

Observations on 2nd and 3rd Order Intercepts of the
Clifton Laboratories Z1501D Active Antenna

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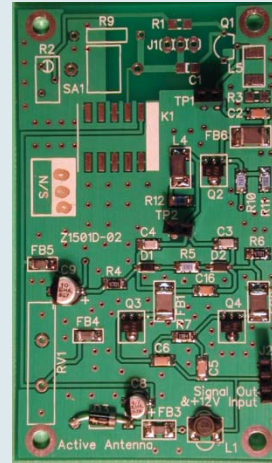
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Z1501D Active Antenna

- ▶ Z1501D is a voltage probe type active antenna.
- ▶ A voltage probe active antenna consists of an electrically short vertical antenna rod or whip, and a high input impedance / low output impedance amplifier.
- ▶ This permits an electrically short antenna to perform nearly as well as one much longer.
- ▶ Since the active antenna may be exposed to strong signals, such as from nearby medium wave (AM broadcast band) signals, resistance to intermodulation distortion is an important performance criterion.
- ▶ Frequency coverage is 20 KHz to 50 MHz.
- ▶ 13.8 V DC power is required, carried over the coaxial feedline. DC power is injected and signal coupled out with Clifton Laboratories Z1203A or similar coupler.

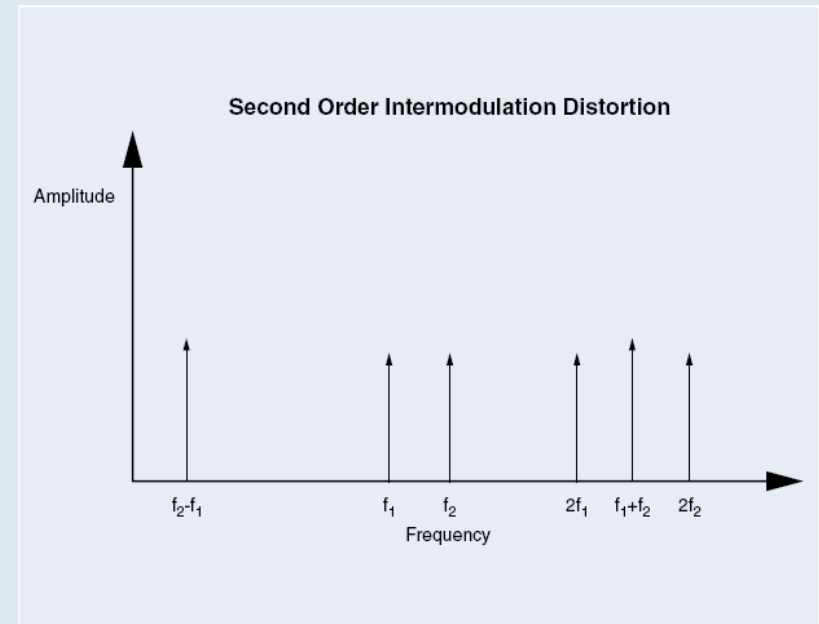


What is Intermodulation?

- ▶ Two or more *desired signals* can combine to create unwanted signals related mathematically to the desired signals. These are called “intermodulation products” and are created in the whip amplifier in an active antenna.
- ▶ Intermodulation products are also generated in receivers, preamplifiers and other equipment.
- ▶ For simplicity, the most common intermodulation test protocol uses two signals, for historical reasons often called “tones.”
- ▶ If the tone frequencies are f_1 and f_2 , the unwanted signals are at $mf_1 \pm nf_2$. m and n are integers.

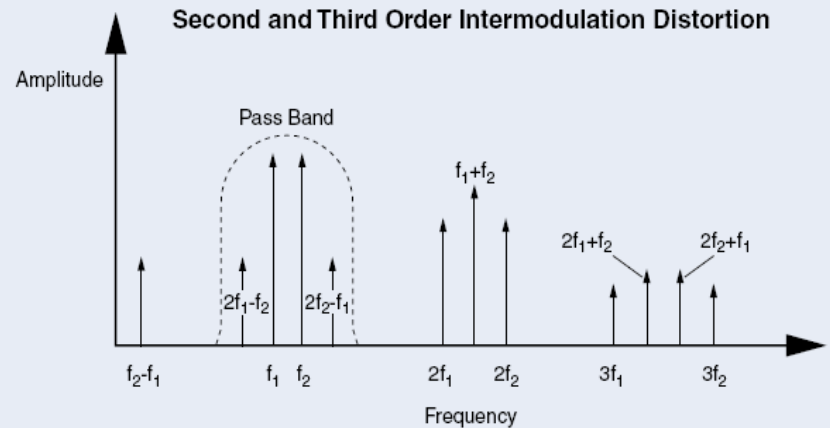
2nd Order Intermodulation

- ▶ For second order intermodulation products, $n+m = 2$, with permitted values of m and n :
 - ▶ $n=0, m=2$
 - ▶ $n=1, m=1$
 - ▶ $n=2, m=0$
- ▶ Thus, the products are at:
 - ▶ $2f_1$
 - ▶ f_1+f_2
 - ▶ f_1-f_2
 - ▶ $2f_2$
- ▶ $2f_1$ and $2f_2$ are the 2nd harmonics of the two test tones. f_1+f_2 is the sum of the test tone frequencies and f_1-f_2 is the difference of the test tone frequencies.
- ▶ For $f_1=3007$ KHz and $f_2 = 4011$ KHz, the intermodulation product frequencies are:
 - ▶ 6014 KHz ($2f_1$)
 - ▶ 7018 KHz (f_1+f_2)
 - ▶ 8022 KHz ($2f_2$)
 - ▶ 1004 KHz (f_1-f_2). (Actually this is -1004 KHz but the sign may be disregarded.)
- ▶ The second harmonic products are usually disregarded in 2nd order testing with the f_1+f_2 and f_1-f_2 products being the only ones considered.



