THIRD ORDER DISTORTION BUILD UP IN A MULTI-CHANNEL CASCADE

R. Richard Bell & P. Rebeles
TRW Lawndale Laboratories and
Semiconductor Operation
Lawndale, California

There have been several papers presented in the past dealing with nonlinear distortions in tube and transistor devices and amplifiers. Papers by Reynolds[1], Thomas[2], Akgun and Strutt[3] discuss the various forms of distortion cancellations that can occur in devices. Nearly all of these papers have dealt with two dominant nonlinearities at the component level. Lambert[4] has addressed the cancellation of second order effects in CATV amplifiers and Lieberman[5] in Systems. Because of the wide spread acceptance of amplifier hybrids we have frequently been called upon to aid in the explanation of distortion build-up behavior. What we aim to illustrate here are several unique cross-modulation and triple beat cancellations that may occur in actual systems. It will be demonstrated that these cancellations, or "poorly behaved nulls" may be extremely sensitive to any of the following operating conditions such as level, temperature, amplifier spacing, channel loading or channel spacing. Also we would like to propose a new test method which may give a better indication of a systems multi-channel capability.

Before getting into the testing methods and test results lets take a look back at how nonlinearity has been classically described. Historically the first paper dealing with the prediction of intermodulation products was by Brockbank and Wass[6] in 1945. The authors proposed that the amplitude transfer characteristic of a nonlinear thermionic amplifier, at that time, could be expressed by the power series

$$V_o = a_1 V + a_2 V^2 + \ldots\ldots a_n V^n$$

where V_o = output voltage

V = input voltage

$a_1\ a_2, \ldots\ldots a_n$ = constants independent of frequency.

Nearly all investigators to date have concerned themselves mostly with the first three terms of the series. This was done in part because of the belief that succeeding constants decreased rapidly enough in magnitude with increasing order that sufficient accuracy could be obtained with the initial three terms. Also, as Wass[7] pointed out in another paper in 1948, that for three sinusoidal input waves the number of products resulting from consideration of fourth and fifth order coefficients would be 277 versus the 37 resulting from second and third order. For 5 input signals the number of products increases dramatically to 1486. Because of the labor of carrying out the substitutions the higher order effects have been mostly ignored.

Today with transistor devices improving in second and third order linearity the effects of the higher order terms become visable. In previous work[8] we have illustrated the interaction of third order nonlinearity on second order distortion. In a paper in press[9] we show the contribution of fourth order nonlinearity on third order distortion. Thanks to the computer, the labor of calculating out the great number of products resulting from the fourth and the fifth order distortions, is considerably easier. Now we've increased the problem from the initial 3 carriers on 1 channel to 40 channels or 120 carriers. The number of beats resulting from second and third order nonlinearity becomes 1,166,440. When fourth and fifth order terms are large enough to be prevalent the number of products increases dramatically.

(Table I gives the number of beats produced by "N" carriers)

Simons[10] has defined the one form of cross-modulation that we base so much of our industry upon. However, in true observation, the measured cross-modulation is the complex addition of modulation information from other sources and not necessarly just the expansion and compression of the carrier in question. For example, consider the case where there are four signals present as indicated in Figure 1. Assuming only second and third order nonlinearities are present and that there are no cancellation mechanisms present, there will be a triple beat, a second order I.M. beat and third order I.M. beat falling on carrier "C". Because the modulated beats fall on the unmodulated carrier there appears to be information on the carrier. A typical cross-modulation measurement could contain a great deal of measurement error. The error would depend upon the degree of modulation on carriers A,B and D, their phase shift, and the phase shift of the beat products through the system to the point of measurement.

Lieberman[5] had indicated that the second order I.M. beat component could be reduced by amplifier spacing. In this case the cross-modulation sidebands would not contain modulation from that beat resulting in a different cross-modulation level depending on their level of contribution. To further illustrate the possibility of this phenomenon occuring Figure 2 shows the amount of cross-modulation measured through a constructed cascade. Because of the unique combination of phase shifts and the cross-modulation contributed by each amplifier, the cross-modulation at the end of the cascade appears to be better then it was after the second amplifier.

With cascade systems carrying 35 channels, at the standard assigned video carriers, most of the beats will build up about the carrier. The FCC specification on carrier frequency accuracy is ± 1 kHz. Second order beats could be up to ± 2kHz away from the carrier and a third order beat as far as ± 3 kHz away.

