They design and manufacture a number of chips from several GHz up to above 300GHz. Silicon Radar's chips make this all possible. For this project, a Silicon Radar chip is re-purposed as a narrow band transverter for ham radio use. The chip was never designed to do this. Silicon Radar's chips are definitely worth a look as many of them are suitable for other leading edge mm-wave systems both in the ham and commercial worlds.

The single chip approach , Pro's and Con's.

The Silicon Radar TRA_120 series chips are devices containing a complete 118 - 126 GHz transceiver with separate integrated on-chip antennas for TX and RX. The chip is available in two different packages with slightly different characteristics. See fig B for the chip block diagram.

See the following Internet link for some more detail :

https://siliconradar.com/datasheets/Datasheet_TRA_120_002_V0.8.pdf

The TRA_120 has some really nice features such as, a relatively high power output of around 0.5mW. That's milliwatts not Megawatts or watts. At 122GHz, half a milliwatt is QRO (High Power). The chip also has a preamplifier in the receive path with respectable gain and noise figure. It's also frequency agile as the internal oscillator is a Voltage Controlled Oscillator (VCO). Using an external Phase Locked Loop (PLL), the internal VCO can easily be frequency locked.

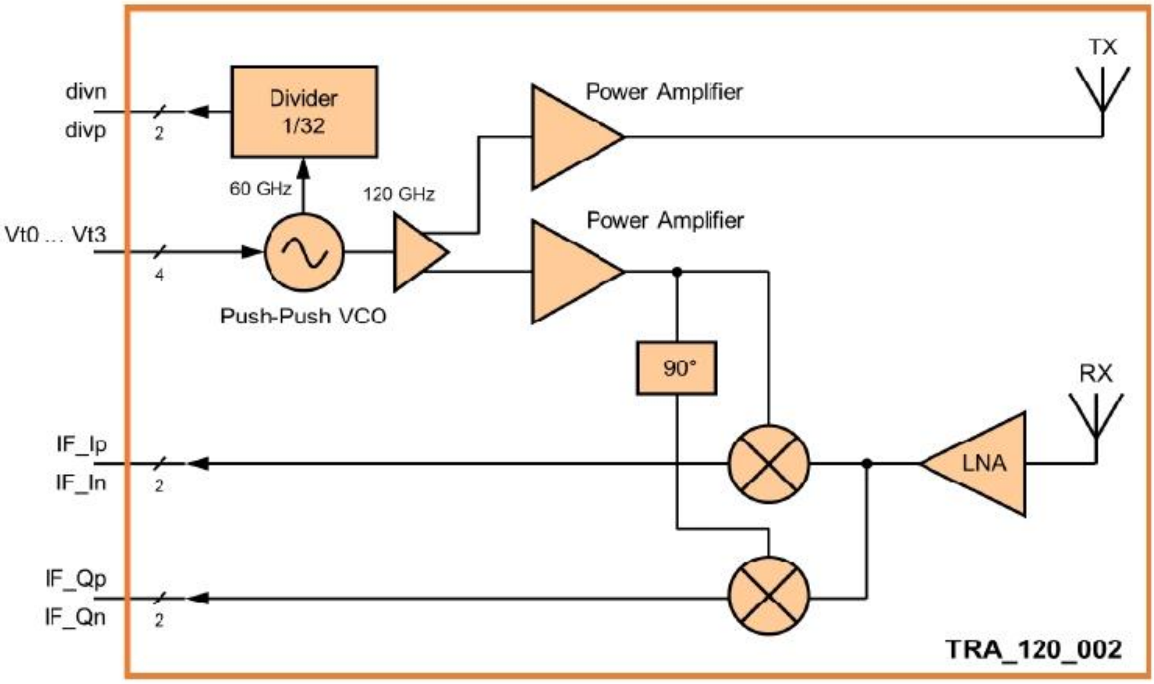

Fig B TRA_120 Chip Block Diagram

The external PLL only has to work at around 1900 MHz as the TRA_120 has a built in R.F. pre-scaler which is pure magic. The PCB's don't have to work at 122GHz, It's all inside the Chip !!!!

This is what is so revolutionary about the Silicon Radar technology, There is no need to deal with 122GHz signals on a PCB which as many would know, is next to impossible because of the extremely high RF losses.

This all sounds great but there are some problems to solve first. As my Elmer buddy Les (VK3ZBJ) would say, "The difficult we achieve immediately, The impossible takes slightly longer".

