

FM constant impedance combiners. Theory and tuning

FM combiners are an integral and crucial part of high power FM broadcasting. This document will cover combiner signal flow, tuning procedures, and intermod calculations for balanced FM combiner systems. Also included is a list of tests to perform during acceptance testing or following combiner retuning.

Many new combiners come with a manual detailing theory, tuning, and response curves. Read it to become more familiar with the particular model in use. RTFM!

Robert Surette at [Shively Labs](#)¹ has written a paper that explains the operation of FM combiners and includes signal flow diagrams. It is a good starting point to gain a better understanding of the history, components, and operation of combining systems. A pdf version is available.

Jampro has an article that simplifies RF combiner theory.

http://www.jampro.com/uploads/tech_docs_pdf/combinertheory.pdf

Objectives

- Install FM combining systems to minimize signal distortion and attenuation. Ensure optimum performance for all stations.
- Perform acceptance testing on new systems as supplied prior to installation and operation.
- Recognize symptoms of problems. Perform basic troubleshooting.
- Understand tuning techniques.

Purpose of combining systems

Due to (or to prevent) tower congestion, a broadband antenna and single feedline can be used to serve multiple FM stations. This may result in revenue generation by supplying antenna capacity to other broadcasters.

Advantages of balanced combiners

Bandpass filters provide good intermod reduction
Emergency (wideband) port available
Easily expanded

Disadvantages

Can be physically large, especially for high power and narrow spacing. Footprint can sometimes be more than four times that of the transmitter!

Adapter kit

High quality adapters from Type-N to EIA flanged and unflanged line sections will allow measurements on coaxial lines and patch panels. Bent, dented, or home made adapters have questionable characteristics and should be avoided. Final results will only be as good as the poorest adapter.

Type-N Adapters and Connector care

From Keysight 85032 manual

- Visually inspect the connectors. If necessary, clean the connectors.
- Carefully align the connectors. The male connector center pin must slip concentrically into the contact finger of the female connector.
- Push the connectors straight together. Do *not* twist or screw them together. As the center conductors mate, there is usually a slight resistance.
- **CAUTION** Do *not* turn the device body. Only turn the connector nut. Damage to the center conductor can occur if the device body is twisted.
- Make sure the connectors are properly supported. Relieve any side pressure on the connection from long or heavy devices or cables.

Test cables

In order to make trustworthy and repeatable measurements high quality cables are needed. They should be properly labeled and kept in a protective case when not being used. I have seen miscellaneous cables that have center pin protruding too far or not properly centered. Faulty center pins can cause damage by spreading open the center pin socket of the female Type-N connectors. Always check the center pin prior to use. Other cables have had boxes stacked on top or have been walked on. This can deform the shape of the cable resulting in impedance mismatches along its length.

Vector network analyzers must be calibrated each time they are used. Their calibration is only as good as the reference calibration kit. Damage the connectors and test results will suffer.

Never connect a network or spectrum analyzer directly to an antenna without first knowing receive signal levels! It is a quick and sure way to cause serious damage to the front end. A high power 20dB attenuator or RF limiter should be included as part of the adapter kit for added protection. Measure levels with the attenuator installed prior to other testing. A wattmeter can sometimes display several watts returning from an antenna due to energy coupled from nearby antennas or other towers.

Testing

Manufacturer supplied test data is often incomplete and inconsistent even between modules. There is no defined series of tests or response curves to be taken upon receipt of a new combiner during acceptance testing or following frequency change.

Prior to accepting new combiners or following retuning or relocation a full test should be performed to ensure the combiner is properly tuned and suitable for use. A thorough set of response curves could be useful later if addition of another station is being planned. It also provides a good reference point for troubleshooting or if the combiner must be tuned in the future. Along with the tests listed later, replicate the test data supplied by the manufacturer for confirmation.

Signal flow

- RF appears at the tuned input port. It is split by the input 3dB coupler and flows through the pair of bandpass filters. The output 3dB coupler recombines the signal at the output port.
- Other signals appear at the wideband port. Signals are split by the output 3dB coupler and appear at the bandpass filters. All signals are rejected and returned to the 3dB coupler where they recombine at the output port.
- The output port of one module can connect to the wideband port of the next. A long chain can be created, limited only by floor space and the power rating of antenna system components.
- While tuning, the input signal will appear at the dump load, wideband input, output port, and reflected back to the input. By monitoring the levels at all ports, with and without terminations present, we can ensure optimal tuning of the modules. It is not enough to merely tune for minimum insertion loss and acceptable input match.

Signal distortion

Wattmeters indicating RF power present and hearing sound from speakers do not guarantee optimum signal. FM combining modules will introduce signal distortion that may reduce stereo separation and limit overall broadcast range.

Asynchronous AM noise

Typically caused by power supply ripple, fan vibrations, etc. Unrelated to combiner system.

Spurs will be evident either side of carrier. Maximum allowed level is defined as 30dB below 100% AM modulation. Easily measured with audio, RBDS, etc removed.

Synchronous AM noise

Often caused by bandwidth limiting or unequal frequency response. The FM carrier is modulated due to response curves of bandpass filters or improper antenna tuning. Signal flow through WB port of combiner can affect close spaced signals more than others. Spurs will appear either side of carrier dependent on modulating frequency. FM sidebands will also be present making it difficult to see or measure spurs. AM spurs create noise in the receiver demodulator circuitry.

No specified maximum allowed level. I suspect this is due to no simple way to measure.

AM noise will result in picket fencing type noise. It will be most noticeable in low signal areas. It effectively reduces coverage area due to inability of the receiver to decode the FM signal.

An easy check for presence of synchronous AM noise is to look at the wattmeter. With no audio presence the needle will be steady. Apply audio and the needle will begin to wiggle in sync with audio. It will likely remain steady even with audio present when connected to a dummy load.

Synchronous AM noise can be minimized during RF tuning by ensuring flat or equal response with adequate bandwidth across the FM channel.

Group Delay

Propagation velocity is not equal for all frequencies. Signal delay is greatest away from center. Signal flow through WB port of combiner can affect close spaced signals more than others, creating asymmetric curve which is more problematic. Phase shift will affect L-R signal and reduce stereo separation. It can also create noise similar to picket fencing where the signal rapidly comes and goes. Severe group delay can also affect mono signal. It can affect the FM signal more than AM noise. As part of overall station tuning compromises try to keep group delay minimized and as symmetrical as possible.

It can sometimes be corrected with external filters or via software within exciter.

A solid state wideband transmitter to wideband antenna with no external filtering should exhibit very little AM synchronous noise or group delay distortion. It may have a noticeably better sound quality and effective range compared to other nearby stations at much higher power connected to a combiner system.

3dB Quadrature hybrid couplers

- When a signal appears at one port it will appear at -3dB at two output ports with one signal lagging by 90° . The fourth port will experience isolation typically in excess of 30dB from the input.
- When two signals of equal amplitude and 90° phase shift appear at adjacent ports, they will combine and appear at the output port. The fourth port should receive very little energy, with typical isolation in excess of 30dB .
- Crossover vs adjacent / non-crossover couplers. Most 3dB couplers in use are crossover types. Kathrein combiners often use adjacent couplers. An ohmmeter or study of circuit configuration can be used to confirm each type.

