IONOS Sim
HF and VHF/UHF Ionospheric Simulator

An open source project (hardware and software) by the Amateur Radio Safety Foundation Inc. and Winlink

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Winlink Development Team

Ionos Propagation Simulator Project

- This presentation describes and provides documentation for a project for the development of a HF and VHF propagation simulator based on the Watterson model, Teensy 4.0 processor and Teensy Audio Library.

Objectives:

1) Evaluate the latest Teensy CPU, Audio components and Audio library.

2) Provide an easy to duplicate, easy-to-use, low cost channel simulator to allow development, optimization, and characterization of HF and VHF/UHF modems and protocols.

Teensy Simulator Function and Flexibility Summary

- **Common standardized* modes: WGN(1 path) or MPG,MPM,MPP,MPD(2 or 4 paths I & Q, (4 or 8 total rays)**
- **WGN added (S:N -40 to +40 dB) to all common modes.**
- **Flat Fading (0-40 dB depth, 0-20 Hz rate) can be applied to all common modes (useful for VHF/UHF modeling)**
- **Static Frequency offset (-200 to +200Hz) can be applied to White Gaussian modes. (auto tune modeling/testing)**
- **VLF FM (0 to +/200Hz deviation, 0-20Hz rate) can be applied to White Gaussian Noise mode (drift and doppler modeling)**
- **Wide range Individual gain/level adjust on all audio inputs (2) and outputs(2)**
- **Selectable bandwidth with Spectrum plots (0-3.5 KHz and 0-6.5KHz)**
- **Built in Test/measurement for calibration tests and self check.**
- **USB serial interface (4800-115200 baud) for automated operation**

*** Conforms to CCIR/ITU Rec 520-2 Recommendation (Use of High Frequency Ionospheric Channel Simulators)**

IONOS Simulator Functions and Specification Summary

- **Watterson Model with HF and VHF/UHF extensions**
- **Channels: WGN, MPG, MPM, MPP, MPD, Flat Fade, Slow FM, Freq Offset**
- **Audio Paths: WGN 1Path, Multipath: 2 or 4 Paths each with I and Q**
- **Connections Modeled: 1 Simulator Half Duplex, 2 Simulators Full Duplex**
- **Audio Bandwidth: 300 Hz-3300 Hz; 300 Hz-6300 Hz, <+/- 1 dB**
- **Noise Modeling: Bandwidth filtered White Noise, -40 to +40 dB, 1 dB Steps**
- **Input/output Connections: Standard 1/8” (3.5 mm) Stereo jacks**
- **Controls: 2 rotary encoders for modes and parameters. Setup saved to EEPROM**
- **Alternate USB serial control for automated testing. (4800-115200 baud)**
- **Display: 320 H x 240 V color TFT display (setup, audio levels, spectrum)**
- **Built in Self Test and calibration verification. (Flat +/- 1 dB over 300-6000Hz)**
- **Audio Levels: Adjustable input/output Gain. Internal level < 2000 mv p-p**
- **Power: + 5 v, < 200 ma via Micro USB connection.**
- **Size 6.1” (155mm)L x 4.7”(120 mm)W x1.4”(36mm)H (excluding knobs)**
- **Documentation: Full Open Source: (Schematic, PCB, Mechanical, C++ Software)**

Ionos Sim 4 Path HF/VHF Channel Simulator
Simplified block Diagram

Channel Type	Spread Hz 2sigma	Delay	Fade Depth
WGN	0	0 ms	
FADE (FLAT)	0		0 to 40 dB
OFFSET/FM	Deviation/rate up to 200 Hz		
MPG	.1	.5 ms	
MPM	.5	1 ms	
MPP	1	2 ms	
MPD	2	4 ms	

Teensy 4.0 uP, 600 MHz
2 Rotary Encoders
Stereo Sound card chip (44.1KHz)
Buffer amps
TFT Graphics display
USB power and serial interface

Desired S:N
-40 to + 40 dB

WGN + 3 or 6 KHz LPF

p-p meas
rms meas
S:N Mixer
Buffer Amps
Output Level Adjust

Audio Out #1

Audio Out #2

Audio In #1
Test Tone
Audio In #2

input Select/ gain adjust

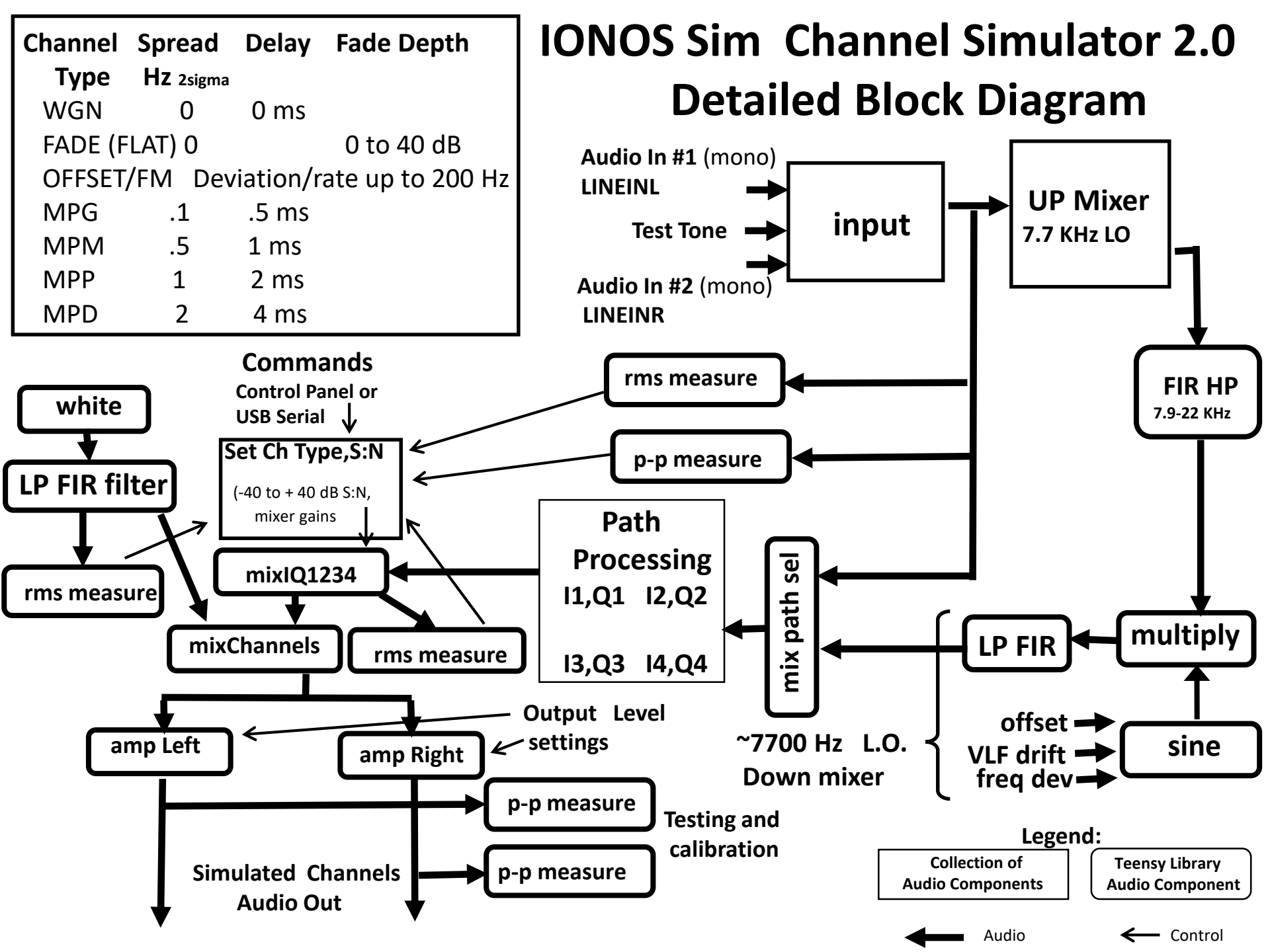
Up/Down Mixers and filters (For Freq Offset and slow FM Modulation)

I and Q Delay processing (2 or 4 I&Q paths)