3rd Order Intermodulation

- ▶ For third order intermodulation products, $n + m = 3$ and permitted values of $(m:n)$ are $(0:3)$, $(1:2)$, $(2:1)$ and $(3:0)$.
- ▶ Thus, the products are at:
 - ▶ $2f_1+f_2$
 - ▶ $2f_1-f_2$
 - ▶ f_1+2f_2
 - ▶ f_1-2f_2
 - ▶ $3f_1$
 - ▶ $3f_2$
- ▶ The 3rd harmonic frequencies ($3f_1$ & $3f_2$) and the associated product frequencies $2f_1+f_2$ and $2f_2+f_1$ are generally ignored and the two close in products, $2f_1-f_2$ and $2f_2-f_1$ are considered to be “the third order intermodulation products.”
- ▶ For test tones of 3007 and 4011 KHz, the two third order products of concern are 2003 KHz ($2*3007-4011$) and 5015 KHz ($2*4011\text{ KHz} - 3007\text{ KHz}$).

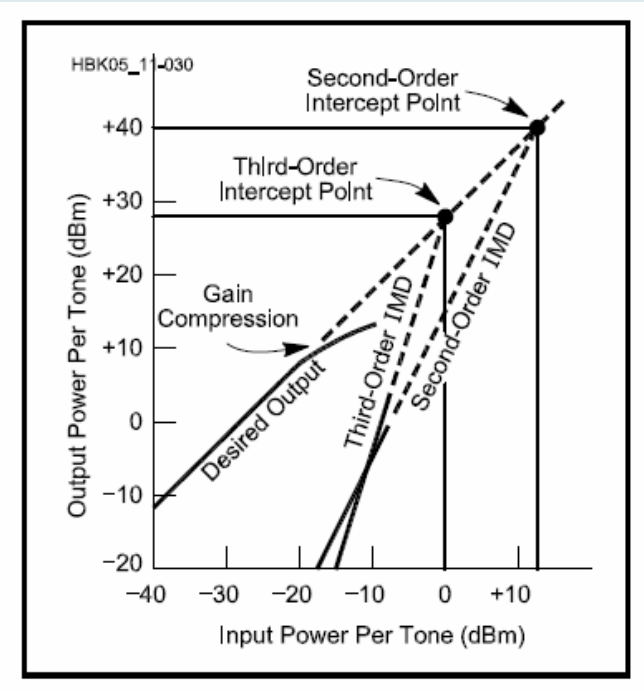


Which intermodulation products are the most troublesome?

- ▶ The short answer is all. But, some are more important than others.
- ▶ An active antenna, such as the Z1501D, is exposed to the RF environment from VLF (say 20 KHz) through low VHF (50 MHz or more). Typically, the strongest, consistent, signals are from medium wave broadcast stations (AM radio band, 535 KHz – 1705 KHz).
- ▶ Consider two AM stations, one at 1100 KHz and one at 760 KHz. These yield 2nd order intermodulation products of 340 KHz and 1860 KHz. The 1860 KHz product will show up in the 160 meter amateur band. In this example, the 2nd order product is of concern to 160 meter operators.
- ▶ The 3rd order products in this example are at 1440 KHz and 420 KHz. These products are not of concern to the 160 meter band operator, but the 1440 KHz 3rd order product may be a problem for medium wave DX'ing.
- ▶ Of course, if you are a NDB DX'er, both the 340 KHz 2nd order and 420 KHz 3rd order products may be objectionable.
- ▶ Other products such as those corresponding to the 2nd and 3rd harmonics of each station can be problems in particular circumstances.
- ▶ For extremely strong signals, higher order products (4th, 5th, etc.) can be troublesome.