Tuning

- Take measurements prior to tuning to confirm operation. This may assist with troubleshooting.
- If necessary, remove input and output 3dB couplers to gain access directly to filters.
- Confirm the 3dB coupler power division, insertion loss, bandwidth, 90° phase shift between ports.
- RF tuning is a compromise. Minimum insertion loss requires wide bandwidth and may lead to poor isolation. You may have to compromise one parameter to gain in another. The goal is to optimize all parameters to create overall acceptable performance.
- Adjust cavity tuning. Typically raising the tuning rods will increase resonant frequency. Monitor S_{11} (return loss) and S_{21} (insertion loss) while making adjustments. Slowly move each cavity towards the new frequency. Once all cavities are rough tuned they must be carefully peaked for return loss (26dB minimum), bandwidth, and minimum insertion loss. There will be compromises between all three.
- If the 3dB couplers can not be removed, tune the assembled combiner by monitoring S_{11} and S_{21} while connected to tuned input and antenna output ports. Remove the dump load termination to display true response of the cavities. Occasionally put the termination in place as a quick check.
- Bandwidth becomes narrower as number of poles increases. It is also affected by cavity coupling. There is a tradeoff between bandwidth and insertion loss. Tighter coupling will reduce insertion loss and provide wider bandwidth. Loose coupling will provide better isolation by reducing bandwidth, but will also increase insertion loss. Adjacent channel spacing and number of poles

- determine requirements. Tuning response too wide for the intended installation will not provide adequate isolation. Too narrow will result in increased insertion loss and heat generation.
- Typical combiner insertion loss is 0.2dB to 0.8dB depending on number and size of the cavities, channel separation, etc. A rough guide is to expect about 0.1dB per pole for a high power combiner and up to 0.3dB per pole for smaller cavities in low power systems.
 - Measure return loss, insertion loss, and phase shift (group delay) through the bandpass filter.
 - Coarse tune second bandpass filter by matching physical measurements from first. Fine tune return loss, insertion loss, and phase to be identical between both bandpass filters. Optimum overall performance will depend upon having both sides tuned properly and matched precisely.
 - Adapters and cables must be identical when comparing the second side of band pass filters. Any difference will create added phase shift.
 - Bandpass filters should provide at least 20dB rejection at adjacent channels. When added to 30dB isolation through the 3dB couplers a total isolation in excess of 50dB will be achieved. Assume transmitter turn around loss is 10dB and 20dB attenuation for the 3rd order spurious through the bandpass filters.
 - For equal power transmitters, the expected intermod level should be better than -80dB from the carrier.
 - The input and output coupling mechanisms are part of the overall combiner tuning. They must be adjusted for proper return loss as well as amplitude and phase response. They are critical to optimized tuning and should not be left out of a full alignment. For minor frequency changes it may be possible to retune without moving these mechanisms. If 26dB return loss cannot be achieved or if insertion loss and bandwidth are not acceptable the input and output coupling will have to be adjusted. Large frequency changes will usually require full alignment.
 - When properly tuned all measurements will be symmetrical around the tuned frequency. Return loss curve will show an individual null for each pole. A two pole filter should display two return loss notches, and one hump. Three poles will have three notches with two humps, etc.
 - Reinstall 3dB couplers and make quick checks to ensure response is reasonable. Even with perfectly tuned bandpass filters, the 3dB couplers may have slight phase and amplitude variations that will affect the assembled module performance.
 - **Fine tuning** will help compensate for slight variations in the 3dB couplers. I haven't seen this method described elsewhere but it has proven to work very well. Connect the analyzer to tuned input and dump load ports. Terminate the antenna port and remove the wideband port termination. Phase or amplitude inequality through the cavities or variation in 3dB coupler response will cause the input signal to appear at the wideband port. The signal will reflect from the open wideband port, split through the cavities and recombine at the dump load. Monitor isolation (S21) and tuned input return loss (S11) while very carefully adjusting the tuning stubs. S11 and S21 curves should look similar within the passband area of the cavities. Minimize S21 to optimize cavity phase and amplitude response. This will improve isolation between tuned input and wideband ports at the tuned frequency. Minimize S11 to ensure reflected signals from the cavities are in phase and sent to the dump load. Energy reflected from the cavities will add to the S21 response. Simultaneously minimize both to ensure the cavities and 3dB couplers are well matched. S11 and S21 should both be better than -26dB. When complete, tuned input to wideband port isolation should be close to maximum provided by the output 3dB coupler, typically better than 36dB. This minimizes RF energy travelling backwards through the combiner chain.
 - During testing, terminations are removed in order to confirm proper signal flow and bandpass filter tuning. With all ports terminated, tuned input return loss will typically be better than 26dB across the entire FM band. Signals away from the tuned frequency will be reflected by the bandpass filters and be absorbed in the dump load. Removing the dump load and measuring the return loss will show the shape of the bandpass filter return loss. Return loss at the tuned channel should change very little, but will become very poor elsewhere.

- Tuned input to dump load isolation is highly dependent upon bandpass filter return loss. Energy reflected from the cavities will appear in the dump load. Low isolation is an indication of poorly tuned cavities. Expect at least 26dB isolation between input port and dummy load.
- Output to wideband isolation at the tuned frequency is dependent upon phase and amplitude relationships between the two bandpass filters. Having both matched precisely will result in very high isolation, determined essentially by the output 3dB coupler alone. Any imbalance in amplitude or phase will reduce isolation. Transmitter power will appear at the wideband port where it could potentially cause intermod problems with other transmitters in the combiner chain. This is part of the fine tuning procedure described above.
- With proper bandpass filter phase and amplitude response, all tuned input energy will appear at the output port. Removal of the wideband port termination should have very little effect upon tuned input return loss. Removing the output termination should cause the tuned frequency return loss to become close to 0dB (2x insertion loss).
- The wideband port should never have the tuned frequency signal applied. All energy will be sent directly to the dump load, likely causing its immediate failure.
- Energy far from the tuned frequency entering the wideband port will be split in the output 3dB coupler and sent to the bandpass filters where it is reflected. RF will recombine and appear at the output port. Adjacent frequencies may experience a phase shift creating an unequal group delay across the channel. This will add to the group delay of the particular channel combiner module.
- Some adjacent channel energy will find its way through the bandpass filters. The majority of the energy will be absorbed in the dump load. This causes higher insertion loss to close spaced channels. Dependent upon amplitude and phase through the cavities some of this energy will appear at the tuned input. The dump load is critical to proper combiner operation. Isolation from wideband port, particularly from adjacent channels to tuned input will greatly decrease if the dump load has failed. Always confirm the dump load as part of the combiner tuning and testing.
- Dump load power can be calculated based upon its isolation to the tuned and wideband inputs. Tuned input to dump load isolation should be about -26dB. With a 20kW transmitter this would be 50W maximum. Adjacent channel rejection from the wide band port should be 20dB minimum. With a pair of 20kW transmitters this would supply 200W per transmitter. Maximum worst-case dump load dissipation with three adjacent channel 20kW transmitters should be 450W. Under these conditions there should be no reason to use a dump load rated in excess of 600W. A wattmeter should be installed to monitor dump load power. Any change in the normal reading could indicate a problem. Confirm proper dump load operation by checking reflected power. It should be zero.
- The wideband port at the end of the combiner chain should have a dump load and wattmeter to allow monitoring of combiner performance. The power level should typically be very low. With 30dB isolation at the output coupler, each 20kW transmitter should supply a maximum of 20W to the dump load. Measure the power under normal conditions and check occasionally. If a cavity or 3dB coupler throughout the chain becomes detuned, the wideband port dump load power will increase. Occasionally check dump load reflected power to confirm proper operation.
- Antenna reflected signal may play a significant role in reducing isolation to adjacent channels. Assume 20dB return loss from the antenna. Cavities add about 20dB isolation to the adjacent channels. The signal will combine at the tuned input port with no added isolation from the 3dB coupler directivity. Isolation now is only 40dB, less than 50dB minimum recommended. Antenna return loss should be considered in turnaround loss and intermod calculations. When testing, temporarily replace the output termination with a 10dB pad and observe change.
- A broadcast antenna also works very well in the receive mode. Nearby towers can deliver high-level signals into the combiner chain. The levels should be known and used for determining required adjacent channel isolation and for potential intermod calculations.