Other hams have also used this TRA_120 chip, Most notably Mike, K6ML, but quickly realized, there's a major hurdle with the two TX and RX antennas in the chip, they're not in the same exact physical place. This is fine if the chip is used bare as it was designed, or with a low gain external antenna. A bare chip is great if you just want a QSO across the street but if you want mm-Wave DX, you'll need a bigger antenna. If a higher gain antenna is added, because the chip TX and RX antennas are in different places, then the TX and RX antenna patterns end up occurring at slightly different directions resulting in more problems. This means having to either re-position the chip or the antenna when swapping from TX to RX. High gain antennas also introduce another challenge of getting them pointed at each other in the first place. As the antenna gain is very high, the antenna beamwidth becomes very small, Pointing it exactly at the other station can be very challenging.

Because we don't have a lot of TX power and our RX's are relatively "deaf as a post", High gain antennas are about the only easy way to add system gain. We must use high gain antennas to get any significant range performance, So we have to find a way to deal with the high gain antenna pitfalls.

We also need to be very careful with what is called Oscillator Phase Noise. The first prototypes ran afoul of this and the received signals sounded like total garbage in a narrow band I.F.

Phase noise is, in simple terms, tiny oscillator frequency and / or phase changes that occur in all oscillators (It's Physics JIM). Quartz crystals are way better than L. C. or other lumped element oscillators. Phase noise is, in another analogy, short term frequency stability, We'll get to long term frequency stability (Frequency Drift) in a moment. Very careful PLL design, correct component selection, screening and noise source de-coupling are required to minimize phase noise. The PLL itself also multiplies the phase noise of the reference oscillator so that needs to be the cleanest, lowest phase noise oscillator we can get, definitely a Quartz crystal. The TRA_120 internal VCO also adds phase noise as does the PLL chip itself and how it's configured. After many hours of development work it's all quiet enough to give a 3 - 4 quality tone in a narrow SSB receiver.

There's another little detail we need to be really careful about, frequency stability (Drift). As we'll need a PLL for the TRA_120 chip, this means we need a frequency reference which could just be any old Quartz Crystal. Once you do the math, you find that an error of 1Hz with a 10MHz reference translates to an error of over 12KHz at 122 GHz. A GPS locked reference will help ensure the frequency error is low enough. I chose a lower cost (and lower DC power) VCTCXO (Voltage Controlled, Temperature Compensated Crystal Oscillator) to give me reasonably low phase noise, A Voltage Controlled OCXO (Oven Controlled Crystal Oscillator) would be even better but uses way more power and way more $. If a good 10MHz external reference is already available use that. If an OCXO is used it's possible GPS locking will not be required.

On the TX side, We can't generate voice SSB with this TRA_120 chip. This is because we can't Amplitude modulate the TX. We can however easily generate FM, or FSK or other types of angle modulation. To generate pseudo Morse CW, the TX carrier is switched on and off channel, (FSK)

The problem solving and design process.

Let's attempt to solve the problems, Firstly the antenna pointing, With a bit of lateral thinking and hours of simulation on the computer, an R.F. chip coupler and combiner was developed, you could also call it a duplexor. This coupler combines the R.F. from the TX and RX antennas on the chip into a single waveguide path without the need to have to re-position the antenna on from RX to TX, one problem solved but..the downside is that we will lose some performance in both TX and RX.

The TRA_120 comes in two versions, I chose the 002 version, which suits the coupler approach.

Mike, K6ML, has very successfully used the 001 version with a servo driven feed re-positioner. Both approaches have their upsides and downsides. I've chosen to use the coupler approach because of its simplicity when built. The re-positioning approach will give slightly better range performance due to there being no coupler losses. It's up to you to decide.

The coupler itself is adjustable to allow optimization of the coupling and isolation. See Fig X

No test equipment is needed on 122GHz, you can do it all with the S meter and an attenuator on your I.F RX. The output of the coupler is a circular waveguide, it is in fact just a 5/64" (2mm) diameter circular hole, Not that difficult. By the way, even though the guide is circular we are exciting it in a linear mode so we are still using linear polarization.