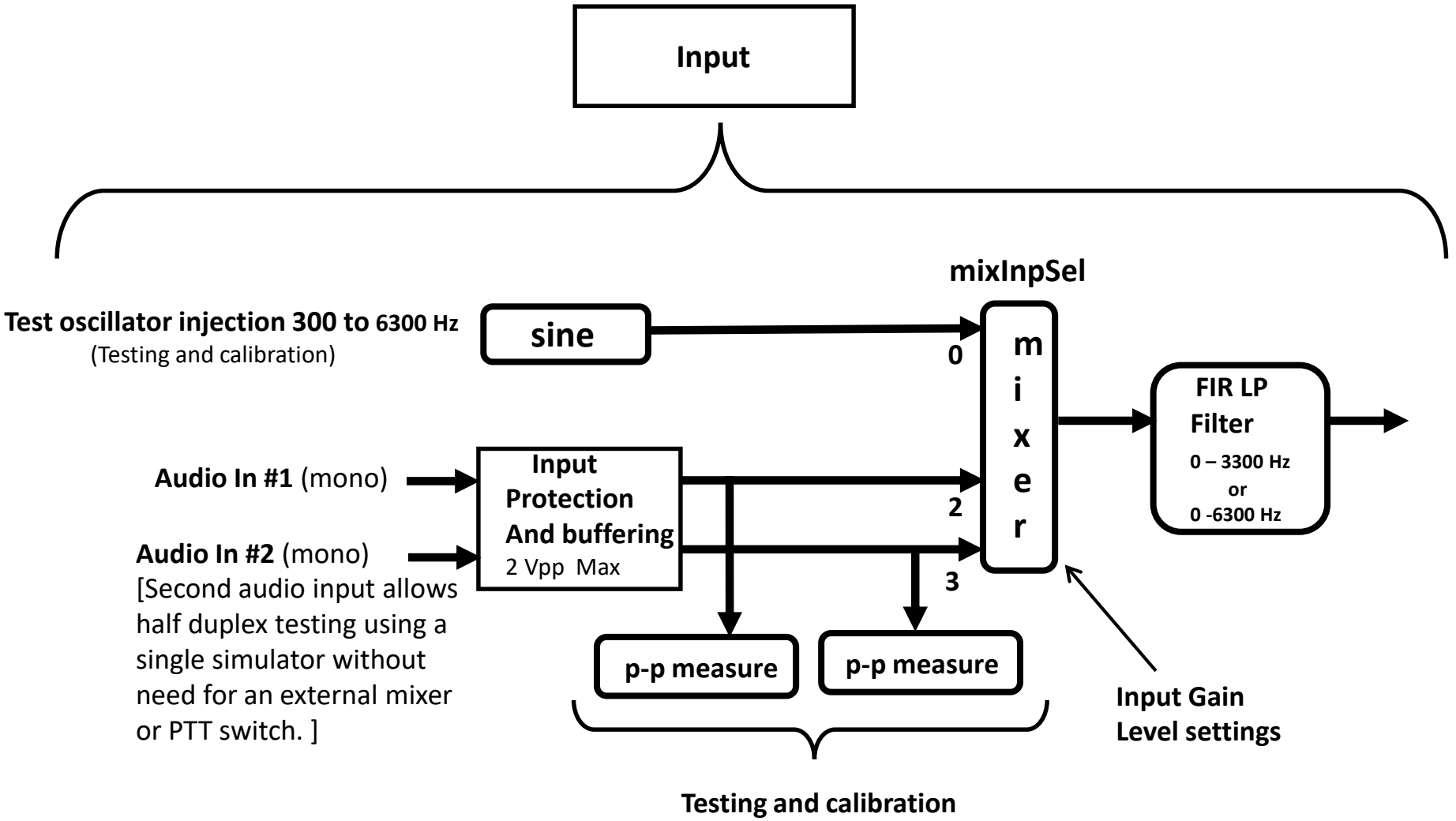
Implemented using 37 Teensy Audio DSP Library Components and 44 virtual connections.

IONOS Sim Channel Simulator 2.0
Detailed Block Diagram

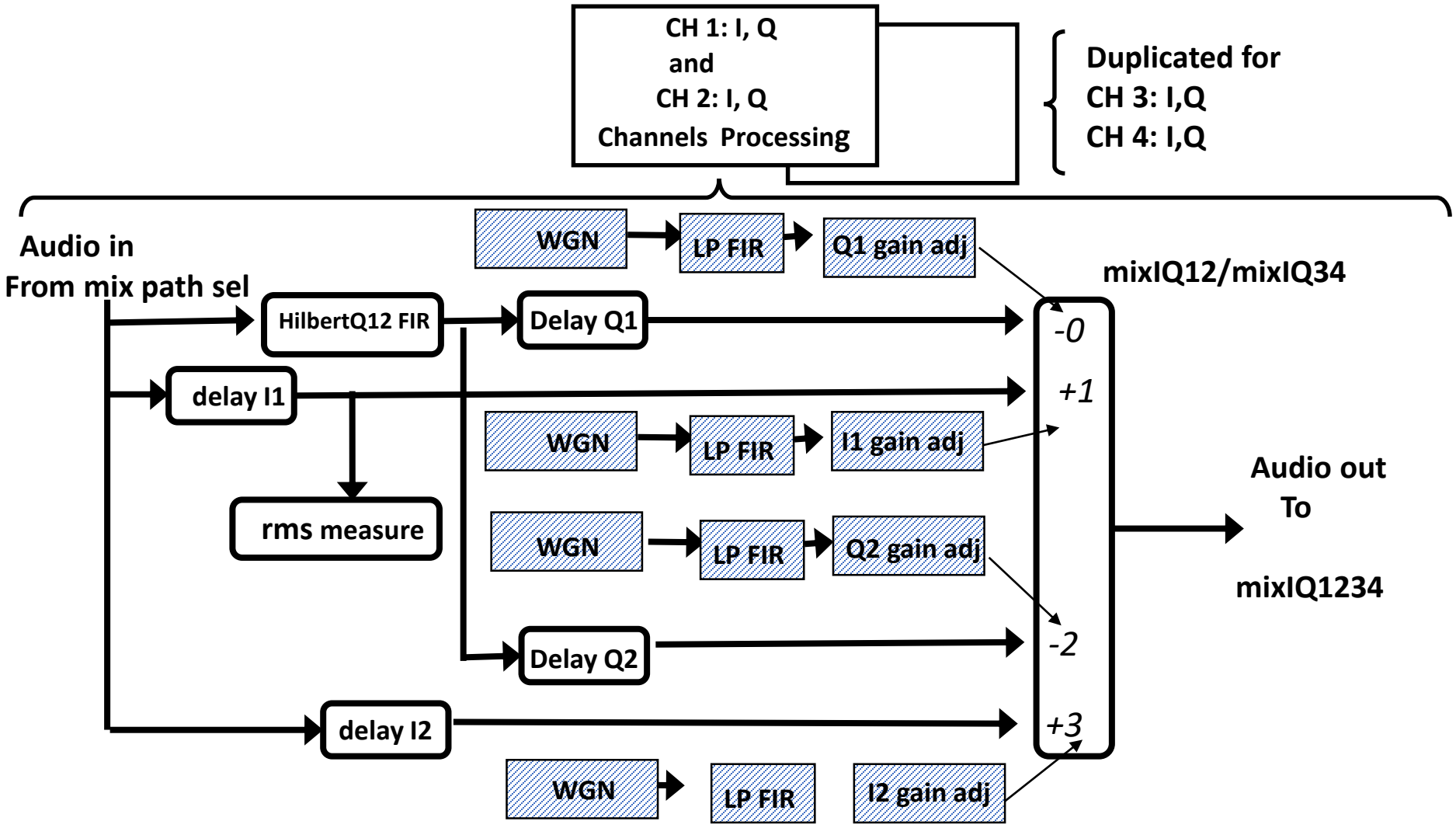
Channel Type	Spread Hz 2sigma	Delay	Fade Depth
WGN	0	0 ms	
FADE (FLAT)	0		0 to 40 dB
OFFSET/FM	Deviation/rate up to 200 Hz		
MPG	.1	.5 ms	
MPM	.5	1 ms	
MPP	1	2 ms	
MPD	2	4 ms	



Input Detail



Path Processing Detail



1. Normal audio processing is done at 44.1KHz sample rate, 16 bit audio.
2. C++ Functions in crosshatched boxes are updated at 64 times the selected path Doppler spread frequency
3. Delay tap values I1,Q1,I2,Q2 are constant for each modeled Path type.
4. mixIQ12 gain signs extract only real parts to send to mixIQ1234 mixer. (see following slide)

Details of IQ processing for Waterson Model

Papers referencing the Waterson model are sometimes incomplete or confusing about the IQ processing details. This summarizes the detailed steps:

1) Create a 90 degree shifted version of the incoming audio using a Hilbert Filter. This becomes the Q1 Channel in the previous slide.
2) Time align (delay) the Real component (to offset the delay through the Hilbert filter). This becomes the I1 Channel.
3) Generate a random complex vector using WGN but bounded in magnitude to lie ***inside*** the unit circle. Call these two components NI and NQ
4) Filter (independently) the NI and NQ components of the complex vector with a narrow band (< 4 Hz@-6dB) filter with ~Gaussian shape and frequency response dictated by the CCIR recommendations. The filter bandwidth is proportional to the Doppler spread of the multipath channel being modeled.
5) Do the Complex (real and imaginary) multiplication of the filtered narrow band noise with the I1 and Q1 in 1) and 2) above. This generates 4 components:

   I1 NI, I1 NQ, Q1 NI, and Q1 NQ.

   The I1 NQ and the Q1 NI are imaginary and discarded since only REAL audio need be sent to the modem.