Computer calculations n our part indicate that for a 35 channel system the largest number of third order beats due to video carriers falling on a video carrier is 350 and occurs on channel 11. When the channel loading is reduced to 12 channels the number of beats about the carrier falls to 21 on channels 9,10 and 11. Table 2 gives the number of beats for several other channels[11].

With the standard frequency assignments (and tolerance) the large number of beats will build up about the carrier and appear as baseband noise a few kHz wide. In a system where the carriers are harmonically related the beats would accumulate in a power manner, versus a voltage manner, due to their random phasing.

The degradation in third order beat level can be expressed in dB for N beats falling on the same frequency as the carrier as $10 \log_{10} n$, where n is the number of additional beats.

For the case of 350 beats each of -70 dB, a new signal to noise level would be:

$$\text{T.B.}' = -70 + 10 \log_{10} 350 = -44.6 \text{ dB}$$

If a 35 channel system was using carriers harmonically related, all of the 399 beats, some of which are second order, would now fall on the carrier in question. Assuming again that each would be -70 dB (highly unlikely) the signal to beat noise level would be:

$$S/N = -70 + 10 \log_{10} 399 = -43.99 \text{ dB}$$

On the other hand if the carriers were randomly spaced the generated products would be distributed across the bandwidth of the channel and fewer would build up.

It has been shown by Switzer[12] that the video carriers can be harmonically related to a 10 kHz fundamental to conserve peak output capability of an amplifier. As mentioned, all the beats would fall on the carrier with complex modulation sidebands appearing as noise on the TV screen. However, since the modulation sideband is noise-like, if the signal-to-noise (or distortion) level is greater than 40 dB a good picture will result.

To experimentally describe these forms of distortion build up a sixteen mainline amplifier cascade was constructed. Amplifiers with 22 dB gain at channel 13 were fabricated using standard TRW CA100 and CA200 hybrid modules. (Table III). Each amplifier contained a passive gain and cable equalizer control. (Figure 3). Specifications on the completed amplifier are given in Table IV.

Each amplifier was firmly mounted to a fan-cooled heatsink and spaced by 550 feet of foamed 75 ohm cable.

The majority of cross-modulation and triple beat testing was done with a DIX HILLS/Model SX-16 32 channel generator and Model R-12 phase lock receiver. Second order testing was done on a TRW designed four channel distortion analyzer (Fig.4). In each case initial data was verified with a HP8554L Spectrum analyzer.

Second order cross-modulation and triple beat data was obtained at +35, 40, 45 and 50 dBmV output levels at each amplifier. The cross-modulation data was taken on channels 2 and 13 for the 12 channel tests, 2, G and 13 for the 20 channel tests and on 2, G, 13, R and V for 32 channel tests.

The second order performance of the system at +35 dBmV is indicated in Figure 5. Build up of the distortion is accuring at a 3 dB rate and appears well behaved across the frequency domain. Projection of the worst case performance, which occurs on channel 2, indicates that the maximum system length, due to a second order beat exceeding -66dB, is 58 amplifiers, or 1276 dB.

As Lieberman has indicated in his previous work second order products may cancel if the phase intercept of the systems response is an odd multiple of π. Figure 6 illustrates the intermodulation products present at the output of amplifier 8 about a channel 13 carrier in a 32 channel system. The spectrum of the output of amplifier 16 (Figure 7) indicates that several of the second order products have decreased in magnitude.

Cross-modulation performance is indicated in Figures 8, 9 and 10. The twelve channel cross-modulation build up is slightly less than a 6 dB rate with the performance being limited by the channel 2 levels. Projection to the point where the cross-modulation level is -57 dB illustrates that the system length would be 58 amplifiers (1276 dB); the same limit as indicated by second order performance.

Increasing the number of channels decreases the maximum system length as shown in Figures 9 and 10. A 20 channel system would be limited to 32 amplifiers (704 dB) and a 32 channel system to 16 amplifiers (352 dB). It should be pointed out that these figures are for a system operated at +35 dBmV, flat and block tilting would increase the system's length.