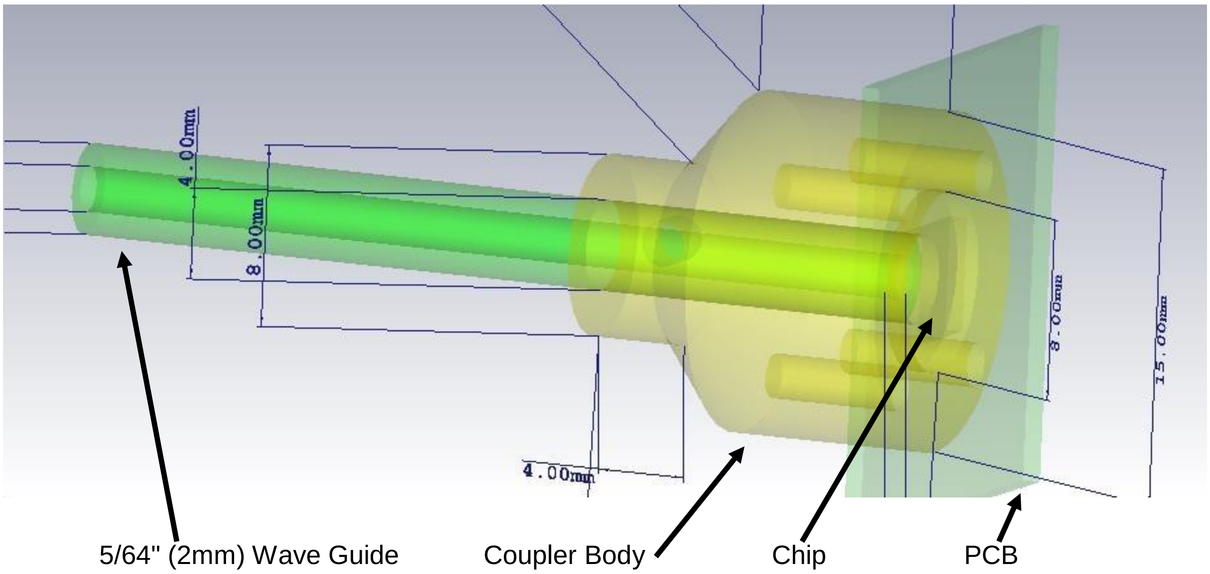

FIG X Coupler, Guide, Chip, PCB

Next problem to solve is the high gain antenna we need to make this all work, Surplus Satellite TV two foot offset feed dishes are often to be found for free in the trash. Many microwave operators consider these as junk. They actually work really nicely even at 122GHz if you take the time to set them up properly. The fine surface accuracy is generally very good which is exactly what we need for 2.4mm wavelengths. It really doesn't matter if the gain is a few dB down on what the theory says because of minor curve errors, The price is right and a 2 footer will give over 50dB of gain. One of these junked antennas at each end gives us a overall system boost of 100dB, NOW YOUR TALKING. The TX E.R.P becomes 0.5mW+50dB = 50Watts, you're going to hear that alright !!!!

OK ..... Let's Build it

There's a development kit for the chips available from Silicon Radar which others have used to experiment with. As this project needs features outside the normal usage of the chip, a new PCB was designed just for the Transverter.

See figures 2,3 & 4 for the PCB, Details of the PCB board layout are :

- Mounting of the TRA_120 chip in a PCB pattern to allow direct connection to a waveguide transition.
- I.F. Output with cable driver to an external receiver. DC to 200 MHz, I/Q output capable.
- Small PCB (2"x2") to allow mounting directly at the feed point of a dish.
- Lowish power consumption to allow portable battery operation, 12Vdc, reverse polarity protected !
- On board Microcontroller (PIC16LF877A) for control of the TRA_120 and PLL.
- 10MHz XTAL GPS locked frequency reference with extra outputs for other gear if required.
- Multi channel switch for easy PLL channel frequency and mode change.
- Mode switching for FM Voice, FM tone, Psuedo CW with a built in morse beacon Ident.
- RS232 diagnostics output for status monitoring and GPS data output to give you a LAT and LONG.