   The I1 NI and the Q1 NQ are both real but the Q1 NQ is 180^0 shifted ($j * j = -1$)

   Subtract the Q1 NQ product from the I1 N1 product to get the Real Audio sum.
6) Repeat above for Paths 2, 3, 4

Details of Fixed Path Delays for IONOS Sim 2.0

For Multipath each I and Q path is independently modulated by a VLF random vector

Mode	# Paths	I delays (ms)	Q Delays(ms)
WGN	1	0	---
MPG	2	0, .5	0, .5
MPG	4	0, .25, .5, .75	0, .25, .5, .75
MPM	2	0, 1.0	0, 1.0
MPM	4	0, .5, 1.0, 1.5	0, .5, 1.0, 1.5
MPP	2	0, 2.0	0, 2.0
MPP	4	0, 1.0, 2.0, 3.0	0, 1.0, 2.0, 3.0
MPD	2	0, 4.0,	0, 4.0
MPD	4	0, 2.0, 4.0, 6.0	0, 2.0, 4.0, 6.0

Filter Details

Low Pass FIR Filters for 0-3.3 KHz and 0-6.3 KHz FIR

TFilter on line design < .5 dB ripple, (Input, Noise, Down Mixer)

High Pass filter for Up Mixer 7.9 KHz – 22KHz FIR

TFilter on-line design < .5dB ripple (Up Mixer)

Hilbert Transform Filter 350 Hz - 6.5 KHz FIR

Iowa Hills Hilbert Filter Designer Version 3.0 (Q channel Generation)

VLF Gaussian FIR filters for WGN modulation for multipath

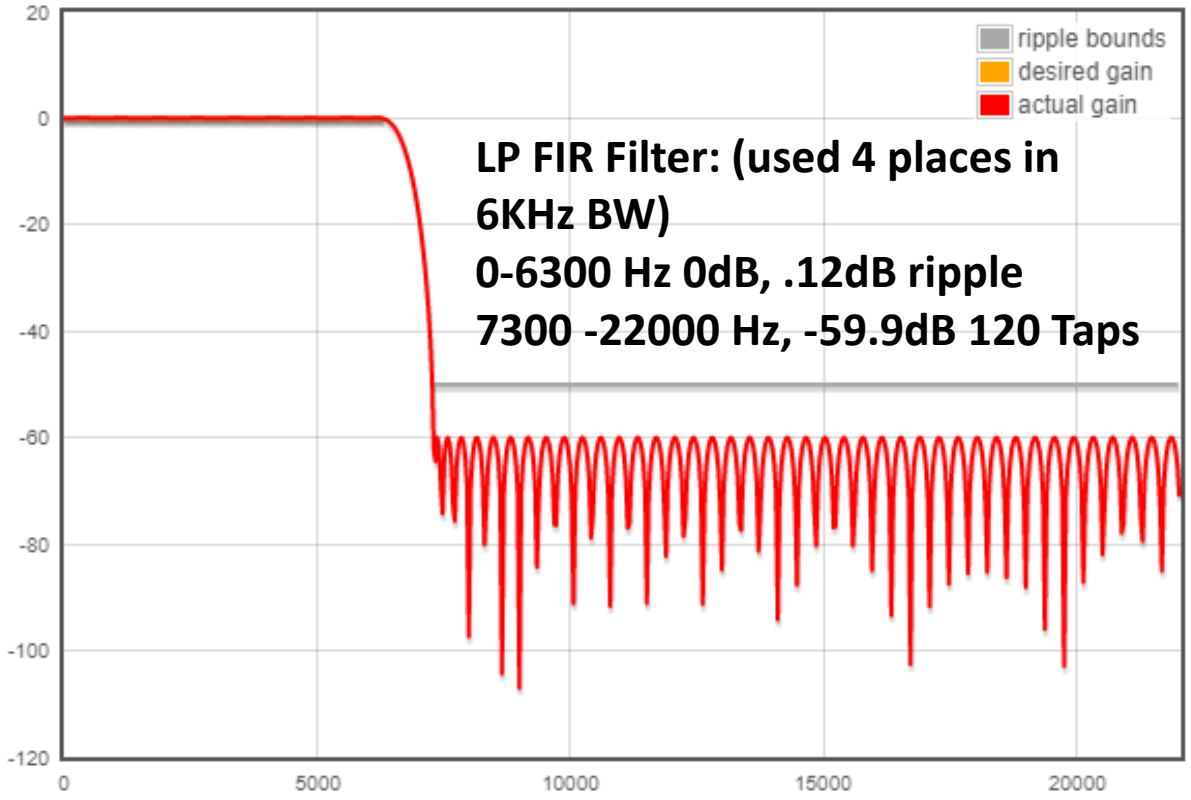
Iowa Hills FIR Filter Designer Version 7.0 (Narrow BW, CCIR shape)

for 2 Paths: 4 independent VLF filters

for 4 Paths: 8 independent VLF filters

(Following 5 slides show design details)

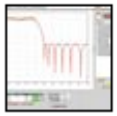
Gain vs. Frequency | Impulse Response | Source Code | Feature Request | Enterprise | IIR Design



need a FIR filter? TFilter BETA

plain text ▼ double ▼

```
-0.0005431005596027716
-0.0015834557610249684
-0.0013682238393217098
-0.0010031110648012998
0.00019221564999620094
0.001064098914080573
0.0010836097182900773
0.0000743571055652606 7
-0.0011492345699937322
-0.0015184352378377816
-0.0005425770075472659
0.0011020429732026347
0.0020138067946888242
0.0012260647671244803
-0.0008201070411614967
-0.0024496967123131116
-0.002096170242123549
```



TFilter, th…

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add passband | add stopband | !predefined ▼

from	to	gain	ripple/att.	act. rpl	
0 Hz	6300 Hz	1	0.5 dB	0.12 dB	
7300 Hz	22000 Hz	0	-50 dB	-59.95 dB	

sampling freq.	44100 Hz
desired #taps	120
actual #taps	120

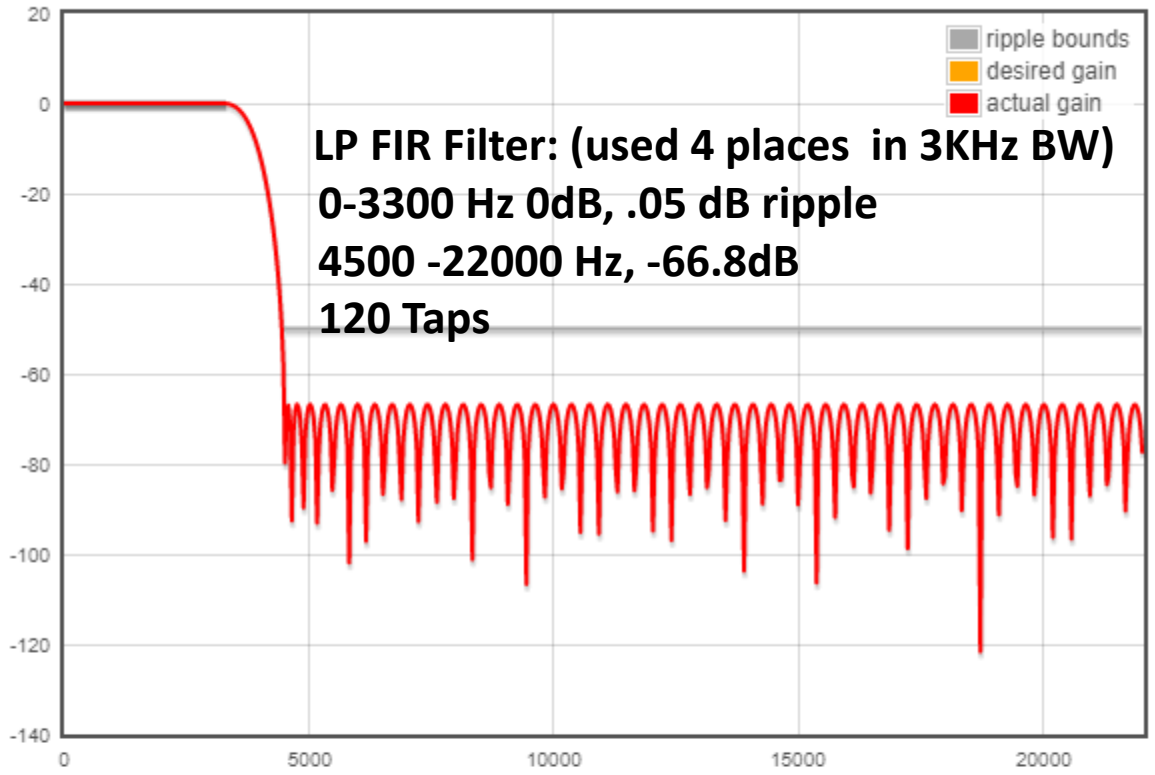
DESIGN FILTER

I am working on **TFilter2**. Screenshot
effect of quantization, save/load/share,

If you want to **advertise here**, contact n

TFilter is being used by many tech com

Gain vs. Frequency | Impulse Response | Source Code | Feature Request | Enterprise | IIR Design



need a FIR filter? TFilter BETA

plain text ▼ double ▼

```
0.0001639708393010892
-0.0001835226617269277
-0.0003341455590704724
-0.0005267154136672266
-0.0006809798344809677
-0.0007173920319099355
-0.0005768894162811259
-0.0002462219087205 3017
0.0002285818955311738
0.0007235356717819803
0.001097203504502563
0.001196125186224 0834
0.000926358886434632
0.0002948796619055 0594
-0.0005687050555198217
-0.0014299040486890633
-0.002005591643934215
```