Power dissipation

It is simple to calculate power loss in a combiner module based upon insertion loss. The standard equation $\text{dB} = 10 \log (P1/P2)$ can be rearranged for P2

$$P2 = P1 / 10^{(\text{dB}/10)} \quad P1 = \text{transmitter power, } P2 = \text{combiner output power}$$

For insertion loss 0.2dB, 20kW transmitter power

$$P2 = 20\text{kW} / 10^{(0.02)} = 19.1\text{kW}$$

$$\text{Dissipation} = 20\text{kW} - 19.1\text{kW} = 900\text{W}$$

For insertion loss 0.35dB, 10kW transmitter power

$$P2 = 10\text{kW} / 10^{(.035)} = 9226\text{W}$$

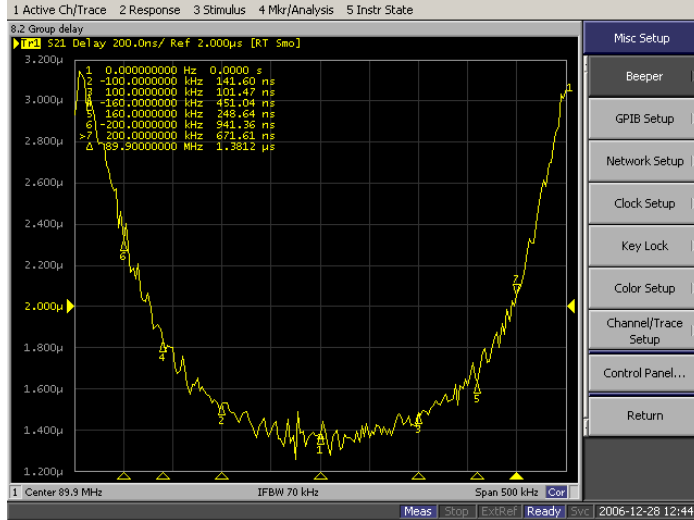
$$\text{Dissipation} = 10\text{kW} - 9226\text{W} = 774\text{W}$$

This power is converted to heat in the combiner room. It is wasted RF energy that could otherwise be sent through the antenna. Combiner loss is factored into ERP calculations. Optimized tuning may improve efficiency of the overall system and ultimately reduce transmitter operating costs.

When multiple combiner modules are installed a substantial amount of heat can be created. The numbers are useful for calculating heat load for cooling systems. It costs money to create the RF energy and more to get rid of the wasted heat energy.

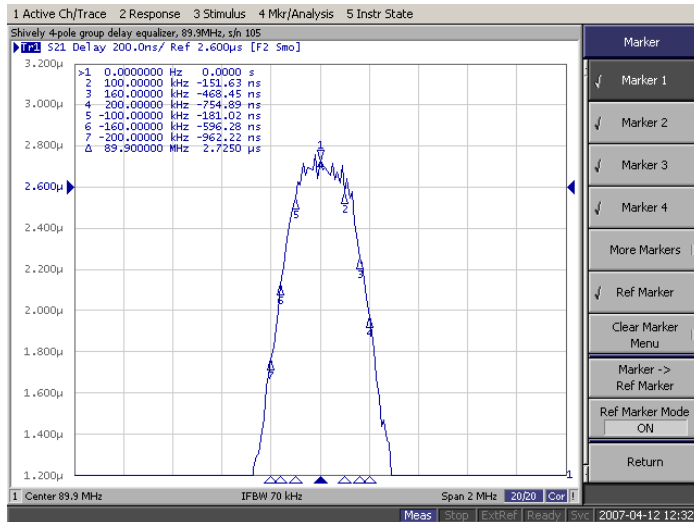
Group delay

Group delay will reduce stereo separation. It should be less than 350ns at $\pm 200\text{kHz}$ referenced to the carrier frequency to ensure 30dB stereo separation. Performance can be improved by pre correction in the exciter or by a passive group delay correction module inserted between the exciter and IPA. A group delay anti curve is created to cancel the combiner delay curve. External correction will increase the overall delay, but equalize it across the FM channel.



Measured group delay of 4-pole combiner with cross coupling.

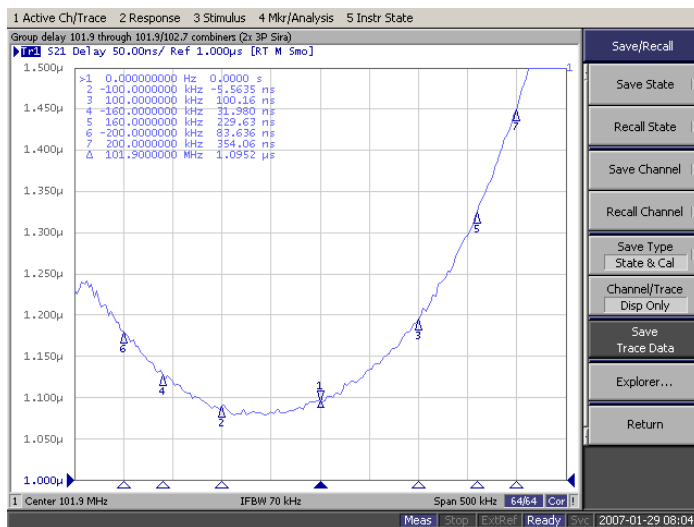
Group delay at $\pm 200\text{kHz}$ is 941ns and 671ns. Correction is needed to maintain acceptable stereo separation.



Measured group delay of external group delay corrector. The correction module usually installs between the exciter and PA, but higher power models can also be installed at the input to the combiner module.

This is the response curve for the blue Shively corrector pictured on the next page. This anti-curve is slightly excessive and overcompensates for the combiner. Overall corrected delay is within 220ns.

A similar anti-curve can be programmed into certain exciters.



Adjacent channels may experience added group delay when passing through the wideband port due signals reflecting from the tuned cavities. It will typically appear as a steep slope. When added to the group delay of their combiner module there will be an unequal group delay characteristics across the channel, typically J-shaped. Asymmetrical group delay will further reduce stereo separation. The same pre correction techniques can be used.

Combiner chain sequencing should be done to minimize one channel having to pass through more than one adjacent channel wideband port. This will minimize attenuation and cumulative group delay. Stereo stations should be placed closer to the antenna than mono stations due to their need for lower group delay. Any sequence will work, but proper planning will provide optimum performance for all stations.



Shively and other manufacturers sell group delay correctors or equalizers. It consists of a 3dB coupler and cavity filters. The input signal is split, gets rejected by the cavities, and recombines at the output port. The corrector is similar to the wideband port of a balanced combiner.

On the right is a corrector made from Sinclair bandpass filters and an FM 3dB coupler. Only one port of each bandpass filter is used. The other ports have the coupling loops removed. Tune the cavities to achieve the desired S21 group delay anti-curve while simultaneously monitoring for acceptable S11 return loss and S21 insertion loss. Insertion loss is usually less than 1dB, but can sometimes be in excess of 3dB. The exciter must be able to compensate with extra drive power.

Tune the cavities slightly higher or lower than the frequency being corrected. The group delay curve can be adjusted to have a positive or negative slope or an inverted U-shape as needed. The coupling loops greatly affect the response.

If the transmitter is used as part of a N+1 backup system the group delay equalizer can often be left inline. It will have very low insertion loss and flat group delay response at frequencies several MHz away from where it is tuned. Exciter power level may have to be adjusted depending upon insertion loss. Confirm tuning prior to operation.

Time domain filter tuning

Some network analyzers provide time domain tuning. This is different than time domain reflectometry for finding faults. It provides a very precise method for tuning individual components within a filter. Read Agilent application notes² 1287-8 and 1287-10.

Typical minimum channel spacing for high power modules

2-pole 1.2MHz, 3-pole 1.0MHz, 4-pole 800kHz, 4-pole with cross coupling 600kHz

Use these numbers as a guideline only. If the combiner is operated at less than its rated power and higher insertion loss figures can be accepted, the tuning can be made sharper to accommodate lower channel spacing. Spec sheets for the Kathrein 2-pole combiner pictured later state it is capable of operation at 1MHz separation. However, an email from Kathrein suggests decreasing tuned input power to about 15kW. Separation suffers, adjacent channel insertion loss increases, and dump load power is very high. It works, but is less than ideal.

Reverse signal flow

A balanced combiner is symmetrical in signal flow. It is possible to exchange ports if required. Sometimes due to plumbing or other physical restrictions it may be advantageous to use the dump load port as the tuned input. This will also cause the wideband and output ports to be exchanged. Similarly the output port can be used as a tuned input, making the original wideband port the new dump load port. The original tuned input becomes the output and the dump load port becomes the wideband. Check response of the combiner in its new configuration. Power ratings will remain the same provided the 3dB couplers and connectors are equal sizes and the cavity input / output couplers are the same.

By placing a standby transmitter at the combiner dump load port its RF will appear at the wideband port and travel backwards along the combiner chain to the last module's wideband input, which is typically terminated with another dump load. Replace this load with a standby antenna and there is a switchless method of standby transmitter operation. A circulator / isolator should be used at the standby transmitter to provide better isolation and protection. This could also be used for an IBOC transmitter. Maximum power is limited by the 3dB hybrid at the low power end of the chain. Check the response curves to confirm proper signal flow and acceptable performance in this mode. Monitor the output signal for spurious signals.