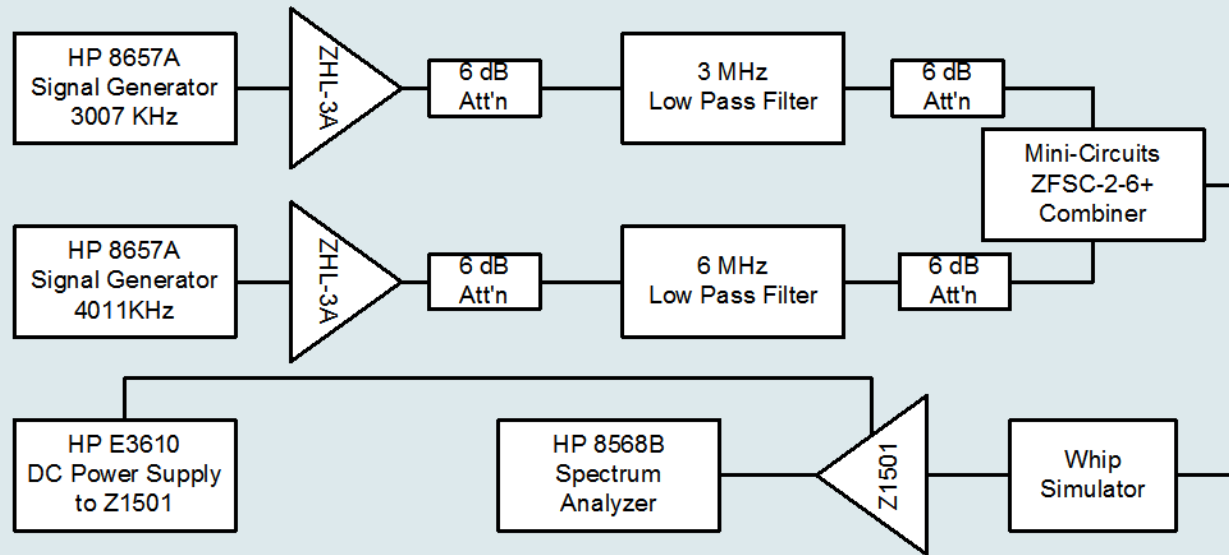
How is Intermodulation Performance Quantified?

- ▶ The traditional measure of intermodulation performance is the so-called “intercept” value.
- ▶ The figure at the right plots the output versus input for a hypothetical amplifier. Three lines are shown, the desired output and the 2nd and 3rd intermodulation product outputs.
- ▶ In a well behaved amplifier, the 2nd order intermodulation product increases twice as fast as does the desired output; the 3rd order increases three times as fast. 3 dB increase in desired signal results in 6 dB increase in 2nd order products and 9 dB increase in 3rd order products.
- ▶ At some point, therefore, in theory the desired output is equal to the 2nd order product and likewise--at a different point--equals the 3rd order product. These are the 2nd and 3rd order “intercept points.”
- ▶ The intercept points can never be reached in a real amplifier, but may be projected from measurements made at lower signal levels.
- ▶ The intercept values may be defined as the “Output Intercept” or “Input Intercept” depending on whether the point of equality is read from the output axis (Y) or the input (X) axis. These are called OIP2 and OIP3, meaning output referenced intercept point, 2nd order (or 3rd order.)
- ▶ Clifton Laboratories uses output intercept values. Since the Z1501D has a slight loss (negative gain) the input intercept value will be greater than the output intercept value.
- ▶ To convert to input intercept values, subtract the device gain. For a Z1501D active antenna, the device gain is typically -2.4 dB. (Active antennas frequently have negative gain as positive gain is almost never needed with a reasonable length whip.)



Measurement Technique-Test Equipment

2nd and 3rd Order Intermodulation Protocol for Z1501D Active Antenna



All power measured in dBm

Adjust signal generator output for 0 dBm per tone at Z1501D output

$$OIP2 = 2 * P_o - *P_{IM2}$$

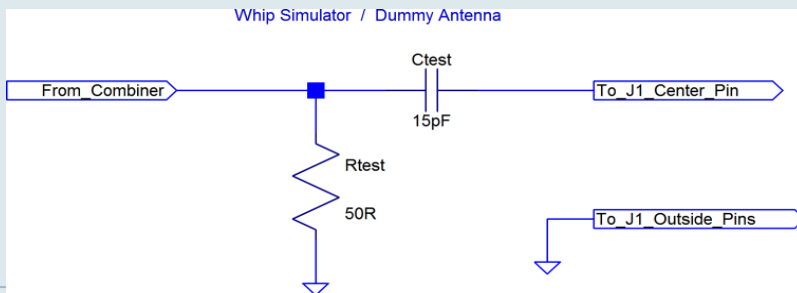
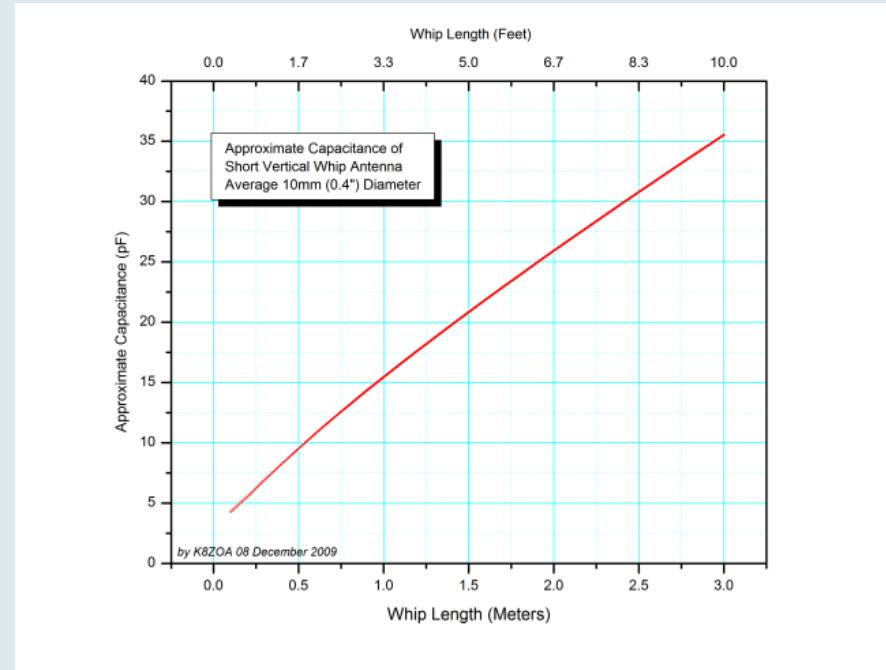
*P_{IM2} = measured power of 2nd order intermodulation products
P_o = test tone output power

$$OIP3 = 1/2 * (3 * P_o - *P_{IM3})$$

*P_{IM3} = measured power of 3rd order intermodulation products.
P_o = test tone output power