TFilter, th…
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add passband | add stopband | !predefined ▼

from	to	gain	ripple/att.	act. rpl
0 Hz	3300 Hz	1	0.5 dB	0.05 dB
4500 Hz	22000 Hz	0	-50 dB	-66.83 dB

sampling freq.	44100 Hz
desired #taps	120
actual #taps	120

DESIGN FILTER

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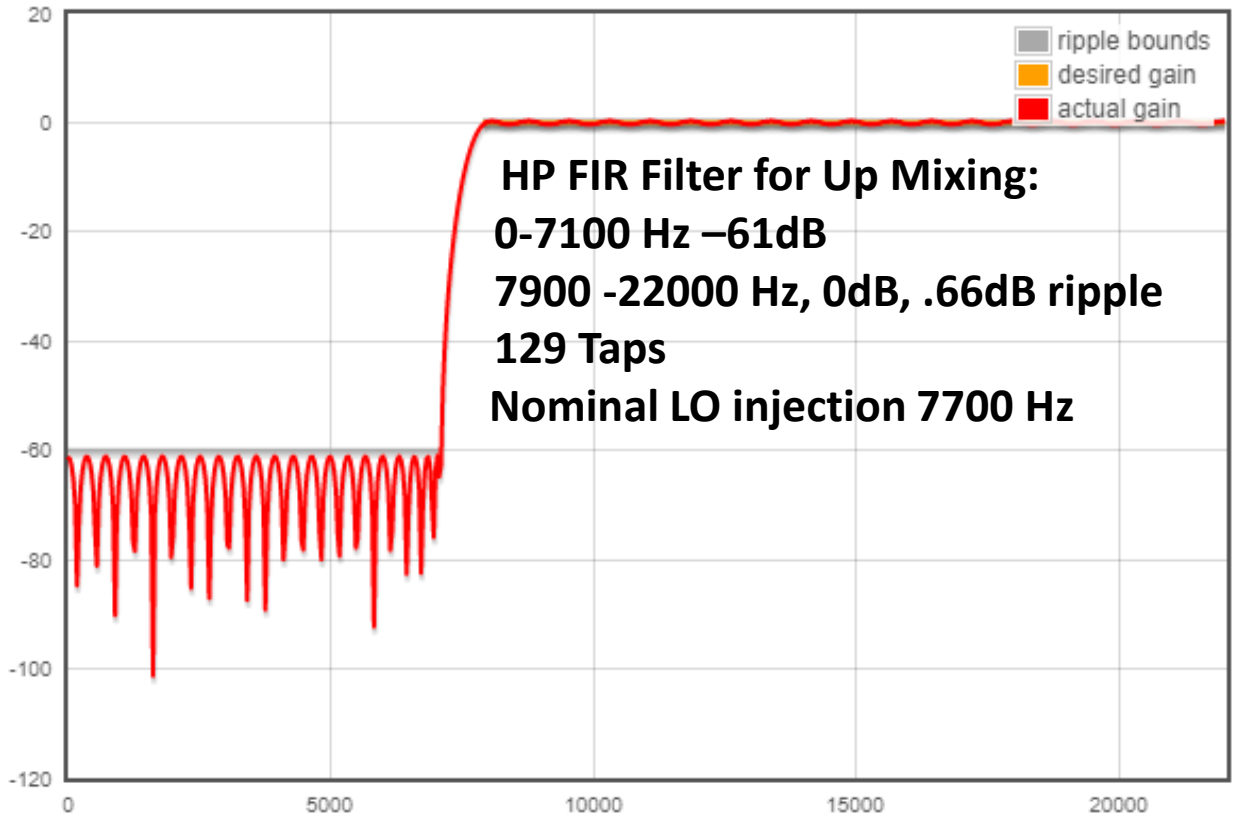
effect of quantization, save/load/share, ali

If you want to **advertise here**, contact me

TFilter is being used by many tech compa

Gain vs. Frequency | Impulse Response | Source Code | Feature Request | Enterprise | IIR Design



HP FIR Filter for Up Mixing:
0-7100 Hz –61dB
7900 -22000 Hz, 0dB, .66dB ripple
129 Taps
Nominal LO injection 7700 Hz

need a FIR filter? TFilter BETA

plain text ▾ double ▾

```
0.005217537253413935
-0.008232577963645788
-0.0016474644713802512
0.009941259980316952
-0.003197433485950914
-0.0001431404514309263
-0.005494128131930125
0.0025602954114935556
0.0011495703448122663
0.00390896664313653
-0.0020188195696074418
-0.0021089650589901
-0.0031823094595710808
0.0019277907597405662
0.002998663212117553
0.00278047357076404 8
-0.002213735027270333
```

TFilter, th…
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add passband | add stopband | !predefined ▾

from	to	gain	ripple/att.	act. rpl
0 Hz	7100 Hz	0	-60 dB	-61.12 dB
7900 Hz	22000 Hz	1	1 dB	0.66 dB

sampling freq.	44100 Hz
desired #taps	119
actual #taps	119

DESIGN FILTER

I am working on **TFilter2**. Screenshot he
effect of quantization, save/load/share, ali

If you want to **advertise here**, contact me

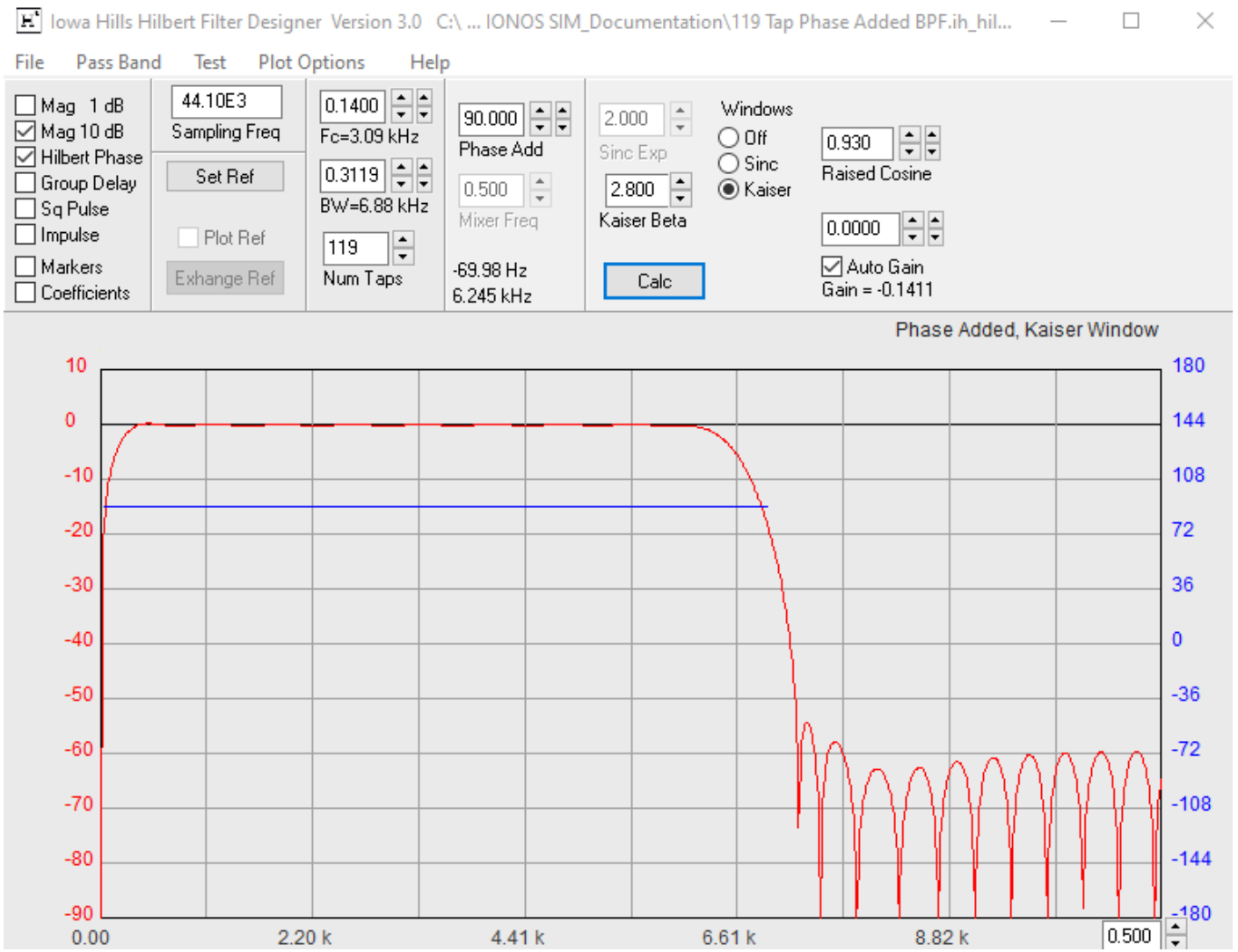
TFilter is being used by many tech compa

Hilbert FIR Filter: (used to Generate Q paths for multipath processing)

330-6500 Hz .5 dB ripple (used for both 3 and 6 KHz BW modes)

7600-22000 Hz –60 dB

119 taps, 1.337868 mS delay, (Iowa Hills Hilbert Filter Designer V 3.0)