Preventive maintenance

Once operating at full power occasionally check the combiner for areas that are unusually hot. No part of the combiner should experience more than a 10C rise in temperature from ambient. The only exception is the dump load if high adjacent power is being absorbed. If fans are needed to cool any part of the combiner module something is wrong. Tuning may be incorrect or the components could be under rated.

The dump load power should remain constant after the temperature has stabilized. The addition of a new service could create extra dump load power. If there is an inline wattmeter occasionally check the reflected power to ensure the dump load is absorbing all energy.

The wideband port of the chain should also have a dummy load and wattmeter. Any change in its reading could be an early indication of a tuning change.

Intermodulation

What is 'IMD'?

Intermodulation distortion (IMD) is the result of two or more signals interacting in a non linear device to produce additional unwanted signals. These additional signals (intermodulation products) occur mainly in devices such as amplifiers and mixers, but to a lesser extent they also occur in passive devices such as those found in many transmission systems. For example, RF connectors on transmission feeds may become corroded over time resulting in them behaving as non linear diode junctions. The same can apply at the junction of different metals or where magnetic materials are used.

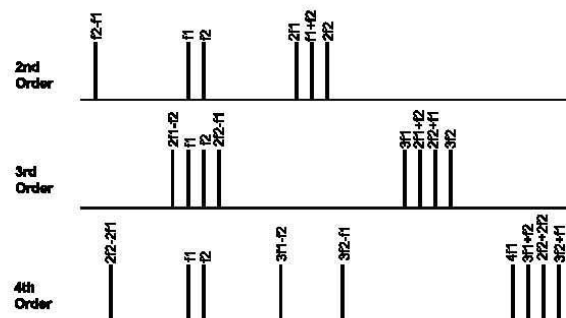
Two interacting signals will produce intermodulation products at the sum and difference of integer multiples of the original frequencies.

For two input signals, the output frequency components can be expressed as:

$$mf_1 \pm nf_2$$

where, m and n are integers ≥ 1

The order of the intermodulation product is the sum of the integers $m+n$. The 'two tone' third order components, $2*f_1-f_2$ and $2*f_2-f_1$, are particularly important because unlike 2nd order distortion, i.e. harmonic distortion at $2*f_1$ or $2*f_2$, they can occur at frequencies close to the desired/interfering signals and so cannot be easily filtered. Higher order intermodulation products are generally less important because they have lower amplitudes and are more widely spaced. The remaining third order products, $2f_1+f_2$ and $2f_2+f_1$, do not generally present a problem.



From IFR RF Datamate, page 30⁵.

Turnaround loss

This is a transmitter specification that is important for calculation of expected intermod products. The transmitter manufacturer sometimes specifies turnaround loss or it can be measured.

From Broadcast Electronics⁴.

"Turn-Around-Loss" or "Mixing Loss" describes the phenomenon whereby the interfering signal mixes with the fundamental and its harmonics within the non-linear output device. This mixing occurs with a net conversion loss, hence the term "Turn-Around-Loss" has become widely used to quantify the ratio of the interfering level to the resulting IM level. A "Turn-Around-Loss" of 10dB means that the IM product fed back to the antenna system will be 10dB below the interfering signal fed into the transmitter's output stage.

"Turn-Around-Loss" will increase if the interfering signal falls outside the passband of the transmitter's output circuit, varying with the frequency separation of the desired signal and the interfering signal. This is because the interfering signal is first attenuated by the selectivity going into the non-linear device and then the IM product is further attenuated as it comes back out through the frequency selective circuit.

"Turn-Around-Loss" can actually be broken down into the sum of three individual parts:

- (1) The basic in-band conversion loss of the non-linear device.*
- (2) The attenuation of the out-of-band interfering signal due to the selectivity of the output stage.*
- (3) The attenuation of the resulting out-of-band IM products due to the selectivity of the output stage.*

Of course, as the "Turn-Around-Loss" increases, the level of undesirable intermodulation products is also reduced.

The same document details a method for measuring transmitter turnaround loss and transmitter output return loss.

A transmitter with a true 50 ohm output will likely have very poor turn around loss. Its efficiency will also be very poor as half the output power will be lost. An ideal voltage source will have a zero ohm output impedance resulting in a very high turn around loss. Most transmitters are designed to operate into a 50 ohm load, but their output impedance is typically very low, on the order of a few ohms.

Industry Canada requirements³BETS-6

This document contains the technical standards and requirements for the issuance of a Technical Acceptance Certificate for FM Broadcasting Transmitters. If the transmitter meets these standards, it is issued a Technical Acceptance Certificate.

Section 6.3.3 At more than 600 kHz from the carrier frequency, the maximum spurious output level allowed is $-(43 + 10 \log P)$ or -80 dB, whichever is stronger. Levels are referenced to the power level of the unmodulated carrier. P = transmitter power in watts.

This is a bench standard for a single transmitter operating into a test load. It does not apply to a transmitter feeding a combining system or when connected to an antenna.

I discussed this dilemma with an inspector from Industry Canada. As there are no 'stand-alone' standards for spurious emission / intermod specs within the broadcast band for in-service FM transmission systems (ie levels at the output of a combiner), the BETS-6 limits are generally applied.

BPR-3

This document details FM/NAV/COM compatibility and the emission limits which are allowed in the NavCom band. It provides a short explanation of the interference mechanisms from FM broadcasting signals to aeronautical frequencies. For a more in-depth look and explanation, refer to Recommendations by the International Telecommunications Union (ITU), ITU-R SM.1009-1⁶.

Section B-6.3.4 If interference to NAV/COM facilities is caused by the FM station during scheduled on-air broadcasting, the holder of the broadcasting certificate will take remedial measures to eliminate the interference, even to the extent of closing down the station, if so requested by the Department.

Section B-6.3.5 Because FM broadcasting stations transmit at much higher powers than NAV/COM facilities, it is important to limit spurious signals from FM stations to prevent interference to NAV/COM reception. The Department requires all regular FM stations to suppress spurious emissions in the band 108-137 MHz to -85dBc as a condition of authorization. This suppression level, which is measured off-air, is more stringent than the suppression level specified in BETS-6, which is a bench test standard. The applicant may have to employ external filtering to comply.

Intermod calculations

When an extra RF signal appears at the output stage of a transmitter it can sometimes create intermodulation products. Typically the most important to consider is the 'two-tone' third order.

$$2 \times F1 - F2 \qquad 2 \times F2 - F1$$

For example 106.5MHz and 107.5MHz appear at a common antenna port. Poor isolation between transmitters could create these two extra signals.

$$(2 \times 106.5) - 107.5 = 105.5\text{MHz} \quad (2 \times 107.5) - 106.5 = 108.5\text{MHz} \text{ (This is in the NAV/COM band)}$$

A quick and easy check is to tune to the intermod frequency in a car. Drive a short distance from the site to ensure the signal is not being generated within the receiver. You should hear a mix of both stations being broadcast if the intermod is present.

The level of the intermod signal depends upon the level of the extra signal F2, the bandwidth of the combiner, and turnaround loss of the transmitter.

Transmitter 1 carrier level is 20kW or 73dBm

Transmitter 2 carrier level is 10kW or 70dBm

Combiner isolation transmitter 1 to transmitter 2 is 50dB (Remember to check the antenna reflected signal as a potential source of F1)

Combiner insertion loss at 108.5MHz is 20dB. This spec can be found on combiner test sweeps.

For this example, assume transmitter turnaround loss is 12dB.

Transmitter 1 power level – isolation = unwanted F1 signal level at output of F2 transmitter

$$73\text{dBm} - 50\text{dB} = 23\text{dBm}$$

Intermod level at output of combining system will be

F1 level – turnaround loss – intermod loss (through combiner)

$$23\text{dBm} - 12\text{dB} - 20\text{dB} = -9\text{dBm}$$

+70dBm – 85dB = -15dBm maximum absolute level for intermod within the NAV/COM band.

Expected intermod level to the antenna output is -9dBm. This is 6dB above the maximum allowed level.

Further filtering will be needed to meet specs. This is a case where sharper combiner tuning or an extra pole in the combiner could be useful.

If antenna return loss at F1 is 20dB, the F1 transmitter level could be up to 33dBm. (53dBm – 20dB)

Intermod level = 33dBm – 12dB – 20dB = +1dBm.

This calculation does not meet the required specification within the NAV/COM. Intermod is 16dB above maximum allowed level.