Whip Simulator

- ▶ Intermodulation performance measurements are not an end in and of themselves. Rather, a useful measurement should replicate, in so far as is reasonably feasible, the “real world” signal environment.
- ▶ Incident electromagnetic field energy is coupled to the amplifier through the antenna rod or “whip.” This process can be modeled by a low impedance signal source, connected to the amplifier through a small value capacitance representing the whip antenna’s impedance. (Electrically short antennas have capacitive impedance.)
- ▶ A 1 meter (approx. 40 inches) long whip antenna of 10mm (about 3/8”) diameter has about 15 pF capacitance.
- ▶ The signal generator, attenuators, combiners and the rest of the test equipment are 50 ohm impedance. To replicate real world incident field to amplifier coupling, the simple whip simulator shown in the schematic and photographs is used. It consists of a 49.9 ohm 1% tolerance 1/8 watt resistor between the signal generator output and ground, and a 15 pF COG/NPO capacitor from the generator output to the whip input. The whip simulator attaches to a short length of 50 ohm coaxial cable and plugs into the Z1501D’s input jack.
- ▶ Directly connecting a signal source with a 50 ohm termination to the high impedance active antenna input yields unrealistically good performance data. In some cases, as much as 10 dB improvement in 2nd order intercept can be seen if the whip simulator is not used. Such direct connection results are misleading since they will not be seen when the active antenna is deployed in the real world.



Instrumentation Floor

- ▶ For accurate measurements, test equipment generated intermodulation products should be at least 6 dB and preferably 10 dB, below the expected products from the Z1501D.
- ▶ To define the test equipment contribution, replace the whip simulator and the Z1501D with a direct connection.
- ▶ With 3007 and 4011 KHz test tones, at 0 dBm level, the equipment noise test floor below. No discrete tones are seen, only noise.

| Order | Frequency (KHz) | Product Level (dBm) | Intercept (dBm) |
|-----------------|-----------------|---------------------|-----------------|
| 2 nd | 1004 | -88 | +88 |
| 3 rd | 2003 | -95 | +47.5 |
| 3 rd | 5015 | -95 | +47.5 |
| 2 nd | 7018 | -88 | +88 |

Procedure Summary

- ▶ Configure test equipment as in the block diagram. Adjust the Z1501D's supply voltage to 13.80 volts.
- ▶ Allow warm up time and execute HP 8568B self-calibration routines.
- ▶ Adjust HP 8567A signal generators to produce 0.0 dBm output from the amplifier under test at the two test tones, normally 3007 and 4011 KHz.
- ▶ Set the 8568B for 10 Hz RBW, 10 Hz VBW, Span 200 Hz, video (trace) average = 16, and center frequency corresponding to the intermodulation product being measured. Set attenuation to 50 dB for 2nd order products and 40 dB for 3rd order products. If the Z1501's bias potentiometer has already been set, record the peak level.
- ▶ If not, before collecting data, adjust the Z1501 bias potentiometer (R2) for minimum 2nd order intermodulation product at 1004 KHz. Adjusting the bias potentiometer under this condition has proven to provide good 2nd order intermodulation performance across the medium wave and shortwave bands.
- ▶ The strategy of adjusting at the frequency of worst 2nd order performance, 7018 KHz in the Z1501D, is not recommended as the optimum bias setting cannot be easily found due to the small change in intermodulation product level with changes in bias voltage.
- ▶ Intermodulation frequencies to be observed:
 - ▶ 2nd order: 1004 KHz
 - ▶ 3rd order 2003 KHz
 - ▶ 3rd order 5015 KHz
 - ▶ 2nd order 7018 KHz
- ▶ The reason for the "odd" tone frequencies instead of 3000.000 KHz and 4000.000 KHz are to prevent discrete synthesizer spurious signals from the HP 8657A signal generators from landing on top of the intermodulation product frequency being measured. Other generators, such as the HP 8640B, do not have this problem and may be used with 3.000 and 4.000 MHz test tones.
- ▶ More broadly, why frequencies near 3 and 4 MHz? These are typical test frequencies used with the World Radio and Television Handbook tests of active antennas a few years ago. Frequencies in this range allow good mid-range HF IMD testing for 3rd order products and into the medium wave band for 2nd order.
- ▶ Test tones in the medium wave band at 603 and 707 KHz are also used at Clifton Laboratories in measuring the Z1501D's intermodulation performance.

Results

- ▶ Data is for an early production Z1501D, PCB rev 02, run. The board is adjusted for best OIP2 at 1004 KHz.
- ▶ Levels are shown to a precision of 0.1 dB. However, the estimated error of these measurements is on the order of ± 2 dB.
- ▶ Unit to unit variation is approximately ± 2 dB.