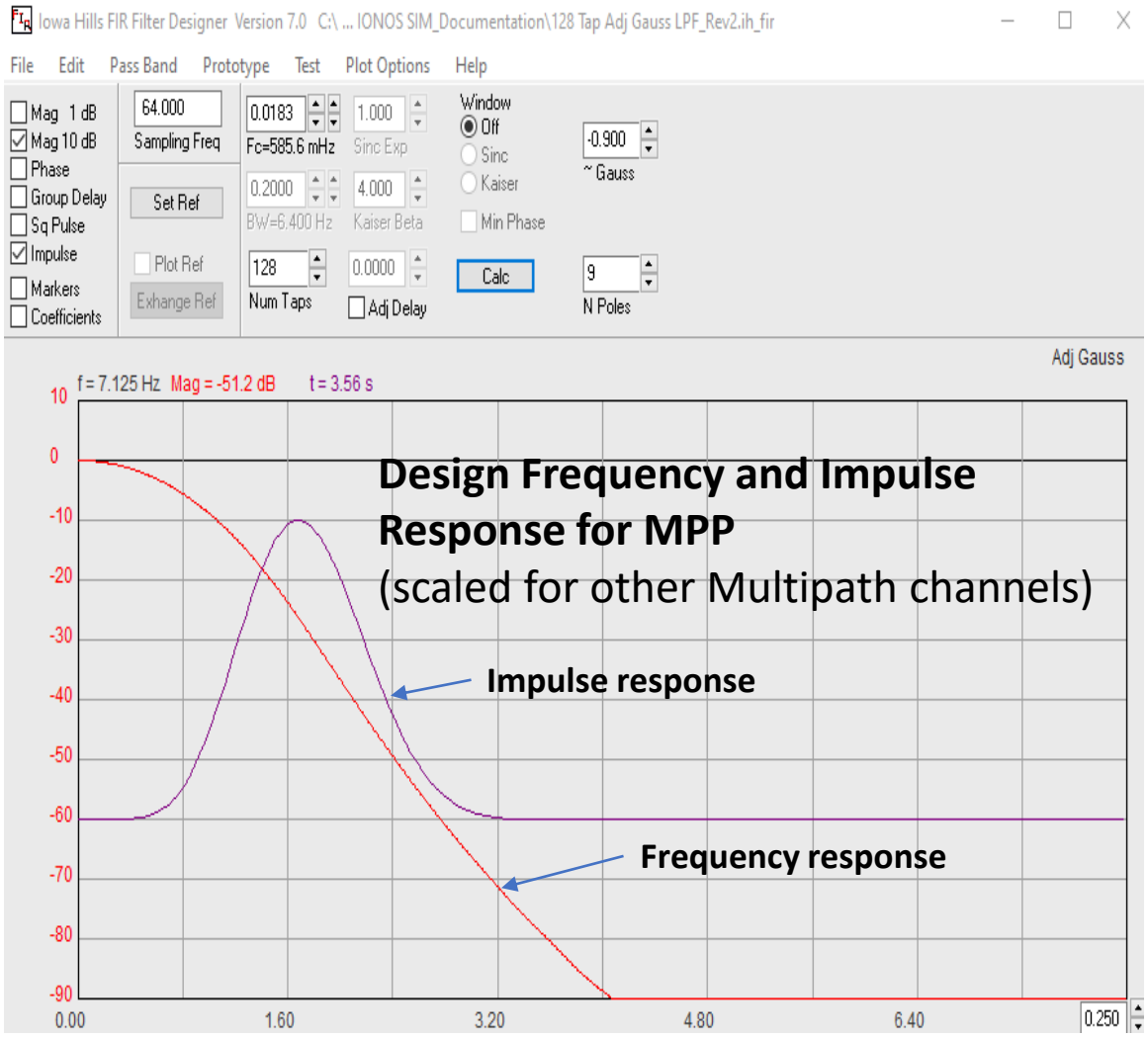
~Gaussian 9 Pole LP FIR Filter:

(used to narrow band filter Gaussian Noise for multipath processing)

Sample rate: 64 x Doppler Spread (2x CCIR recommended minimum)

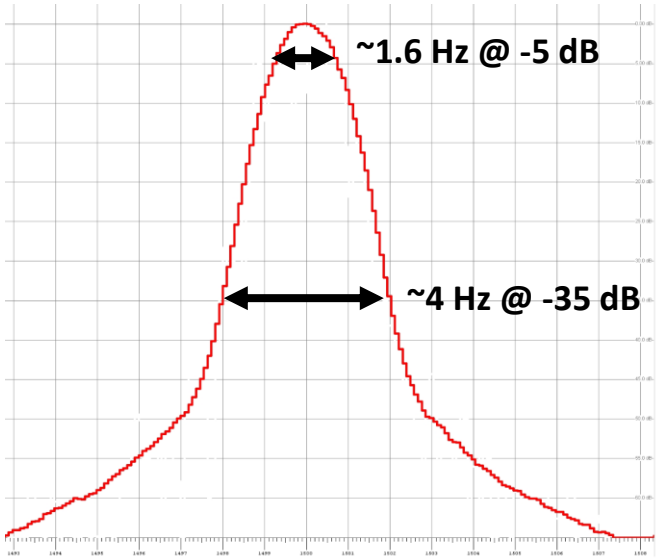
Follows CCIR guidelines for Bandwidth and roll off.

Iowa Hills FIR Filter Designer Version 7.0



High resolution Spectrum Analyzer measured Response for MPP

(scaled for other Multipaths)



Manual User Encoder Interface

Left Encoder		Right Encoder
MODE		**PARAMETER / Range /Power On Default***
WGN		S:N **/**-40 to +40 ,1 dB steps**/ +40***
MPG	Common	S:N **/**-40 to +40 ,1 dB steps**/ +40***
MPM		S:N **/**-40 to +40 ,1 dB steps**/ +40***
MPP		S:N **/**-40 to +40 ,1 dB steps**/ +40***
MPD		S:N **/**-40 to +40 ,1 dB steps**/ +40***
MULTIPATHS		# of Multipaths used**/** 2, or 4**/ 2**
FADE DEPTH (dB)		Depth of Fade dB**/** 0 to 40 dB**/ 0**
FADE FREQ (Hz)	Less used	Fade Frequency**/**0,.1,.2,.5,1,2,5,10,20**/0** (Hz)
OFFSET		Freq Offset**/**-200 to +200 Hz, 10 Hz steps**/0** (Hz)
FM DEVIATION(p-p, Hz)		FM Deviation**/** 0,1,2,5,10,20,50,100,200**/0** (Hz)
FM RATE (Hz)		FM Rate**/** 0,.1,.2,.5,1,2,5,10,20**/0** (Hz)
CH1 IN (Gain)		Ch1 Input Gain/0,1,2,5,10,20,50,100,200**/10**
CH2 IN (Gain)		Ch2 Input Gain/0,1,2,5,10,20,50,100,200**/10**
CH1 OUT (Gain)		Ch1 Output Gain**/** 0,.01,.02,.05,.1,.2,.5,1,2**/1**
CH2 OUT (Gain)		Ch2 Output Gain**/** 0,.01,.02,.05,.1,.2,.5,1,2**/1**
BANDWIDTH		Audio bandwidth**/**3 KHz or 6 KHz**/3**
SERIAL		Serial baud rate 4800-115200 baud**/9600**
TEST3K Sine	Built in Test	Test/Cal Measure Ch1,2, In p-p, Out p-p 3KHz BW
TEST6K Sine		Test/Cal Measure Ch1,2, In p-p, Out p-p 6KHz BW

* Except for Path S:N, power on default may be saved to EEPROM with push of right encoder

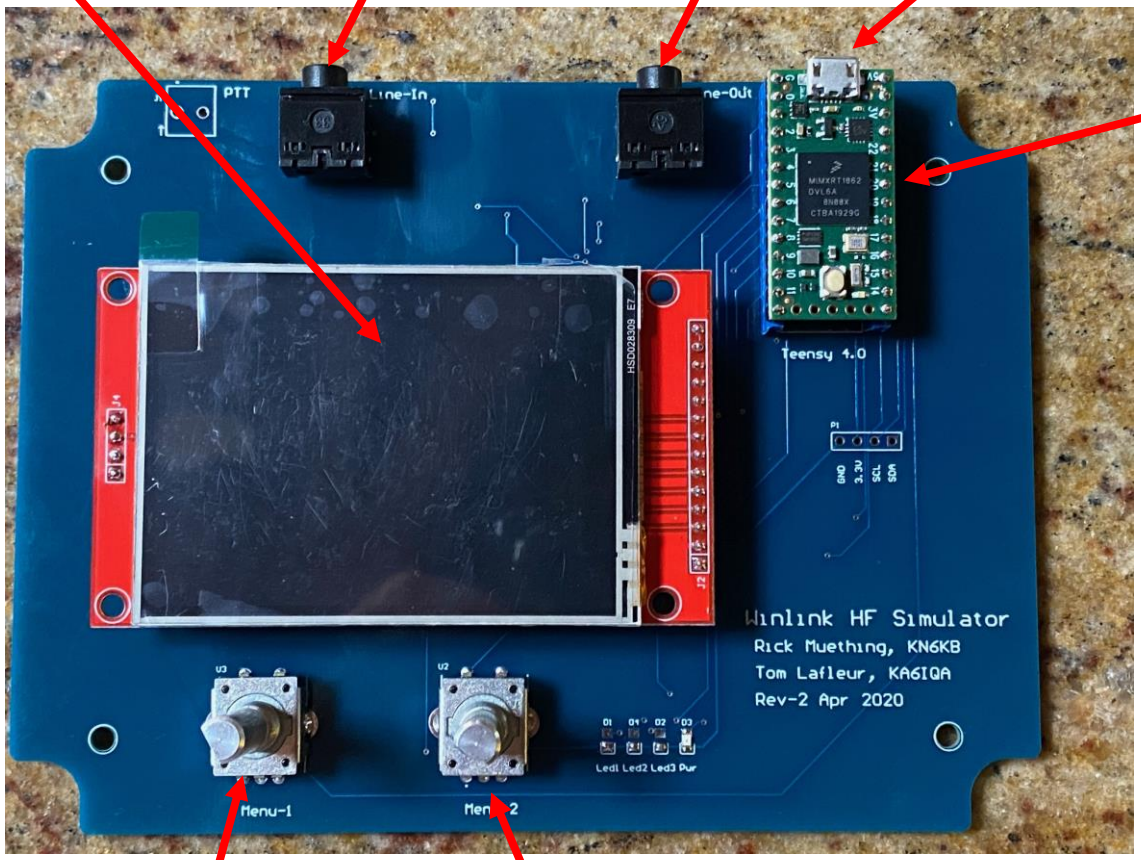
Photo of Rev 2 prototype PCB

Color text/graphics
TFT Display 320 x 240 pixels

CH1,2 Audio In

CH1,2 Audio Out

Micro USB, (Serial, +5v Power)