Extreme care must be taken in selecting the cross-modulation test method. A common test method incorporates the use of a video frequency phase detector. When the output indicator is dependent upon phase comparison the phase shift through the cascade can generate considerable error in the measurements as is indicated in the comparison of Figures 10 and 11.

The cascades triple beat performance and channels 13 and R is indicated in Figure 12. In each case the adjacent channels were slightly detuned so that the $\alpha+\beta-\gamma$ beat would fall close to the center carrier. The beat was then measured on the phase locked receiver. It's not generally recognized that two forms of triple beat may cancel due to phase shift through the cascade. Figure 13 describes the $\alpha+\beta+\gamma$ triple beat throughout the cascade resulting from channels 4, 5 and A falling on R and channels 2, 3 and 6 appearing on 11. Both forms can cancel as theory would indicate[13].

As can be seen from Figure 10 the measured cross-modulation on channels "V" and "R" appears 10 dB or better than channel "2". Although the measured "cross-modulation" is lower the number of beats falling about the channel 13 carrier are greater than channel 2. (Figures 13 and 14). The beats generated by 32 carriers undergo considerable phase shift throughout the cascade and the resultant effect may be the reinforcement or cancellation of apparent cross-modulation if the beat falls directly upon the carrier. If the beat falls along side the carrier the typical video beat interference can be observed upon the TV set. It should be mentioned that both of these conditions may appear at the same time. When a great number of beats fall about the carrier the end effect is a horizontally noisy picture. Figures 13, 15 and 16 display the number of beats that fall with the video bandwidth of channel 2 after 16 amplifiers for a channel loading of 12, 20, and 32. Figure 14 displayed the beat spectrum on channel 13 after 16 amplifiers for the 32 channel case. As would be expected the observer might not notice this "Intermodulation noise" provided that the noise was somewhat random and the signal to, beat caused, noise level remained better than 40 dB. It is possible that if the system was reduced to fewer channels then any single beat above -66 dB may be observed as beat interference.

In summary, what we have tried to show, here today, is that theory predicts that several forms of third order distortion can cancel and that the present test methods may not be adequate to accurately describe the performance capability of the system. We've indicated that highly loaded systems are limited by intermodulation noise rather then by purely cross-modulation or beat interference.

Several years back we learned of the noise method of distortion measurement used by the telephone companies. They have very similar problems where the system loading is intermodulation noise limited. In the past we suggested that CATV should consider utilizing this approach and are now gratified to learn of the increased interest in this area. There is a great amount of effort necessary before this approach can be considered for use by the industry. We plan to further investigate this test method along with our customers in the joint interest of improving our products and providing the industry with, what may prove to be, a more meaningful indicator of system performance.

The scope of our involvement as a component supplier with our customers, and end user, is considerably more complex than if we merely made carbon resistors. It is our hope that this information is of direct benefit and that our communications will continue to be two-way.

Acknowledgements

The authors are indebted to Gary Pumroy for his assistance in the fabrication of the cascade and to Margaret Stavros of UCS, Inc., for her aid in the development of the computer programs.

References

1. J. Reynolds, "Nonlinear Distortions and Their Cancellation in Transistors," IEEE Trans. Electron Devices, Vol. ED-12, No. 11, PP. 595-599, Nov.1965

2. L. Thomas, Eliminating Broadband Distortion in Transistor Amplifiers," BTSJ, PP. 315-342, March, 1968.

3. M. Akgun and M. Strutt, "Cross-Modulation and Nonlinear Distortion in RF Transistors," IRE Trans. Electron Devices, PP. 457-467, Oct. 1959.

4. W. Lambert, "Second-Order Distortion in CATV Push-Pull Amplifiers," Proc. IEEE, Vol. 58, No. 7, PP. 1057-1062, July, 1970.

5. D. Lieberman, "Cascading of Inter-Modulation Distortion in Cable Television Systems," NCTA offical convention Transcript, Vol. 20, PP. 130-150, July, 1971.

6. R. Brockbank and C. Wass, "Nonlinear Distortion in Transmission Systems," Pt. 3, Jrl. IEE, Vol. 92, No. 17, PP. 45, 1945.