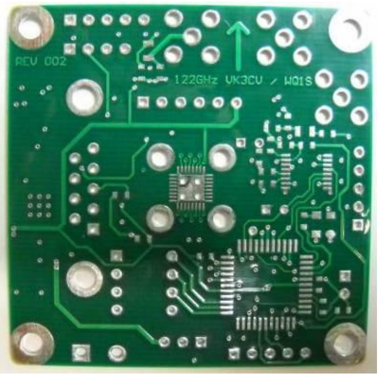

Fig 2 Bare PCB

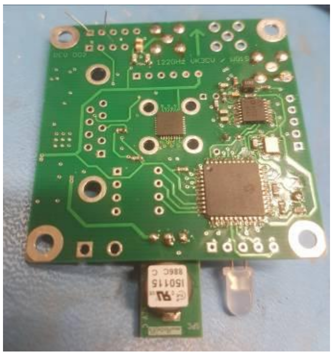

Fig 3 PCB Front , (Note the the TRA_120 chip in the centre square hole pattern)

Fig 4 PCB Rear

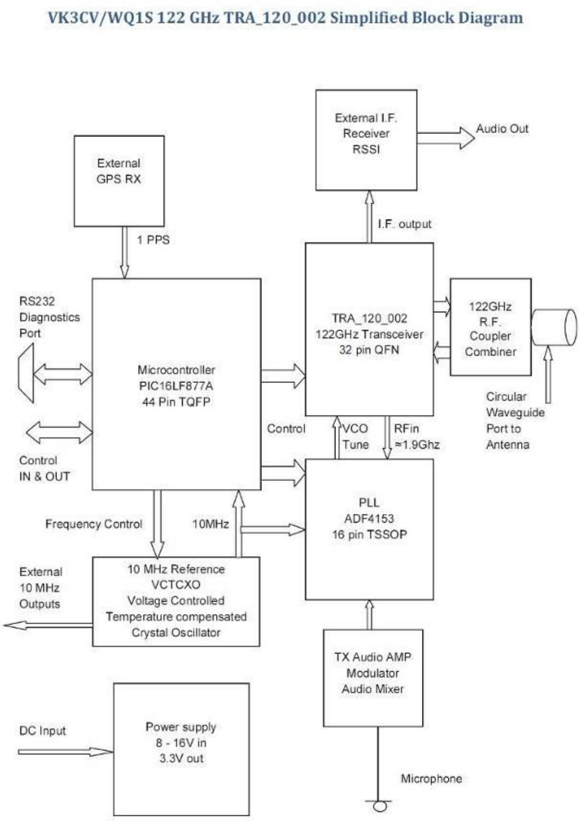

Fig 5 System Block Diagram

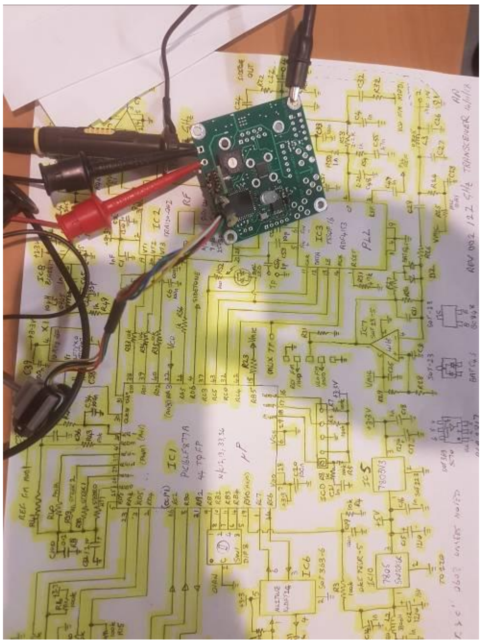

Fig 6 Assembled PCB and original schematic

For the full circuit schematics, PCB artwork, construction details, mechanical drawings and microprocessor code see :

https://www.dropbox.com/sh/oesw3j4jwrf1pb2/AAA06dkaindVJy8k0dbw82B9a?dl=0

We'd need the whole magazine to put it here. Fig 5 shows the simplified block diagram.

Circuit theory of operation

With reference to the simplified block diagram and circuit schematic, An external power supply of a nominal 12V DC is applied through a reverse polarity protection diode to a 5V regulator then to a second 3.3V regulator which supplies all the active circuits. All functional control for the board is handled by a PIC16LF877A Microcontroller. The clock for the microcontroller and reference signal for the Phase Locked Loop (PLL) is provided by a Voltage Controlled Temperature Compensated Crystal Oscillator (VCTCXO) running at 10MHz.