Teensy 4.0

Sound Card chip and
Additional components
Mounted on back side
Of PCB.
(Teensy Audio Shield
not required)

Rotary Encoders
(mode / parameter)

Layout , assembly and photo by Tom Lafleur, KA6IQA

Photo of First prototype production Run

Size: 6.1” x 4.7” x 1.4” (155 mm x 120 mm x 36 mm) (excluding knobs)

Simulator USB Serial User Interface

USB Serial Commands and Responses for optional automated testing

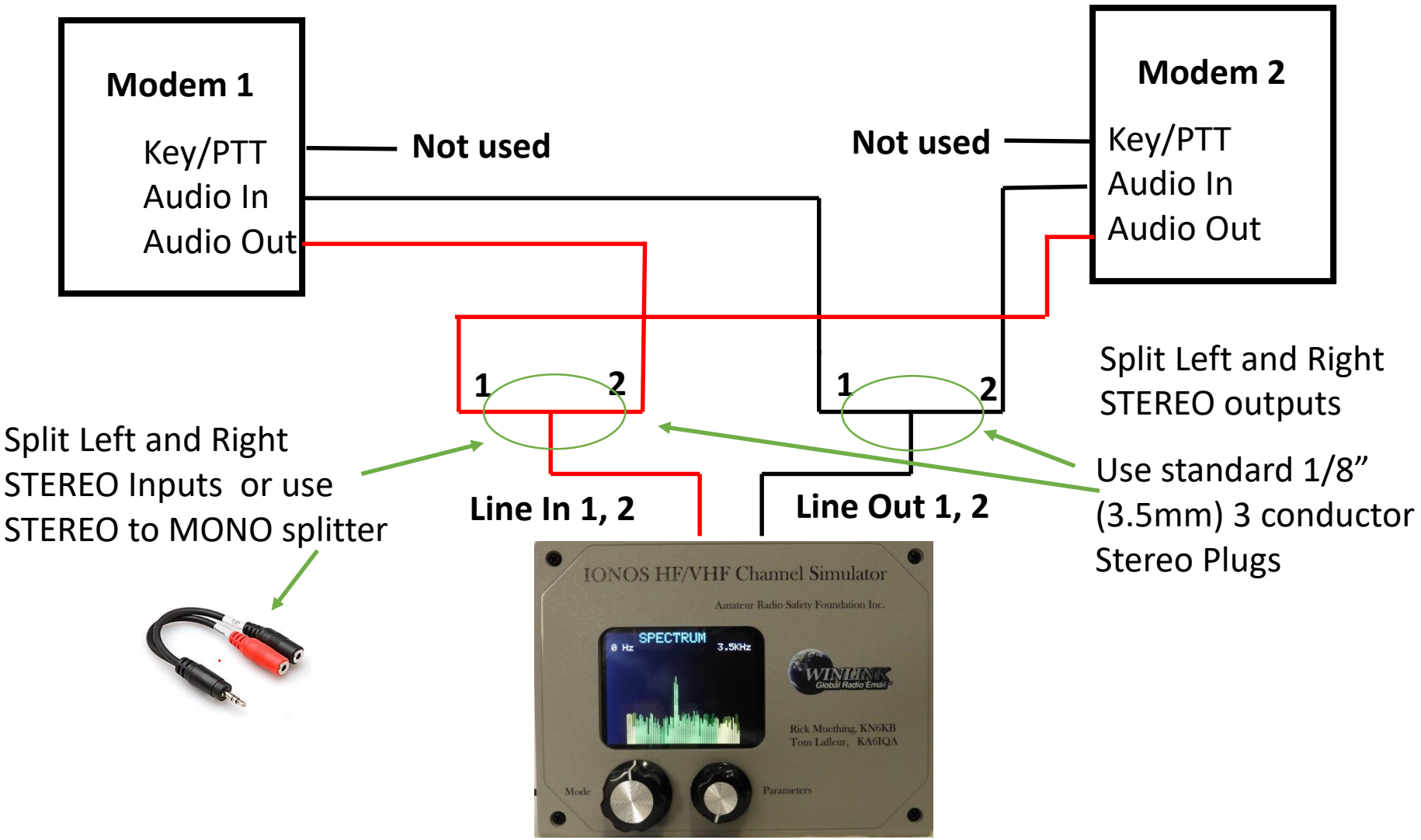
(Mimic manual commands from Mode and Parameter Encoders)

Command: value/range	Acknowledge Response/ Interpretation
WGN:20 (-40 +40dB)	OK(Cr) or ?(Cr) / WGN +20dB S:N [8]
MPG:20	OK(Cr) or ?(Cr) / MPG +20dB S:N [8]
MPM:-10	OK(Cr) or ?(Cr) / MPM -10dB S:N [8]
MPP:+20	OK(Cr) or ?(Cr) / MPP +20dB S:N [8]
MPD:20	OK(Cr) or ?(Cr) / MPD +20dB S:N [8]
MULTIPATH: 2 or 4	OK(Cr) or ?(Cr) / # of multipaths used
FADE DEPTH: 0-40	OK(Cr) or ?(Cr) / FADE DEPTH:0-40dB
FADE FREQ: 0-20 [6]	OK(Cr) or ?(Cr) / FADE FREQ:(log)[5] Hz
OFFSET: -200 - +200	OK(Cr) or ?(Cr) / OFFSET: +/-200 Hz
FM DEVIATION:0-200 [5]	OK(Cr) or ?(Cr) / FM DEVIATION:(log)[5] Hz
FM RATE: 0-20 [6]	OK(Cr) or ?(Cr) / FM RATE:(log)[6] Hz
CH1 IN:0-200 [5]	OK(Cr) or ?(Cr) / CH1 IN gain,(log)[5]
CH2 IN:0-200 [5]	OK(Cr) or ?(Cr) / CH2 IN gain,(log)[5]
CH1 OUT:0-2 [7]	OK(Cr) or ?(Cr) / CH1 OUT gain,(log)[7]
CH2 OUT:0-2 [7]	OK(Cr) or ?(Cr) / CH2 OUT gain,(log)[7]
BANDWIDTH:3000	OK(Cr) or ?(Cr) / BANDWIDTH = 3KHz

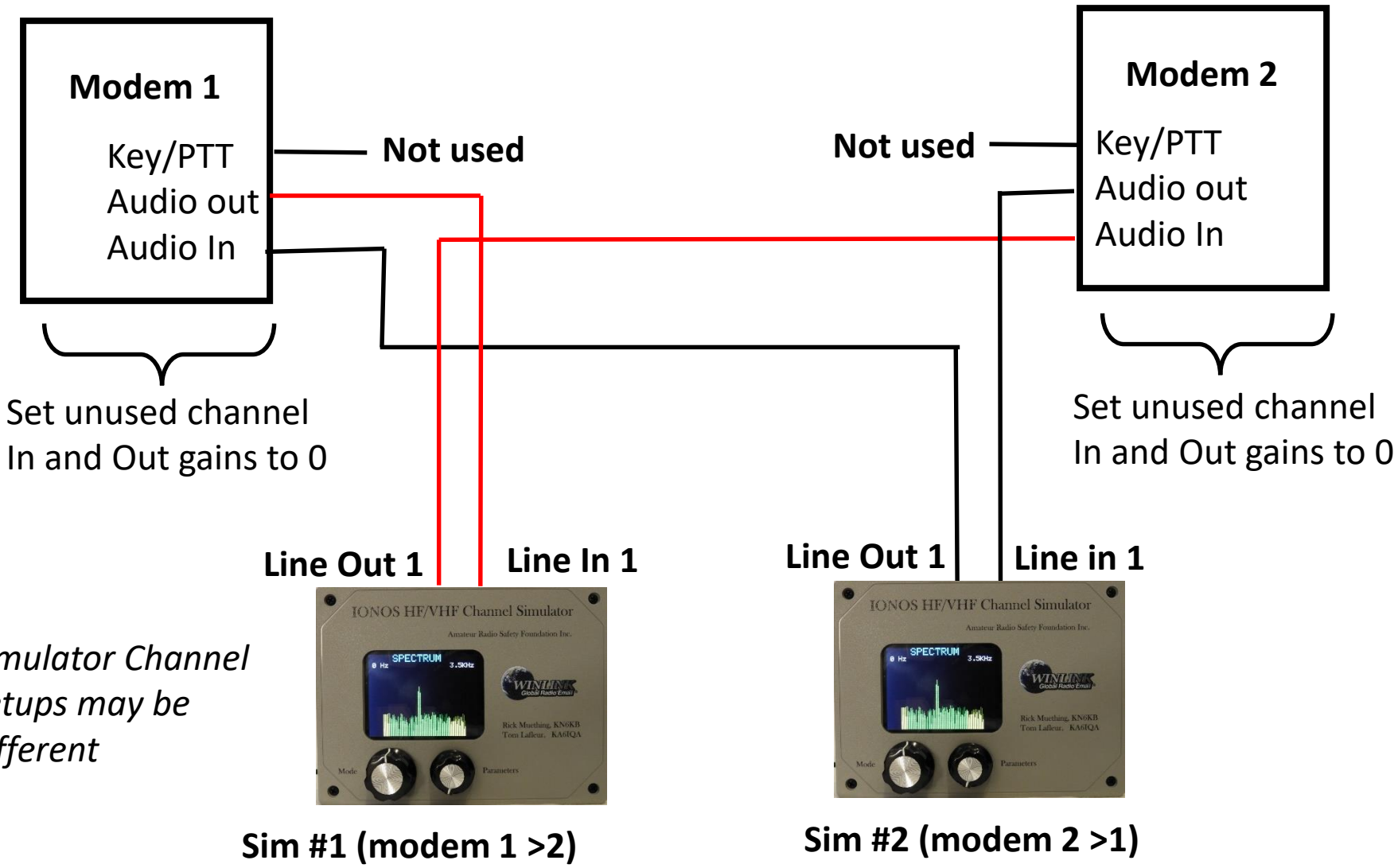
Note: 1. All commands case insensitive. "+" signs ignored. All commands and replies terminate with (Cr).