Note that antenna return loss less than 30dB may result in lower than expected isolation through a balanced combiner.

If not properly tuned, S-P type combiners may provide less than 15dB isolation at channel edges, and the intermod reduction is even less.

$$73\text{dBm} - 15\text{dB} = 58\text{dBm}$$

Intermod level output

$$58\text{dBm} - 12\text{dB} - 10\text{dB} = 36\text{dBm} \quad \text{This would be 4 watts!}$$

Transmitter would miss NAV/COM spec by 51dB and could be shut down immediately.

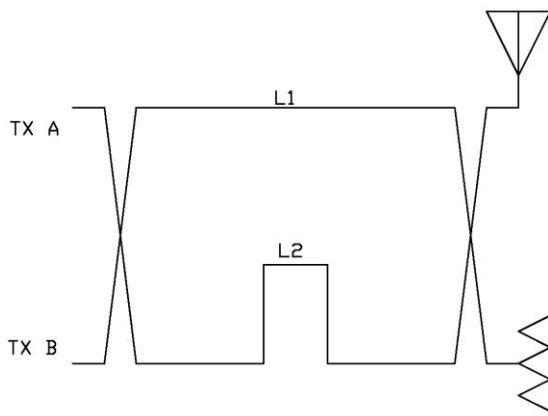
TV aural / visual combiners

Visual RF appears at the input port of a 3dB coupler. Between the two couplers are filters for aural carrier, and possibly notches for -3.58MHz and +7.16MHz. Any energy at those frequencies is reflected back to the input coupler where it appears at the dump load. At the output coupler the visual energy recombines at the antenna port.

Aural RF appears at the output 3dB coupler, gets split and sent towards the input 3dB coupler. When it arrives at the aural notches it is reflected back to the output coupler where it recombines and appears at the antenna port.

Runout / Resonant loop combiner

This combiner connects two different frequency transmitters to common antenna by use of phase adjusting line. The runout line must be multiple of full wavelength at one channel, and an odd multiple of half wavelength on the other channel. Isolation supplied by 3dB coupler only. Nominal 35dB, often requires bandpass filters at the transmitter outputs.



TV Channel 52/58 combiner

Design combiner for channels 9 and 13
 Wavelength in inches = $984 \times 12 / F(\text{MHz})$

Channel 9 186 - 192MHz. Center 189MHz
 Full wavelength = 61.5 inches
 Half wavelength = 30.75 inches

Channel 13 210 - 216MHz. Center 213MHz
 Full wavelength = 55.44 inches
 Half wavelength = 27.72 inches

Runout line calculation

Odd multiple of half wavelength at channel 9 (A)

Multiple of wavelength at channel 13 (B)

Channel 9	Channel 13
30.75	55.44
92.25	110.88
153.75	166.32
215.25	221.76
276.75	277.20
338.25	332.64

In the calculation, 276.75 and 277.20 are within half an inch. Choose length midway, 276.52 inches.

Use 7/8 inch foam line, LDF5-50. Velocity factor 0.89

Cable physical length $276.52 \times 0.89 = 246.1''$, 20' 6.1"

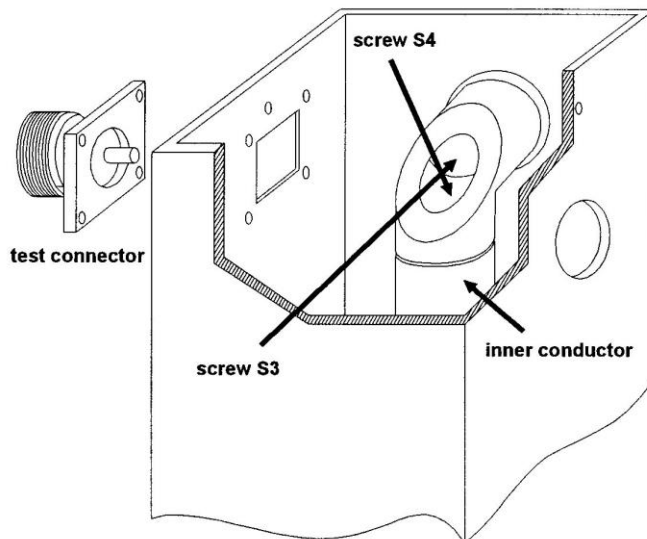
Bolt both couplers together with one mounted above the other with about 4 inches of line (L1) between.

Make the L2 cable slightly longer, 20' 8" to compensate for the extra 4 inches between couplers.

Assemble and monitor dump load rejection for both channels. Adjust L1 as needed to optimize system.

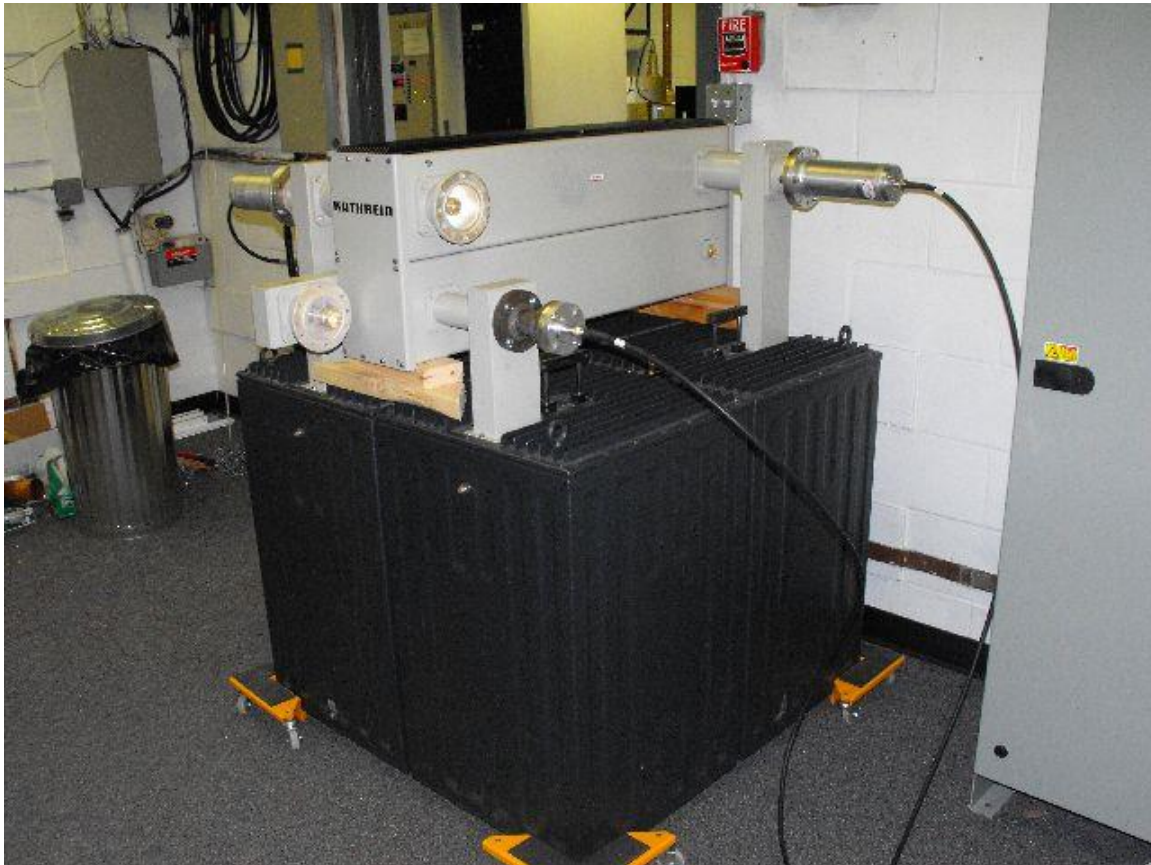
Kathrein combiner tuning

- Older Kathrein combiners have 3dB couplers mounted permanently. Tuning is relatively simple and is usually performed with the system fully assembled.
- Begin by adjusting input and output coupling loops to mid range or follow recommendations in the combiner tuning guide. Remove the square covers at top of the four lines between the cavities and 3dB couplers. The input and output coupling loops can be seen inside the cavities. When tuning is complete, all four must be in the same position for optimum performance.
- Connect test equipment to tuned input and output ports. Remove dump load termination to prevent masking of bandpass filter return loss outside tuned channel. Simultaneously tune for best return loss (S11) and lowest insertion loss (S21). Occasionally install wideband terminations or remove wideband port termination. Confirm very little change to response curve within pass band of the filters. Fine tune as described earlier by checking S21 and S11 between input and dump load.
- In order to optimize input return loss and insertion loss, monitor tuned input to dump load isolation. Maximum isolation should correspond to best return loss and minimum insertion loss. It is easier to peak 26dB dump load isolation than it is to minimize 0.2dB insertion loss.
- When the top covers are removed as shown below, the right angle elbows can be disconnected from the 3dB coupler inputs. The coupler insertion loss can be measured from wideband to output port or tuned input to dump load. It should be less than 0.05dB.
- I have Kathrein tuning instructions available for several combiner modules. Email for copies.
- Some Kathrein combiners are built to allow adapters to install at inputs of the couplers. Square plates may be seen near the coupler ports to mount type N connectors. At least two (preferably four) of these adapters should be purchased from Kathrein. The combiner remains physically assembled, but independent testing and tuning of cavities and 3dB couplers can be performed as described earlier.