The 122GHz transceiver chip is controlled by the Microcontroller in addition to being frequency locked by the PLL (ADF4153). The 122GHz TX and RX circuitry is all contained within the TRA_120_002 chip. A divided by 64 output of the internal 122GHz Voltage Controlled Oscillator (VCO) in the TRA_120_002 chip is fed to the PLL which can then lock its internal VCO to the desired operating frequency. The VCO in the TRA_120_002 is always operating either on the TX or RX frequency and its frequency is determined by the control data sent to the PLL chip by the Microcontroller.
Note that the PLL operates in the region of 1.9 GHz. A test point is available to observe this 1.9GHz signal to allow testing of the system. The PLL phase comparator output is fed via a loop filter to the VCO tune inputs of the TRA_120_002. This voltage is monitored by the Microcontroller as well as the PLL lock signal to ensure the PLL is correctly locked.

Modulation inputs are included in the PLL circuit to allow modulation of either the VCO error voltage or of the reference tune voltage resulting in FM modulation of the VCO. There are selection links to choose which modulation path is used, Normally the reference signal path is used giving a nominal 5 KHz of FM deviation. The modulation signal is supplied from a simple modulation limiting microphone amplifier which is connected to an external electret type microphone.

The VCTCXO tune voltage is derived from a resistive voltage summing network. Inputs to this network are provided from the Microcontroller to provide frequency error locking to an external GPS signal as well as FM tone Modulation. An external GPS derived one pulse per second (1PPS) signal is fed to the Microcontroller which under software control, uses this to lock the 10MHz internal reference to the external 1PPS signal resulting in a frequency error much less than 1Hz when locked. The frequency locked 10MHz signal is also available externally and can be used as a reference for other equipment.

The TRA_120_002 chip has two separate internal linearly polarized antennas for TX and RX which are separated physically within the structure of the chip. The TX and RX signals are combined in a specially designed external chip to waveguide coupler which sits directly over the TRA_120_002. The coupler external antenna port is a 5/64" (2mm) diameter circular waveguide which is then fed to an external antenna. This approach ensures that no errors in the antenna main lobe direction occur between TX and RX which would be very significant if a high gain antenna were used without the coupler . The coupler feed waveguide is circular but the polarization remains linear. See the marker arrow on the PCB for the linear E field polarization direction. Two types of antenna have been made, A Chaparral™ type with 10dBi gain for use as a offset type dish feed and a 21dBi Gain Conical horn for beacon use. When the dish feed is used with a 2 foot dish, a gain of over 50dBi is possible.

Received Signals from the internal chip RX antenna on 122GHz are first amplified and then converted down to the I.F. frequency by a mixer inside the TRA_120_002 chip. The I.F. signals are available as I/Q differential signals for use by an external Software Defined Radio (SDR) or in an analogue format via a buffer amplifier for use by an external I.F. receiver. The I.F. frequency is nominally 144.4 MHz. This can be changed to anywhere in the range from DC to 200MHz under software control. There is a significant amount of degradation in the FM received signal to noise performance of the system due to the inherent phase noise of the 122GHz L.O. Use of the narrowest I.F. bandwidth FM demodulator available will give the best results. Note that as the VCO in the TRA_120_002 is always running, Full duplex operation is possible in FM mode. This is done by having the local system and the remote system operating on frequencies separated by the I.F.

Transmit signals on 122GHz originate from the VCO inside the TRA_120_002. They're then fed via an internal TX amplifier and then on to the internal chip TX antenna.

Software Operation

The Microcontroller takes inputs from several sources which it then uses to control various features and functions of the system under control of the internal software. The Microcontroller has control of the following : Bi-Colour RED/GREN LED, FM modulation tone generation, External sidetone generation, GPS frequency locking, Microphone amplifier enable, PLL RF frequency, RS232 diagnostics port, TRA_120_002 mode, External mode control inputs, External mode outputs and Channel selection. Note that only 2 channels are currently used being A and B corresponding to "0" and "1" on the least significant bit of the channel selection lines. If a channel switch is fitted to the PCB, the DIP switches must be set to all open or position "0" for a rotary HEX switch

The system software is contained in Flash memory within the Microcontroller. Software programming is achieved via the provided In Circuit Serial Programming (ICSP) port on the board. Refer to the relevant Microchip data sheets for information and software programming details.

On power up, The microcontroller configures all the required inputs and outputs and initializes the required internal registers and external peripherals. A dual colour LED is available to give operator feedback on operation. The LED will initially be RED during power on an then change to GREEN to show correct operation and that the PLL is locked. If the PLL is not locked, The Led will remain RED and flashing. The LED will also go to RED when the system is in the TX mode. An rapidly alternating RED/GREEN LED flash indicates low DC input voltage. (less than approximately 10V).