7. C. Wass, "A Table of Inter-Modulation Products," IEE, Vol. 95, PP. 31-39, 1948.

8. R. Bell, "Distortion Nulls Predicted by an Offset on the Transfer Characteristic," T.M. 73-1466-01, TRW Semiconductors

9. R. Bell, "The Effects of the Fourth-Order Distortion Coefficient," Technical Memorandom in process.

10. K. Simons, "The Decibel Relationships Between Amplifier Distortion Products," Proc. IEEE, Vol.58 No. 7, PP. 1071-1086, July 1970.

11. R. Bell, "Third-Order Distortion Build-UP in Multi-Channel Cable Systems," T.M. 73-1466-02, TRW Semiconductors, January 1973.

12. I. Switzer, "Superposition of Coherent Carriers,"

13. "Transmission Systems for Communications," Fourth Edition, Bell Telephone Laboratories, 1970.

14. R. Bell, "Prediction of Intermodulation Levels in Transistors by S-parameter Analysis," Technical Memorandom in process.

TABLE I NUMBER OF BEATS PRODUCED BY "N" CARRIERS

Number of Product by Type.

N CARRIERS	$\alpha\pm\beta$	$\alpha\pm\beta\pm\gamma$	$2\alpha\pm\beta$	2nd, 3rd. HARMONICS	TOTAL
1	-	-	-	2	2
2	2	-	4	4	10
3	6	4	12	6	28
4	12	16	24	8	60
5	20	40	40	10	110
6	30	80	60	12	182
7	42	140	82	14	278
12	132	880	264	24	1300
15	210	1820	420	30	2480
20	380	4560	760	40	5740
21	420	5320	840	42	6622
25	600	9200	1200	50	11050
30	870	16240	1740	60	18910
35	1190	26180	2380	75	29825
40	1560	39520	3120	80	44280
120	14,280	1,123,360	28,560	240	1,166,440

TABLE II NUMBER OF VIDEO BEAT PRODUCTS FALLING ON EACH VIDEO CARRIER IN A 12, 21 AND 35 CHANNEL SYSTEM.

(STANDARD FREQUENCY ASSIGNMENT)

CHANNEL	CHANNEL LOADING			CHANNEL	CHANNEL LOADING		
	12	21	35		12	21	35
2	13	40	159	9	21	90	348
3	15	45	171	10	21	87	349
4	13	47	180	11	21	84	350
5	8	17	31	12	18	78	349
6	8	17	31	13	13	72	348
A	-	74	274	J	-	-	345
B	-	85	288	K	-	-	342
C	-	89	299	L	-	-	337
D	-	91	308	M	-	-	332
E	-	92	316	N	-	-	326
F	-	92	323	O	-	-	321
G	-	92	329	P	-	-	315
H	-	92	334	Q	-	-	309
I	-	92	338	R	-	-	301
7	15	92	342	S	-	-	293
8	18	91	345	T	-	-	283
				U	-	-	273
				V	-	-	260

TABLE III MAINLINE MODULE SPECIFICATIONS

		CA100	CA200
Operating Bandwidth		30-320MHz	30-320MHz
Gain & Flatness		16-17dB (± .2)	16-17dB (± .2)
Cross Modulation @ +32dBmV	12CH	-93dB	-100dB
	20CH	-87dB	- 94dB
	32CH	-84dB	- 91dB
Triple Beat @ +50dBmV		-68dB	- 75dB
2nd Order I.M. @ +50dBmV		-66dB	- 70dB
Noise Figure	CH13	7.5dB	10dB
Return Loss	Input	18dB	18dB
	Output	18dB	18dB
Current Requirement @ +24 VDC		180mA	220mA

TABLE IV COMPLETE AMPLIFIER SPECIFICATIONS

Operating Bandwidth		30-320MHz
Gain & Flatness		20.5 ± .3dB
Cross Modulation @ +35dBMV	12CH	-94dB (Worst case CH2)
	20CH	-86dB
	32CH	-83dB
Triple Beat @ +50dBmV	CH13	-74dB
	CH R	-68dB
2nd Order I.M. @ +50dBmV	CH 2	-90dB
	CH G	-85dB
	CH13	-77dB
	CH R	-71dB
Noise Figure	CH13	6.6dB (1MHz Bandwidth)
Return Loss Input		18dB
Output		18dB
Current Requirement @ +24 VDC		400mA