Kathrein tuning (continued)

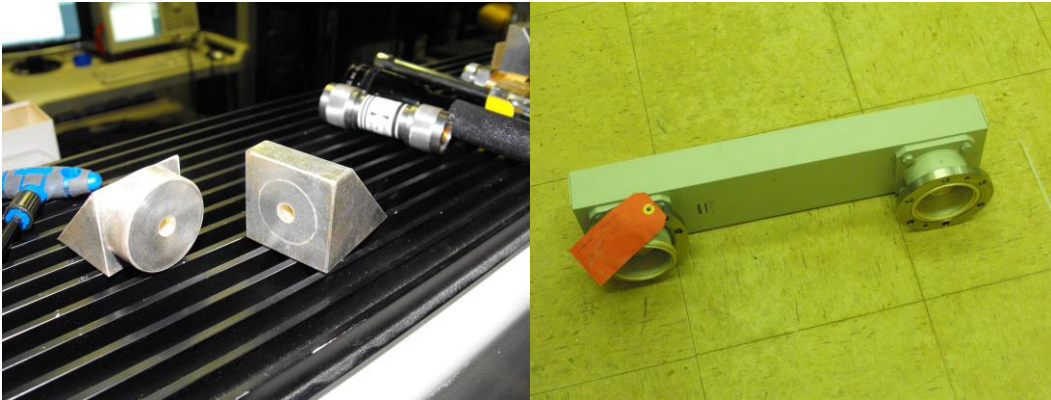
- I built adapters which allow the bandpass filters to be disconnected from the 3dB couplers if problems are encountered. Support 3dB couplers with wooden blocks prior to disconnecting supporting square transmission lines.
- Unbolt the base of the rectangular transmission lines and rotate 180° to have the mounting holes facing outwards. Attach adapters to either 3-1/8" or 1-5/8" and then adapt to Type-N.
- The 3-1/8" adapters were found as part of an unused rectangular U-link. The smaller adapter came from a decommissioned FM antenna power divider. It needed a small brass spacer fabricated for the center conductor. It may have been for adapting between 2-1/4" and 1-5/8" flanges and fits the smaller Kathrein connector very well. These adapters are available for loan if needed. Results with these 'home built' adapters have proven quite reasonable. There is no other way to connect to the cavities directly so potentially lowered performance is acceptable.



The yellow corner dollies in this picture are available at Princess Auto. Product #8097032. They greatly assist with moving combiner modules and other large heavy objects.

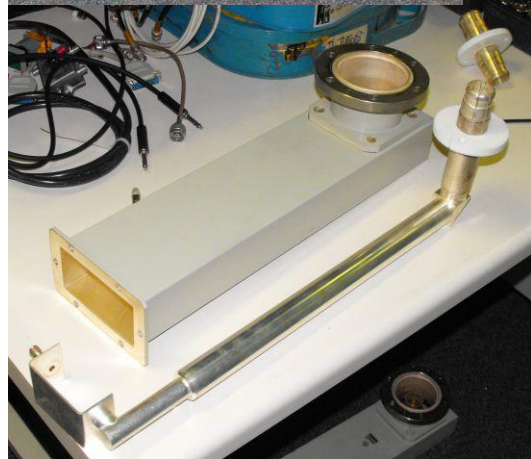
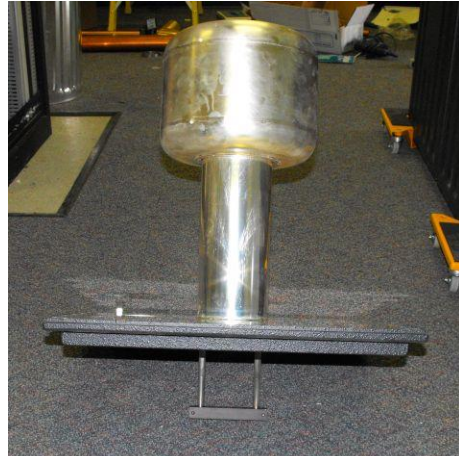
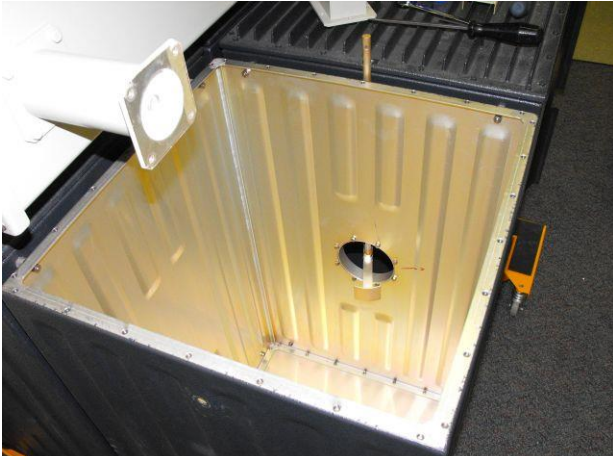
Kathrein (continued)

The right angle elbows should have any sharp points removed to prevent arcing, especially when approaching full power of the combiner. External rectangular U-links are a source for replacement right angle connectors. Parts for the 3-1/8" adapter also came from these U-links.

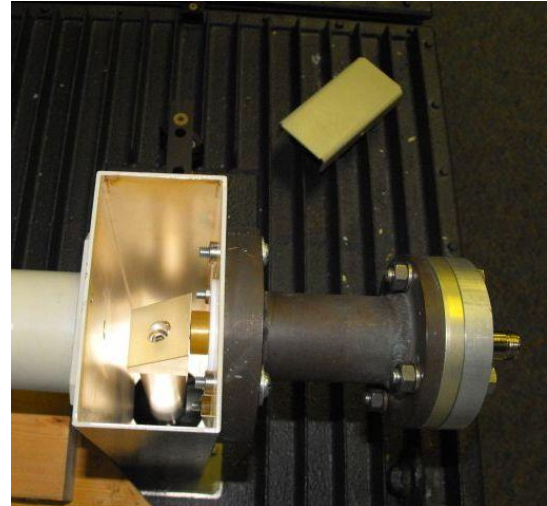
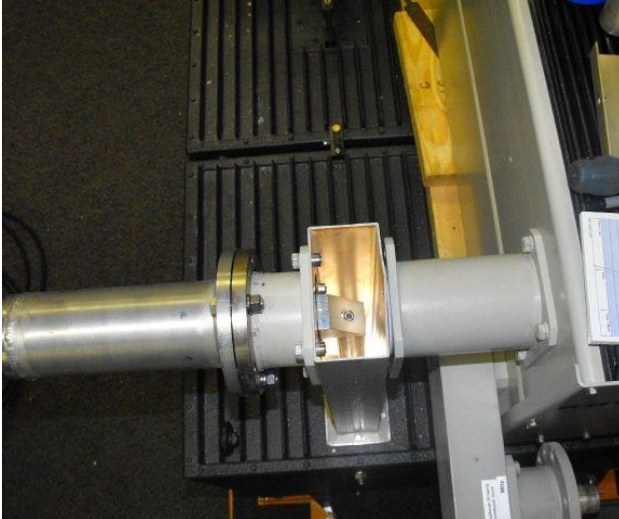


These are the adapters used on the Kathrein combiner module on the previous page.