Depending on the selected mode of operation, the Microcontroller has a built in Morse Code Keyer available which can provide a continually repeating Morse code message such as a call-sign on the transmitter to aid with testing and for use as a beacon. The transmitted string can be changed in the Software as desired. It is located in the string definition section near the end of the assembly language file.

The full Assembly language source code file is also available in the DropBox archive. All information in the archive is provided free of charge and without any direct or implied warranty.

Construction

The PCB is laid out to allow easy interface to the TRA_120 chip, Note that the design is a 4 layer board with an almost continuous internal ground plane to keep all the signals where they're supposed to be. Mounting the chip itself is challenging, good optical magnification, a steady hand and a source of heat, there's plenty of YouTube videos on how to do it. It's suggested to mount the TRA_120 chip first, observe basic anti-static practices but the chip is quite robust in this respect. Once the chip is down, as a sanity check, you can look with an Ohm meter at all the chips signal pins to ground to check if there is a diode junction present on all the connected pins. (The diodes you see with the meter are ESD protection on all the pins) Reflow it again if there are any issues. Everything else can be placed and soldered manually using a small tip iron with the assistance of optical magnification.

Code for the Microcontroller is written in Assembly language, the source is available in the DropBox archive for those who want to change anything. Any external GPS board that has a one pulse per second output (1PPS) is suitable for the oscillator disciplining. I mounted the GPS receivers in a small external plastic box which plugs into the control box with a separate regulator to reduce noise.

Firing up the system

Now the fun stuff. Firstly get two boards with bare chips to communicate across the shack you'll see the thing actually works. If you have some test gear it's also possible to see the 1.9GHz PLL signals and check that everything is locked and stable. No test gear on 122GHz is required. Diagnostics data is also available on the RS232 port at 9600Bd N,8,1.

Several options for antennas are possible. Bare chips, Conical Horns made on a lathe, and dishes. All the antennas, feeds and coupler mechanical details are again in the DropBox archive.

The machining of the Chaparral™ feed is a challenge, A special tool made from a broken tap is shown in Fig 8. Another tool (Fig 7) was made to bore out the internal tapered hole in the conical horns.

Fig 7
Horn boring

Fig 8
Tiny Multi Choke Ring dish feed
Commonly known as Chaparral™
(The centre hole is 5/64" Diameter)

Fig 9 Horn, Adjustable and fixed feeds

The ultimate step is to use the larger dishes. Good stable tripods and telescopic sights are required when you get to this point. A purpose designed multi choke ring feed (commonly known as a Chaparral™ feed) was made for the dishes. Experiments were done with both a fixed and adjustable coupler and feed, the adjustable one works much better and is documented in the archive. The adjustable version allows optimization of the chip coupler. The chip coupler/combiner is built into the PCB waveguide mounting flange. The dish feeds have ≈9dBi gain to suitably illuminate the dishes. As a sanity check a comparison was done between the Chaparral™ feed and the bare chip. The difference is around 1dB which suggests the feed is working very well indeed. The bare chip antenna gain is around ≈10dBi as shown in the chip specifications.

Fig 10 Feed point and Telescopic sight

Fig 11 Control Box with GPS unit (Black Box)

FIG 12 Ready for action

Setting up the dishes is time consuming and you'll need to be patient and methodical. Set up one of the boards with a bare chip just out past the R.F. near field at 25 yards from the dish system. Try to have the test area clear of reflective objects, which at 122GHz is just about anything. Connect your I.F. receiver to the test unit and put an adjustable attenuator in the line if you have one. The attenuator is handy to keep the S meter on your receiver in a useful range. The I.F. is 144MHz.