2. "OK" reply indicates command was interpreted OK and executed.
3. "?" reply indicates command was not understood, corrupted or out of range.
4. Commands must be sequenced by sender using Acknowledge Response
5. Log scale values: 0,1,2,5,10,20,50,100,200.
6 Log scale values: 0,.1, .2, .5, 1, 2, 5, 10, 20.
7. Log scale values: 0, .01, .02, .05, .1, .2, .5, 1, 2.
8. Mode and S:N will be updated on TFT if displaying WGN thru MPD

Connecting the simulator: 1 Simulator Half Duplex, Channels will be symmetric



Connecting the simulator: 2 Simulators Full Duplex, non symmetric channels:

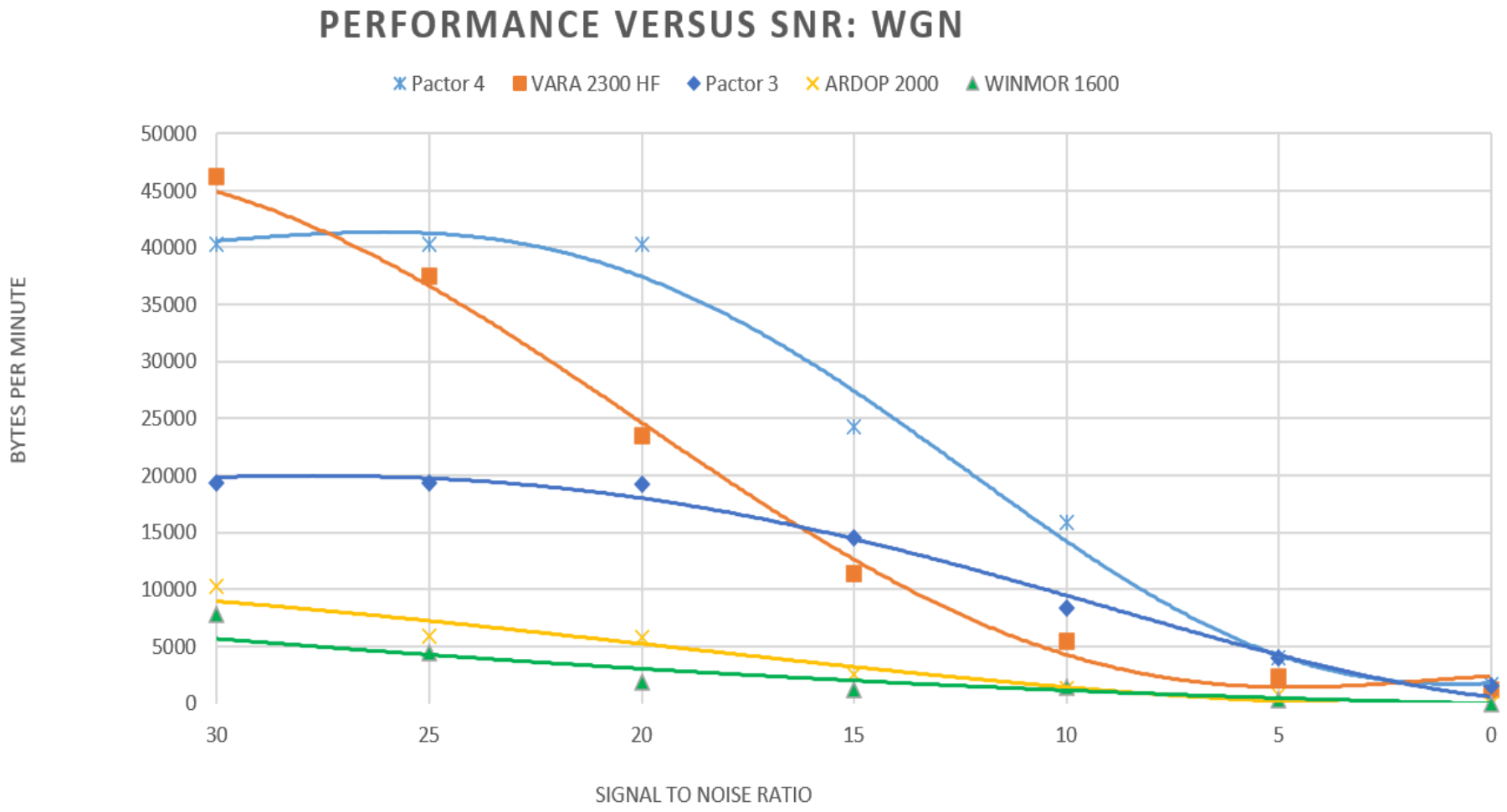


Simulator Channel Setups may be different

Sim #1 (modem 1 >2)

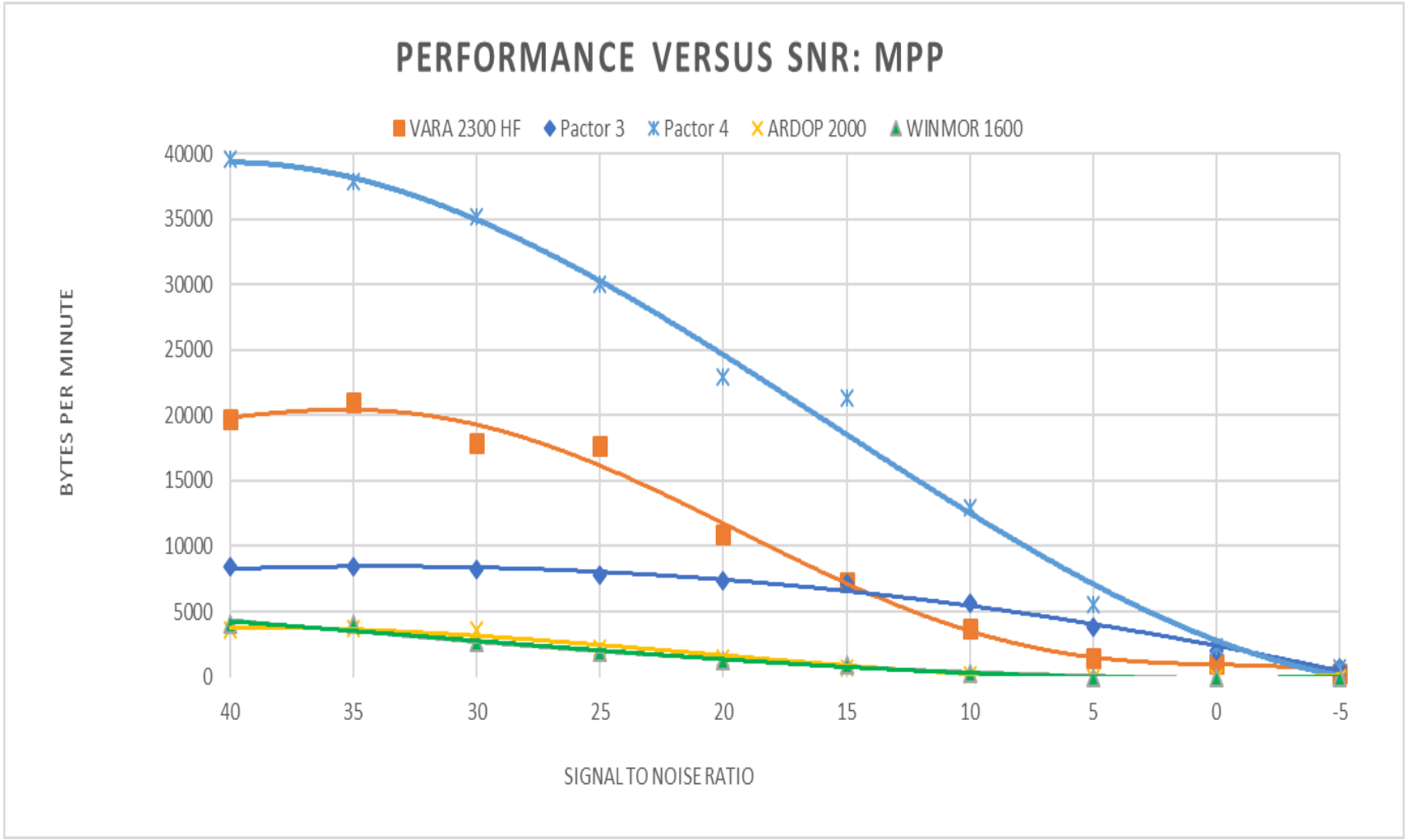
Sim #2 (modem 2 >1)