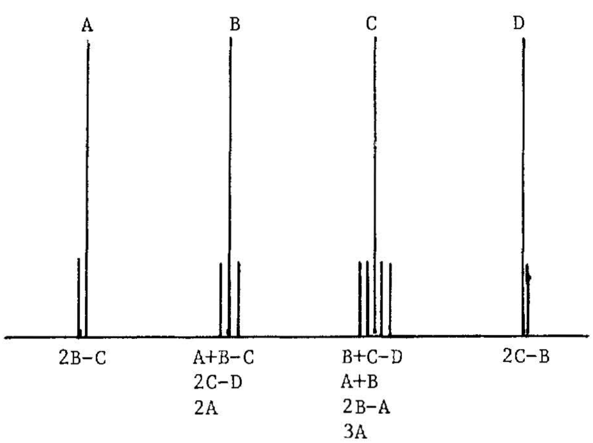


Figure 1. Four carriers spaced to produce four types of beats on carrier C.

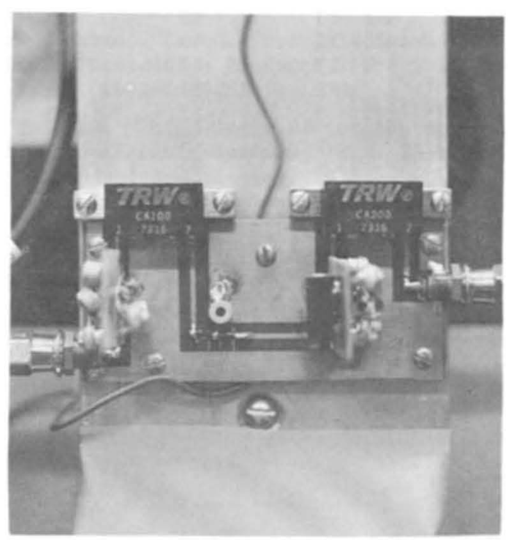
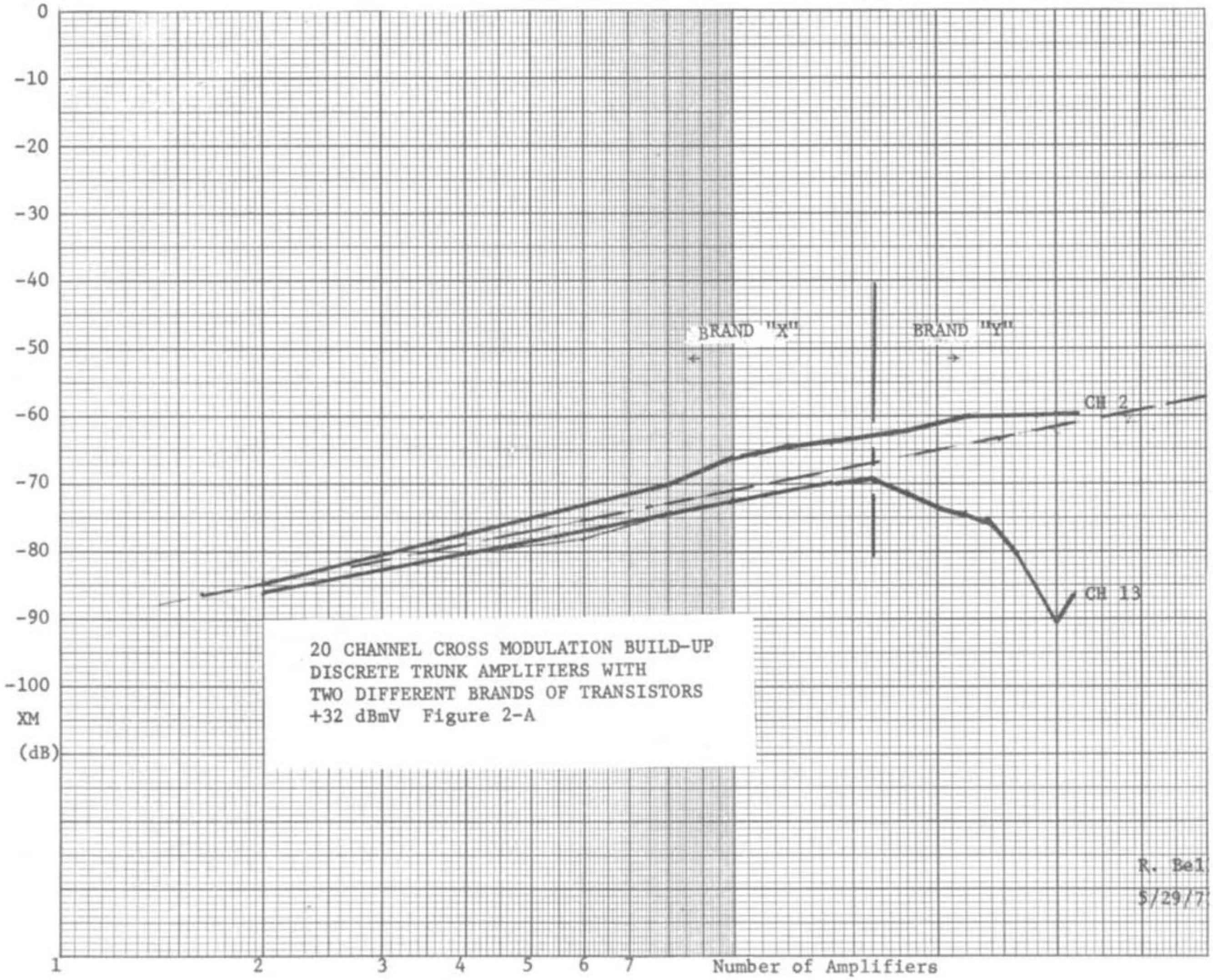