3007 & 4011 KHz

| Order | Freq (KHz) | Product Level (dBm) | OIP (dBm) |
|-------|------------|---------------------|-----------|
| 2nd | 1004 | -87.7* | 87.7* |
| 3rd | 2003 | -80.5 | 40.25 |
| 3rd | 5015 | -80.3 | 40.15 |
| 2nd | 7018 | -73.1 | 73.1 |

* Limited by test equipment floor.
Actual OIP is $> +87.7$ dBm.

603 & 707 KHz

| Order | Freq (KHz) | Product Level (dBm) | OIP (dBm) |
|-------|------------|---------------------|-----------|
| 2nd | 104 | -67.4 | 67.4 |
| 3rd | 499 | -79.4 | 39.7 |
| 3rd | 811 | -79.4 | 39.7 |
| 2nd | 1310 | -82.7 | 82.7 |

How does this data compare to other active antennas, both loop and voltage probe type?

| Manufacturer | Model | IP2 (dBm) | IP3 (dBm) | Price |
|----------------------|---------------------------|--|-----------------------------|-----------------------|
| Clifton Laboratories | Z1501 | Worst case +67, typically +80, best > +88 dBm* | +40 dBm* | TBD |
| AMRAD | Active LF Antenna | +53 dBm* | +37 dBm* | N/A |
| DX Engineering | DXE-ARAV2-1P | Not specified | +30 dBm | \$289.95 |
| RF Systems | DX One Pro MK II | +80 dBm | +52 dBm | \$799.75 |
| RF Systems | DX 10 | +70 dBm | +40 dBm | \$449.95 |
| Dressler | ARA 60 | Not specified | +50 dBm | \$349.95 |
| Dressler | ARA 100HDX | Not specified | +55 dBm | \$549.95 |
| WiNRadio | AX-815 | +60 dBm | +30 dBm | \$189.95 ⁵ |
| MFJ | MFJ-1024 | Not specified | Not specified | \$159.95 |
| LF Engineering | HF-800 | Not specified | Not specified | \$149.00 |
| Wellbrook | ALA 1530PE North American | +70 dBm | +40 dBm | \$276.11 |
| Wellbrook | ALA=1530+ ¹ | +75 dBm | +41 dBm | \$309.91 |
| Wellbrook | ALA=1530S+ ¹ | +80 dBm | +43 dBm | \$391.46 |
| Datong | AD-370 ² | +66/+46 dBm ³ | +36/+27 dBm ³ | N/A |
| Naval Electronics | VPA 30 | +60 dBm | +38 dBm | Unknown |
| McKay Dymek | DA-100 ² | Not specified | +23 to +25 dBm ⁴ | N/A |

Notes

¹ Loop antenna. All others are electric field active antennas.

² No longer in production. For historical reference only.

³ Figures are in form preamplifier out / preamplifier in

⁴ Estimated, based on 1 dB compression point

⁵ DC power supply and coupler not included in price

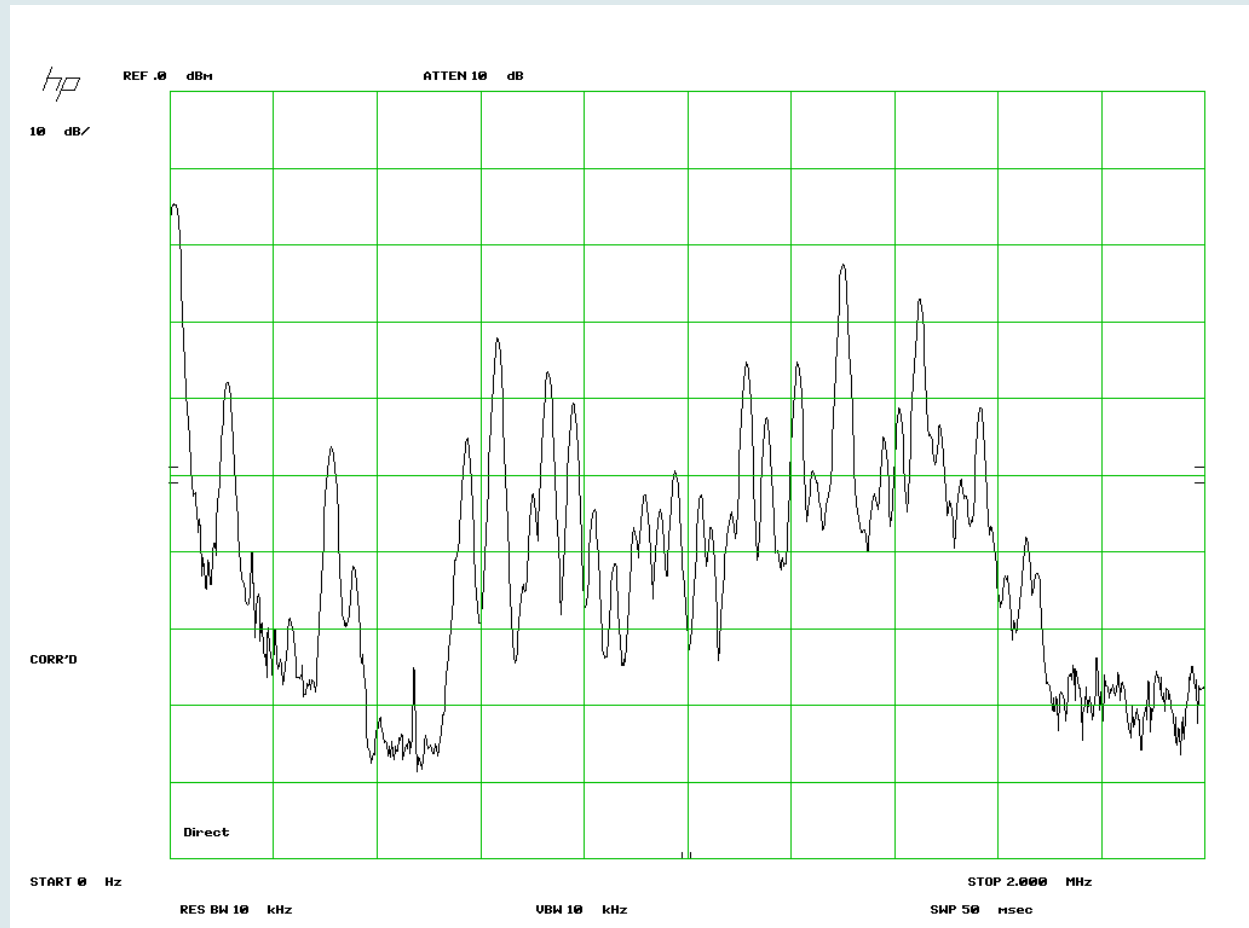
* Output intercept value. Unless identified as output, it is unknown whether the values are input or output based intercepts.