Example HF Use: 5 HF sound-card protocols, MPG (2 paths) 0 to +30 dB S:N



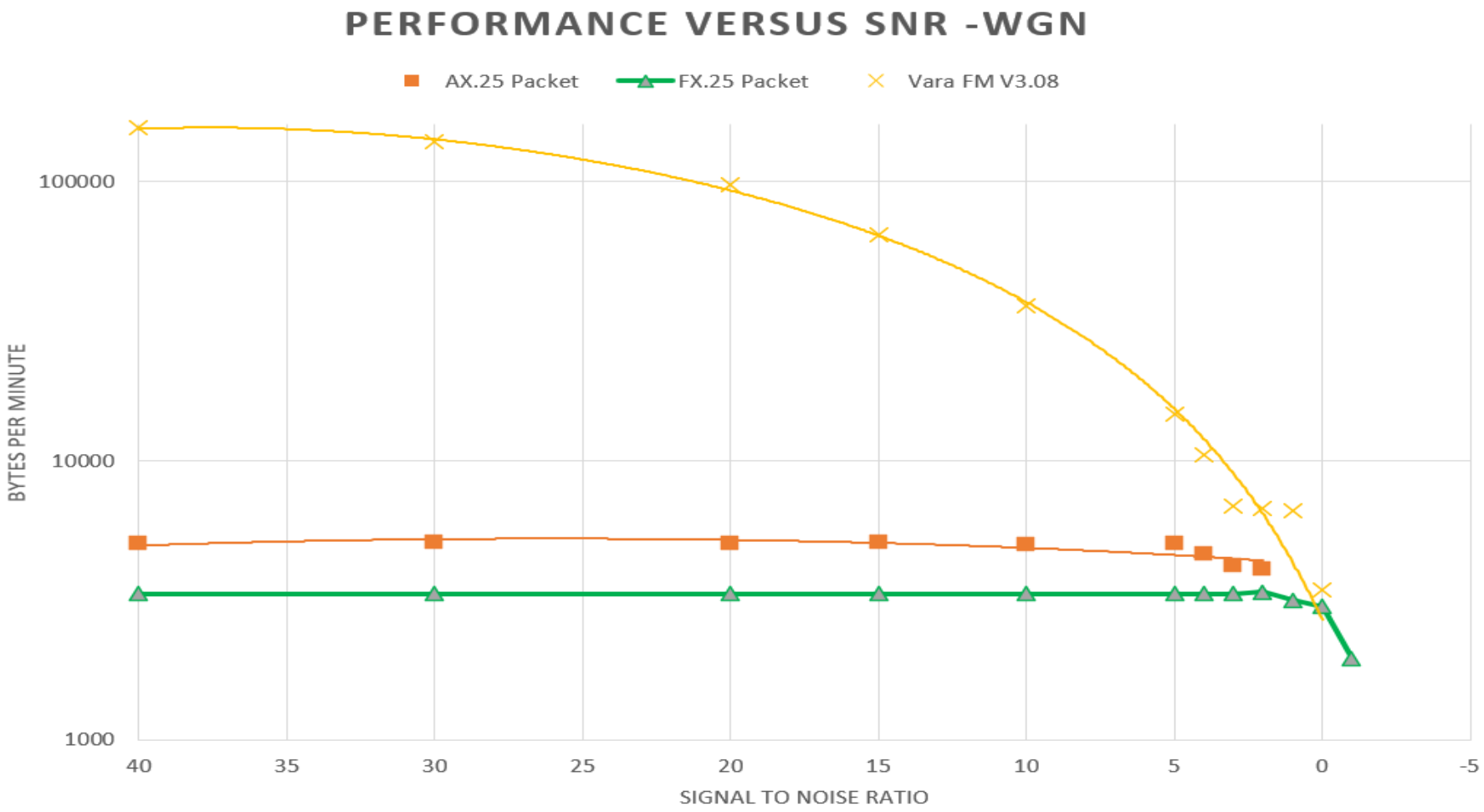
Tests performed by Tom Whiteside N5TW

Example HF Use: 5 HF sound-card protocols, MPP (2 paths) -5 to +40 dB S:N



Tests performed by Tom Whiteside N5TW

Example VHF FM Use: 4 VHF sound-card protocols, WGN -3 to +40 dB S:N

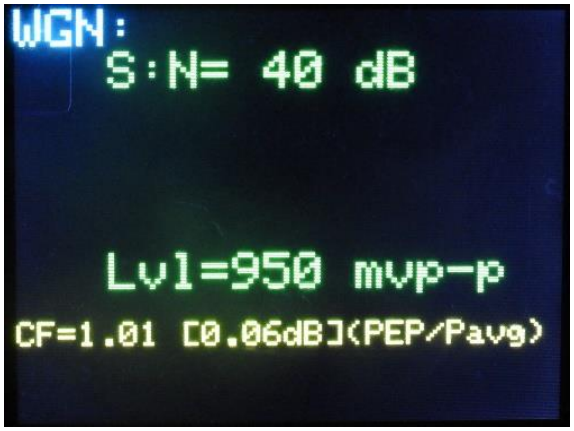


Tests performed by Tom Whiteside N5TW

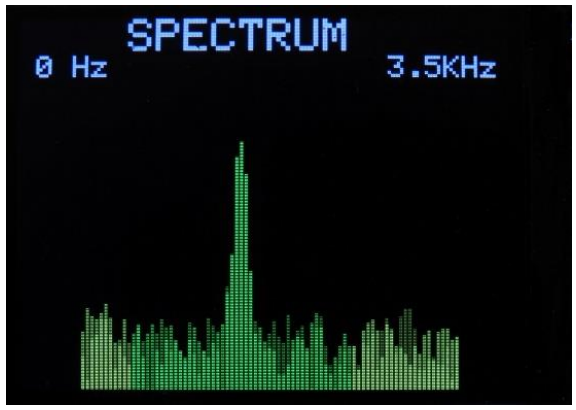
Example VHF FM Use: VARA FM (3.06)
WGN 30 dB S:N with deep flat fading
(.1, 1, 3 Hz fade rates)

Tests performed by Tom Whiteside N5TW

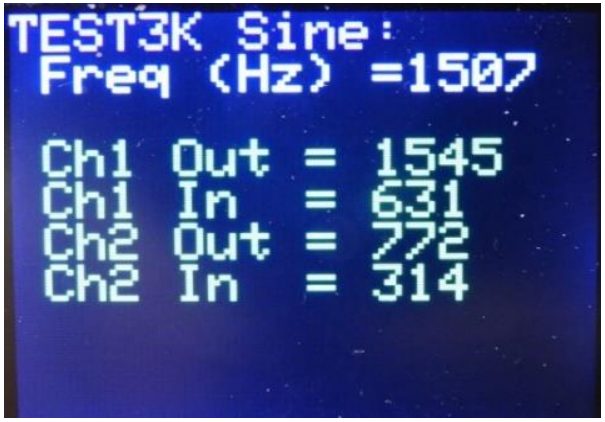
Example TFT Screen Shots



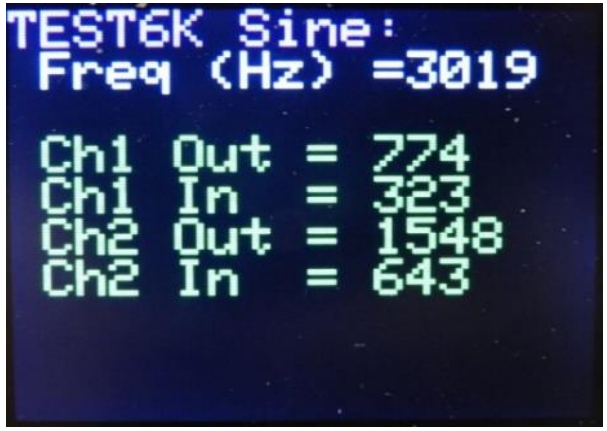
Mode/Parameter Setup example
Level and Crest Factor displays
(Similar for all modes)



Spectrum Display 3.5KHz
1500 Hz tone @ 19dB S:N



Built in Self Test And
Calibration Verification (3KHz BW)



Built in Self Test And
Calibration Verification (6KHz BW)

Status 11/18/2020 (Rev 2.03)

- All functions of simulator coded and tested using Rev 2 prototype PCB. Teensy Audio shield not needed.
- Approximately 2400 lines of code using 7% program and 38% RAM memory.
- 25 Rev 2 Beta prototypes built and tested
- Beta testing and characterization tests completed (Firmware rev .9.81)
- Color graphics display (240x320 pixels) used for Modes, Parameters, Spectrum, and Self test plots.
- USB Serial commands for Simulator automation completed
- Simulator Testing on Packet, VARA FM VHF, VARA HF, Pactor 3, Pactor 4, ARDOP, WINMOR completed by Tom Whiteside, N5TW
- Connection and operational documentation complete.
- Mechanical drawings (case drill/route guides) complete
- Auto Test and Calibration: 3KHz, 6 KHz complete.
- Silk screen and mechanical drawings complete
- Schematic complete
- Documentation and manual with specification and references complete