The optimum feed point of the dish needs to be correctly identified in all 3 dimensions X,Y and Z. A good starting point is the original position of the old satellite feed. Use trial and error by peaking for maximum signal from the remote beacon board. Accuracy and stability is important here, The feed positioning accuracy needs to be less than a 1/32" in all X,Y and Z planes to realize peak gain, Also each time you move the feed, the dish needs to be re-peaked to see the effect, It took a few days to do both dishes. A temporary mounting bracket with slotted holes to hold the TRA_120 board in the dish focus point to allow everything to be adjusted is very useful. Make small changes then record the peak result and also the size and number of significant side lobes. Generally there are more and larger side lobes when the feed is not in the right place. It's just like focusing an optical lens, The image needs to be sharp, not fuzzy. Lots of side-lobes indicate bad focus. When correctly focused, The dish is by design meant to have few, and smallish side-lobes. A 2 foot dish should realize over 50dB of gain and have a 3dB beam-width of around 0.3 degrees. Optical telescopic sights which are available at reasonable cost again on Ebay are very useful to ensure alignment once the feeds are set up correctly. Align the Optical sights after the dish feed positions are optimized in the field by using a far field test, you'll need a 600 yard dish to dish distance to align the sights correctly.

The dish itself (Fig12) will end up at an angle in the vertical plane when the actual main lobe is perfectly horizontal, The angle is normally around 20 to 30 Degrees. This is due to the whole offset feed arrangement. Imagine playing pool, The angle a ball leaves the pool table cushion is the equal and opposite of the angle at which the ball hits the cushion. It's the same for the R.F. wave-front hitting the dish surface, It bounces off at the opposite but equal angle. Not all satellite dishes are created equal however. Don't assume that just because you have two dishes which visually look similar, that they are exactly the same as far as the optimum feed position is concerned. Offset feed dishes give slightly better gain than a prime focus dish because there is no feed obstruction.

Note that there are added adjustable stabilizing rods to the sides of the dish and back to the feed point. This assists in keeping everything stable, especially going up to a mountain top to try to make some contacts. The adjustment rods also assist in realizing a few more dB of gain by slightly changing the shape of the dishes to be closer to the ideal shape. Again careful adjustment and trial and error to get peak efficiency and thus gain.
Final systems are housed in a box with the control switches, a rechargeable battery, attached telescopic optical sights, and a bubble level to get the system perfectly horizontal to aid pointing in the right place. Note that the arrow on the PCB shows the E field polarisation sense.

Three systems have been built so far, two dish systems (Fig 12) and a development system which is useful as a test beacon and also as a mobile station (Fig 13). Inside of the feed box is shown in Fig14

Fig 13 Development Unit

Fig 14 Inside the dish feed box

Does it actually work ?

The results in the field are impressive. First contacts were from dish to horn at over 3miles with a large margin at sea level (Fig15). A mobile contact was made at over 1.8 miles just for a bit of fun. The next step was 12 miles dish to dish in good atmospheric conditions, at an altitude of 1000 feet, with more than 30dB of margin. More mountain sites are yet to be conquered but currently the performance has been pushed out to over 36 miles. The system may not break any world distance records where it's currently located in Australia but it's expected that the range can be pushed out to something above 50 miles in ideal conditions, Definitely more distance is possible with very tall mountains but there aren't any of these in VK land. A mountain on a calm day in winter like Mt Washington in New Hampshire would be ideal.

The system as described is programmed to be full duplex, I.E. Each end is offset in frequency by the I.F. A headset with an attached boom microphone is ideal to chat away for hours. Some really interesting propagation effects due to air movement QSB, Doppler chirps from passing cars and just dealing with the extra losses due to water vapor and air pressure are some of the charms of 122GHz. The system as described supports NBFM and CW. The residual phase noise will be evident on FM.

Future work to be done includes using the I/Q outputs of the TRA_120 to go directly to a SDR (Software Defined Radio) I.F. and demodulator. TX with Digital Modes such as WSJT is also a possibility. There's lots of experimenting and further development yet to be done. Better phase noise will also improve the system. Any suggestions and comments are welcomed.

QSY to 2.4 mm.

73's Andrew WQ1S / VK3CV

Fig 15
Operating from the Cerberus Car Park ,
Black Rock, Victoria, AUSTRALIA

Acknowledgments.

Silicon Radar for making the "Magic" chips for all this to be possible, and for their excellent support.
Sally, my YL for helping with field measurements and for keeping me watered and fed.
Ken Anderson, my late Dad, who taught me how to use my brain, my hands and a lathe.
Les Jenkins, VK3ZBJ (Silent Key), My mate and mentor, what Uncle Les didn't know about RF isn't worth knowing.
Karl, VK3LN, for field operations, assistance and sourcing the surplus dishes.
Noel, VK3NH, for field operations and assistance.
Mike K6ML, Alan VK3XPD, Dave VK3HZ, and others for ideas and peer review.

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