Comments on Performance Comparisons

- ▶ In order to qualify for the table, the antenna must be currently available and have published performance values.
- ▶ Several antennas are included for historical reasons, such as the AMRAD design published in QST, September 2001.
- ▶ The specific test frequencies and levels used in testing are not available for the other antennas in the table. Nor is any value provided for unit-to-unit variation.
- ▶ It is usually unknown whether the other antennas data is stated on the basis of output intercept point or input intercept point. (One exception is the AMRAD antenna, where the data is for output intercept.)
- ▶ Hence, the performance comparisons should be regarded as a rough guide only.
- ▶ The Z1501D's complementary symmetry output stage is one reason for its excellent 2nd order performance. A balanced approach, such as push-pull or complementary symmetry is used in several of the other high performance active antennas.
- ▶ For an independent measurement of the Z1501D's performance, see the measurements by Dr. Dallas Lankford later in this document.

Using Intercept Data to Predict Unwanted Intermodulation Product Levels

- ▶ If the signal levels are known, it is possible to use the 2nd and 3rd order intercept values to predict unwanted product levels.
- ▶ The spectrum analyzer image at the right is taken at Clifton, VA (suburban Washington DC area) with a Z1501D prototype active antenna and shows the spectrum from 0 to 2 MHz which includes the medium wave broadcast band.
- ▶ This prototype Z1501D uses a 10 ft (3 meter) whip and is mounted with the base of the whip approximately 6 feet (2 meters) above ground, located about 25 feet (8 meters) from the nearest structure.
- ▶ The strongest station observed is at -23 dBm, 1310 KHz. The second strongest is 1460 KHz, at -28 dBm.