Kathrein combiner pictures



Upper left shows inside cavity. Upper right shows tuning element removed from cavity. Lower left is the interstage coupling. Closest to the wall is minimum coupling, perpendicular for maximum. Lower right shows the input coupling loop in the minimum coupling position. Turn the loop 180 degrees for maximum coupling. The rectangular line normally connects to the 3dB couplers, not the 3-inch adapter and bullet pictured. The picture was taken during fitting confirmation of the adapters as seen below.



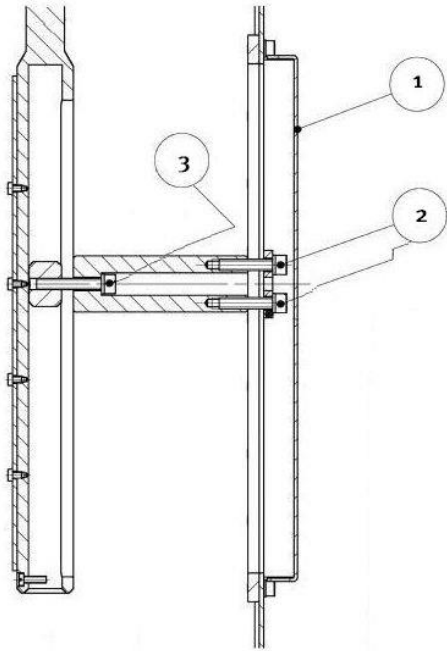
Closeup of adapters to allow direct connection to cavities

Sira tools

The tuning wheels for high power Sira band pass filters lock with a 26mm nut. Inter cavity coupling also uses a 26mm nut to lock a rotating screw. This nut will require a special tool to hold the screw in place while tightening the nut. Get a 26mm deep socket with 1/2" drive. The lower part may need to be machined to allow it to fit properly. A pair of chain type vice grips is used to hold the socket while a long Allen key fits through the hole in top of the socket. Lower power filters have smaller wheels and a smaller bolt. A similar, smaller scale tool is useful.



While tuning Sira combiners, the bolt at the end of the long threaded rod attached to the tuning wheel will sometimes come loose. You will have to remove the cover of the module and tighten the bolt. All bolts from around the upper edge of the cover must be removed. Remove the tuning element and tighten the bolt. One combiner also had the bolt holding the coupling mechanism fall out. Check and tighten this bolt when the combiner is dismantled. If you are experiencing problems with the combiner drifting or having difficulty tuning it may be a good idea to dismantle each cavity to ensure things are properly tightened.

Rymsa input and output coupling

- a) Remove the cover (1) of the input and output coupling mechanisms.
- b) Release the 2 screws (2) locking the coupling post
- c) Back off the screw of the coupling post (3).



A long "T-handled" hex-head wrench (Allen key) will maintain the correct angle while being used as a pry bar on the sliding post.



The coupling mechanism on Rymsa combiners can be difficult to adjust. It often binds and jams and is hard to move without modification. In order to adjust these sections the sliding nut inside the mechanism should be removed and machined to round the sharp edges. The nut can be seen at the end of part #3 in the diagram above. The outer sliding surfaces should be smooth. Powdered graphite may assist as a lubricant. This will allow the mechanism to slide more easily and reduce jamming.

The picture is from the coupling loop of a 10kW - 15kW bandpass filter. Lower power filters have a smaller coupling loop but the same machining helps with adjustments.

Acceptance tests

Other than full band measurements, center sweep on operating channel. Adjust trace as needed for best vertical resolution. Replicate all factory tests to confirm no detuning during transit.

- 1.1 Dump load return loss, full band, 5dB/div
- 2.1 Tuned input return loss, 2MHz span. Minimum 26dB
- 2.2 Tuned input return loss, dump load removed, 2MHz span. Return loss $\pm 200\text{kHz}$ from carrier should remain unchanged, but poor elsewhere.
- 2.3 Tuned input return loss, output load removed, 2MHz span. Return $\pm 200\text{kHz}$ from carrier should be poor, but unchanged elsewhere.
- 2.4 Tuned input return loss, wideband termination removed, 2MHz span. Should be no change from 2.1
- 3.1 Tuned input to output insertion loss, 1MHz span, 0.1dB/div. Approx 0.1dB per pole.
- 3.2 Tuned input to output insertion loss, 4MHz span. 5dB/div. Markers at $\pm 600\text{kHz}$, $\pm 800\text{kHz}$, $\pm 1.0\text{MHz}$, $\pm 1.2\text{MHz}$
- 3.3 Tuned input to output insertion loss, full band. Useful to see filter bandwidth. See sweep 9.1
- 4.1 Tuned input to wideband isolation, full band, 10dB/div. 55dB minimum except near tuned frequency. 36dB minimum near tuned frequency.
- 4.2 Tuned input to wideband isolation, full band, 10dB/div, dump load removed. Isolation will decrease near carrier.
- 4.3 Tuned input to wideband isolation, 4MHz span. 5dB/div. Markers at $\pm 600\text{kHz}$, $\pm 800\text{kHz}$, $\pm 1.0\text{MHz}$, $\pm 1.2\text{MHz}$ to show adjacent channel rejection. Should be better than 30dB at tuned frequency, higher as separation increases.
- 4.4 Tuned input to wideband isolation, 4MHz span, 5dB/div, dump load removed. Isolation will decrease near carrier.
- 4.5 Tuned input to dump load isolation, 2MHz span, 5dB/div. Should be better than 26dB $\pm 200\text{kHz}$ from carrier, reducing to 0dB elsewhere.
- 4.6 Tuned input to dump load isolation, 2MHz span, 5dB/div, wideband load removed. Should be no change from 4.5
- 4.7 Tuned input to wideband isolation, 2MHz span
- 4.8 Tuned input to wideband isolation, output load replaced with 20dB RL load. 2MHz span. Isolation should decrease near carrier.
- 5.1 Wideband input to output insertion loss, 2MHz span, 5dB/div. Same curve as 4.5. Markers at $\pm 400\text{kHz}$, $\pm 600\text{kHz}$, $\pm 800\text{kHz}$, $\pm 1.0\text{MHz}$
- 5.2 Wideband input to output insertion loss, full band. Reduces to 0.05dB/div away from tuned frequency
- 5.3 Wideband input to output insertion loss, F-800kHz. Markers at $\pm 100\text{kHz}$, $\pm 200\text{kHz}$, $\pm 300\text{kHz}$, $\pm 400\text{kHz}$
- 5.4 Wideband input to output insertion loss, F+800kHz. Markers at $\pm 100\text{kHz}$, $\pm 200\text{kHz}$, $\pm 300\text{kHz}$, $\pm 400\text{kHz}$
- 6.1 Wideband input return loss, 2MHz span, 5dB/div.
- 6.2 Wideband input return loss, dump load removed, 2MHz span, 5dB/div. Return loss near carrier should be poor, but unchanged away from carrier.
- 6.3 Wideband input return loss, output load removed, 2MHz span, 5dB/div. Return loss near carrier should remain unchanged, poor away from carrier.
- 6.4 Wideband input return loss, full band, 5dB/div
- 6.5 Wideband input return loss, dump load removed, full band, 5dB/div. Return loss near carrier should be poor, but unchanged away from carrier.
- 6.6 Wideband input return loss, output load removed, full band, 5dB/div. Return loss near carrier should remain unchanged, but poor away from carrier.
- 7.1 Wideband input to dump load isolation, 2MHz span, 5dB/div. Show -20dB bandwidth. Similar to 3.1
- 7.2 Wideband input to dump load isolation, full band, 10dB/div. Markers F $\pm 600\text{kHz}$, F $\pm 800\text{kHz}$, F $\pm 1.0\text{MHz}$
- 8.1 Group delay tuned input to output, 1MHz span, 100ns/div
- 8.2 Group delay tuned input to output, 500kHz span, 20ns/div
- 8.3 Group delay wideband input to output, F +800kHz, 1MHz span. Markers $\pm 100\text{kHz}$, $\pm 200\text{kHz}$, -300kHz, -400kHz
- 8.4 Group delay wideband input to output, F -800kHz, 1MHz span. Markers $\pm 100\text{kHz}$, $\pm 200\text{kHz}$, +300kHz, +400kHz
- 9.1 Rejection tuned input to output on NAV/COM band, 88-138MHz.