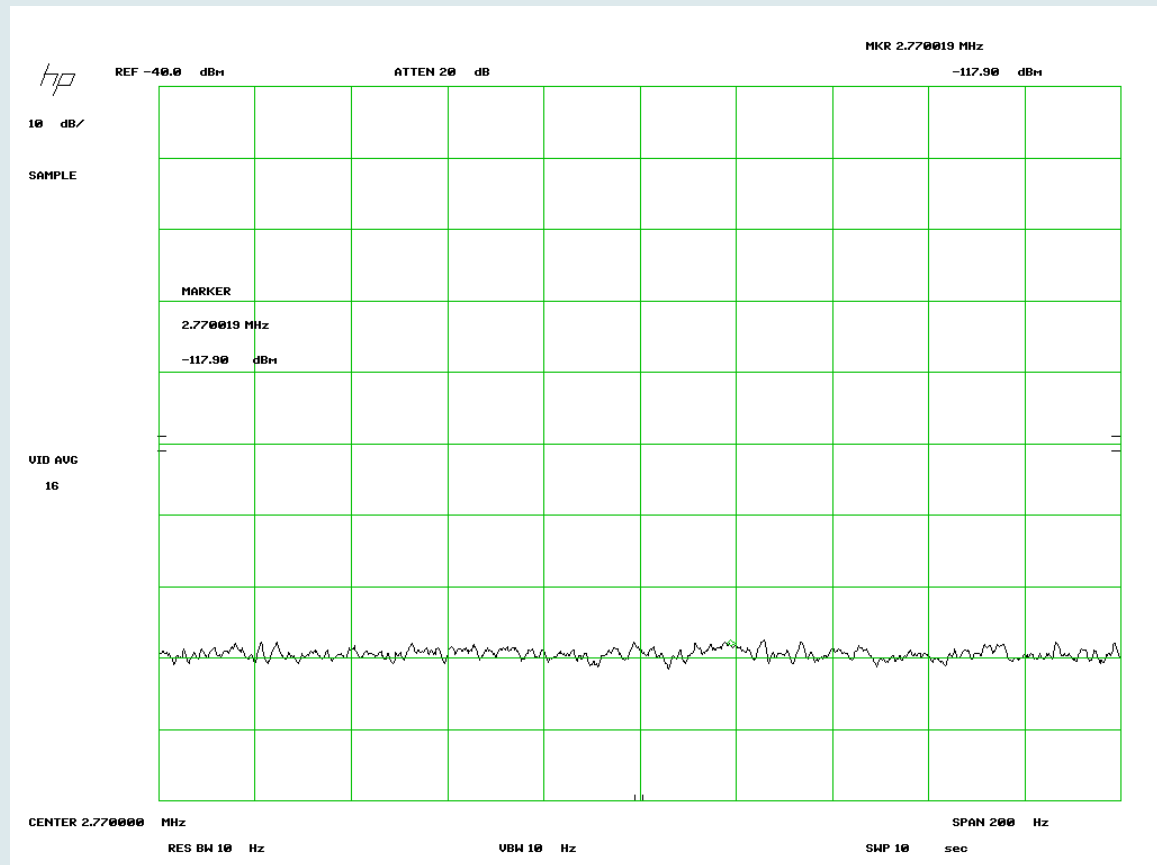


Using Intercept Data to Predict Unwanted Intermodulation Product Levels (continued)

- ▶ Assume the station at 1460 KHz is slightly stronger, so that it equals the signal level of the strongest station, 1310 KHz at -23 dBm. What strength will the 2nd order product at 2770 KHz be? And what strength will the 3rd order product at 1610 KHz be?
- ▶ Rearranging the equations for 2nd and 3rd order intercepts found on the test equipment setup diagram page, we find:
 - ▶ $P_{im_2} = 2P_0 - OIP2$
 - ▶ $P_{im_3} = 3P_0 - 2OIP3$
- ▶ For an antenna with $OIP2 = +80$ dBm, the values are:
 - ▶ 2nd order at 2770 KHz = $2*(-23 \text{ dBm}) - (+80 \text{ dBm}) = -126 \text{ dBm}$
 - ▶ 3rd order at 1610 KHz = $3*(-23 \text{ dBm}) - 2*(+40 \text{ dBm}) = -149 \text{ dBm}$
- ▶ If we convert these dBm readings to “S” meter values, assuming 50uV @ 50 ohms = S9, and 6 dB = 1 “S-unit,” we see:
 - ▶ 1310 and 1460 KHz signals are 50 dB over S-9
 - ▶ The 2770 KHz 2nd order product at -126 dBm is S-0.2 (just over S-0). This is below the noise level unless your location is exceptionally quiet.
 - ▶ The 1610 KHz 3rd order product at 1610 KHz at -149 dBm is two “S-units” below S-0, if such a thing exists. In any event, it’s well into the background noise.

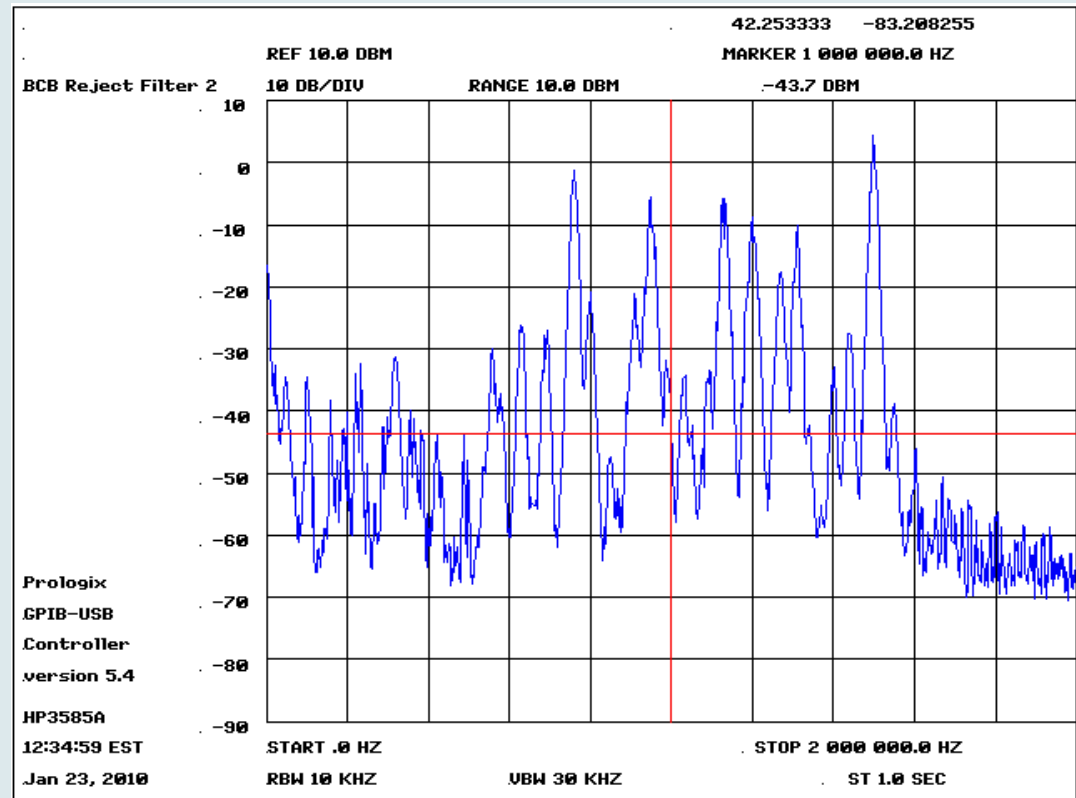
Using Intercept Data to Predict Unwanted Intermodulation Product Levels (continued)

- ▶ How good is our prediction for the 2nd order product at 2770 KHz?
- ▶ The HP 8568B spectrum analyzer image to the right shows the predicted product is not visible above the instrument's noise floor of -118 dBm. Since our prediction is -126 dBm, we can say the prediction is not disproven, and indeed is plausible.
- ▶ It's important that test equipment intermodulation products are not mistaken for those of the device being tested. For example, when connected to the Z1501D and viewing 2770 KHz and employing less than 20 dB input attenuation, the HP 8568B displays internally created intermodulation products in the -100 dBm range, not those that might be present from the Z1501D.
- ▶ The traditional test to distinguish internal spectrum analyzer products from "upstream" products is to change the input attenuation. Changing the attenuation 10 dB will change internal 2nd order products by 20 db and internal 3rd order products 30 dB. However, intermodulation products generated ahead of the spectrum analyzer will be changed only 10 dB.



Using Intercept Data to Predict Unwanted Intermodulation Product Levels (continued)

- ▶ Some people live in areas of exceptionally strong medium wave signals. The spectrum analyzer image at the right is from one such person, living in the downriver Detroit, Michigan area. The strongest medium wave station he observes is +5 dBm.
- ▶ He uses a Z1501 prototype active antenna, mounted on the vent pipe of a single story house, approximately 15 feet above ground. The whip length is approximately 5 feet (1.7m).
- ▶ The strongest station he observes is 1500 KHz, at +5 dBm, and the second strongest is 760 KHz at -2 dBm.



Using Intercept Data to Predict Unwanted Intermodulation Product Levels (continued)

- ▶ In his case, assume both stations are at +5 dBm for simpler calculations. (This corresponds to 78 dB over S-9, although I've never seen an S-meter calibrated this high!)
- ▶ Also assume the same performance characteristics as before, OIP2 = +80 dBm and OIP3 = +40 dBm.
- ▶ The 2nd order product at 2260 KHz can then be computed at -70 dBm, or 3 dB over S-9.
- ▶ The 3rd order product at 2240 KHz can then be computed at -65 dBm, or 8 dB over S-9.
- ▶ At these intensely strong signal levels, even a very good active antenna will create many audible intermodulation products. So, in most cases, will the receiver connected to the active antenna.
- ▶ Indeed, higher order products, such as 4th, 5th, 6th, etc. may reach significant levels when exposed to signal levels as high as seen in this suburban Detroit location.
- ▶ In addition, each pair of strong signals will produce intermodulation products, not just the two strongest stations. For a detailed analysis, all pairs of signals must be considered. (Specialized software is available to make this computation.)
- ▶ With respect to the active antenna, a partial solution is to reduce the whip length so that the strongest medium wave station is on the order of -10 to -20 dBm.

Dallas Lankford's Measurements of a Z1501D

- ▶ Dallas Lankford, who has written extensively about his active antenna designs, amplifiers and related topics,* has provided independent measurements of a production Z1501D.
- ▶ He has consented to including his measured data in this report.
- ▶ The measurements are performed at 0 dBm output.
- ▶ Dr. Lankford's data corresponds well to the earlier data, given the margin of error previously stated.

* <http://www.kongsfjord.no/dl/dl.htm>

Test frequencies: 600 KHz & 700 KHz

| Frequency (KHz) | OIP (dBm) | IIP (dBm) | Product Source |
|-----------------|-----------|-------------|---------------------|
| 1300 | OIP2: +93 | IIP2: +99.5 | 600 KHz + 700 KHz |
| 1900 | OIP3: +41 | IIP3: +47.5 | 2*600 KHz + 700 KHz |
| 2000 | OIP3: +40 | IIP3: +46.5 | 600 KHz + 2*700 KHz |

Test frequencies: 3000 KHz & 4000 KHz

| Frequency (KHz) | OIP (dBm) | IIP (dBm) | Product Source |
|-----------------|-----------|-------------|-----------------------|
| 1000 | OIP2: +88 | IIP2: +94.5 | 4000 KHz - 3000 KHz |
| 2000 | OIP3: +39 | IIP3: +45.5 | 2*3000 KHz - 4000 KHz |
| 5000 | OIP3: +40 | IIP3: +46.5 | 2*4000 KHz - 3000 KHz |
| 7000 | OIP2: +73 | IIP2: +79.5 | 4000 KHz + 3000 KHz |

▶ OIP2, OIP3 are intercepts based upon signal levels at the Z1501D's output

▶ IIP2, IIP3 are intercepts based upon signal levels at the Z1501D's input, applied through the whip simulator circuit described earlier. (6.5 dB measured loss from simulator input to Z1501D output.)