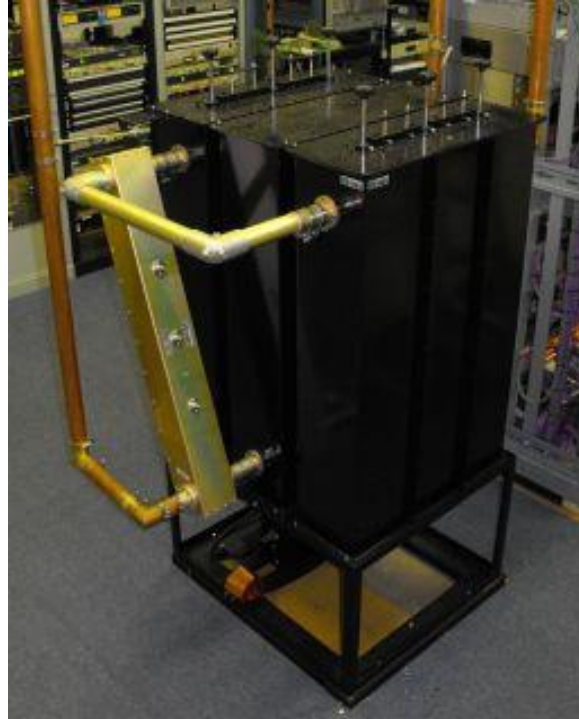
Other combiner types

Right: Bandpass filter connects to wideband port of balanced combiner. Saves cost over full combiner module. This is a Rymsa 3-pole balanced combiner with a 3-pole bandpass filter at its wideband port.

Below left: Two or more bandpass filters are connected with a Tee connector to form a starpoint combiner. Isolation is provided by the bandpass characteristic of each filter. Bandwidth and insertion loss can be optimized by the inter cavity coupling. Typical minimum spacing is a few MHz.

This is a Kathrein type 720 602 starpoint combiner rated for 2x20kW inputs. Minimum spacing 5MHz from spec sheet can be narrowed. Insertion loss will increase and power rating is reduced.

With adapters and 3dB couplers it could be reconfigured for use as a balanced combiner, or it could be used as a 6-pole bandpass filter.



Right: A pair of 3dB couplers and a length of coaxial cable can be used to create a stretch line combiner. Isolation between transmitters is that of the 3dB hybrid, typically 35dB. This can make it poorly suited for wideband transmitters. Extra band pass filters are required at the transmitter outputs.



In this picture is a Sira UHF Commutating Line TV combiner, model DPLX UC/U-1.

The 3dB coupler in the foreground has two UHF transmitters attached at the upper right and lower left connectors. The coil of cable at the top adjusts phase of both channels to the output 3dB coupler. The antenna output is on the lower left of the other 3dB coupler. Both 3dB couplers are adjacent or non-crossover types.

Stop / Pass band cavities are often used to create a starpoint combiner. These are becoming less common as they become replaced with balanced combiners. Intermod rejection is often poor. Peaking all notch cavities to the same frequency can result in poor isolation at channel edges, creating intermod problems. Spacing between cavities will vary according to the reject frequency. Center to center between the cavities and from the first cavity to the Tee connector should be a quarter wavelength at the reject frequency.



ERI 3-pole S/P starpoint
2x20kW



Simroc 2-pole S/P starpoint
2x20kW



Simroc 2-pole S/P starpoint
2x1kW

A balanced combiner may also use notch or S-P filters in place of the bandpass filters. This is common for TV visual/aural combiners.

This picture is an FM / Ch 6 balanced combiner. I built it using surplus parts to allow use of a wideband FM antenna for channel 6 television and FM after the original antennas fell off during a wind storm. It uses two Shively FM S/P cavities and two 3dB couplers.

<https://members.renlist.com/warren/StAndrewsCombiner.PDF>



References

1. FM Combining Systems : Robert Surette, Shively Labs
http://www.shively.com/tb-balcombiner_basics.php
http://www.shively.com/tb-balcombiner_basics.pdf

2. Agilent application notes
Simplified Filter Tuning Using Time Domain (AN 1287-8)
http://www.home.agilent.com/agilent/redirector.jsp?action=ref&cname=AGILENT_EDITORIAL&ckey=1000000497%3Aeps%3Aapn&lc=eng&cc=US&nfr=-11143.0.00&pselect=SR.General

Network Analysis Solutions Advanced Filter Tuning Using Time Domain Transforms (AN 1287-10)
http://www.home.agilent.com/agilent/redirector.jsp?action=ref&cname=AGILENT_EDITORIAL&ckey=1000001873%3Aeps%3Aapn&lc=eng&cc=US&nfr=-11143.0.00&pselect=SR.General

3. Industry Canada Documentation
http://www.ic.gc.ca/eic/site/ic1.nsf/eng/h_00013.html#b

BETS-6, Issue 2, August 2005
Technical Standards and Requirements for FM Broadcasting Transmitters
[http://www.ic.gc.ca/eic/site/smt-gst.nsf/vwapj/bets6-e.pdf/\\$FILE/bets6-e.pdf](http://www.ic.gc.ca/eic/site/smt-gst.nsf/vwapj/bets6-e.pdf/$FILE/bets6-e.pdf)

BPR-3, Issue 5, Amendment 1, June 2010
Part 3: Application Procedures and Rules for FM Broadcasting Undertakings
[http://www.ic.gc.ca/eic/site/smt-gst.nsf/vwapj/bpr3.pdf/\\$FILE/bpr3.pdf](http://www.ic.gc.ca/eic/site/smt-gst.nsf/vwapj/bpr3.pdf/$FILE/bpr3.pdf)

RIC-40, Issue 3, June 2008
Frequently Asked Questions on Low-Power FM Broadcasting
[http://www.ic.gc.ca/eic/site/smt-gst.nsf/vwapj/ric40e.pdf/\\$FILE/ric40e.pdf](http://www.ic.gc.ca/eic/site/smt-gst.nsf/vwapj/ric40e.pdf/$FILE/ric40e.pdf)

4. A Study of RF Intermodulation Between Transmitters Sharing Filterplexed or Co-located Antenna Systems, Geoffrey N. Mendenhall, P.E., Broadcast Electronics, Inc., Quincy, Illinois.
http://bdcast.com/fgal/white_paper/BeRfIntermod_BCEWHP.pdf

5. IFR Advancing Wireless Test RF Datamate, Part No. 46891/885, Issue 1, January 2001.
<http://www.ifrsys.com> (Available as pdf)

6. Recommendations by the International Telecommunications Union (ITU), ITU-R SM.1009-1, *Compatibility Between the Sound-Broadcasting Service in the Band of About 87-108 MHz and the Aeronautical Services in the Band 108-137 MHz*
(Available for a fee from the ITU website at <http://www.itu.int>)

Other suggested reading

Theory of the Quarter Wavelength (3dB) Hybrid: Doc Daugherty, Harris Corporation

RF Combiners. Paper given at WEBE, Virginia Beach, VA. Marvin Crouch, Tennaplex: Oct 1985
<http://members.rennlist.org/warren/RFCombiningSystems.pdf>

Further information

These are my personal notes and thoughts from the past several years. I've done my best but can not guarantee 100% accuracy throughout. Do your homework and double check before using the information in any critical application. I appreciate constructive suggestions and ideas for improvement. Please let me know if you have found the information useful or if you find errors or typos.

I've written this document in hopes of assisting others. Feel free to distribute. It is simply impossible to recognize every piece of information that I have come across. I try to reference things and give credit as appropriate. If you find something that should be acknowledged please let me know. It is not my intention to steal credit from anyone.

The latest changes and updates to this article are available on my personal web page.

<http://members.rennlist.org/warren/FMCombinerTuningAndTesting.pdf>

Other items I've been working on.

Antenna splitter cable replacement, power divider calculations, etc.

<http://members.rennlist.org/warren/SplitterCableDesign.pdf>

Relative humidity measurement and remote monitoring, dehydrator theory.

<http://members.rennlist.org/warren/RelativeHumidityAndDehydrators.pdf>

Construct a simple and inexpensive dew point monitor for monitoring dehydrator performance.

<http://members.rennlist.org/warren/DewPointMonitor.pdf>

Broadcast and RF related grounding ideas.

<http://members.rennlist.org/warren/grounding.pdf>

Please contact me with any feedback or questions.

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Last change 27 February 2019