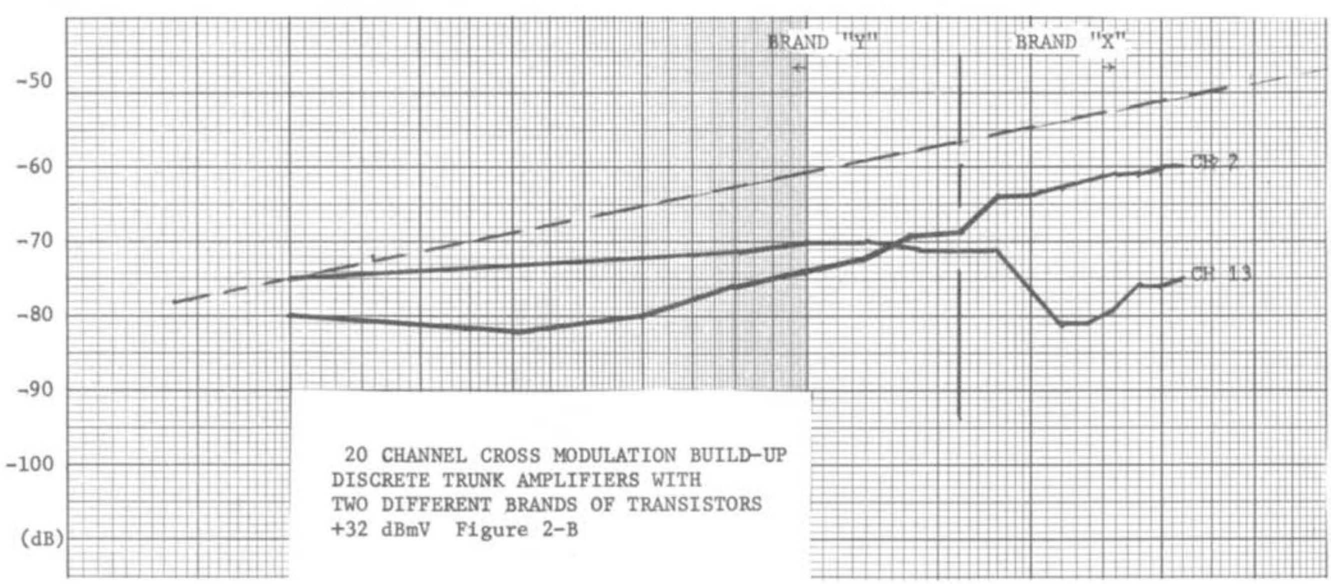


Figure 3. Mainline Amplifier with equalizer and gain-tilt controls.



20 CHANNEL CROSS MODULATION BUILD-UP
DISCRETE TRUNK AMPLIFIERS WITH
TWO DIFFERENT BRANDS OF TRANSISTORS
+32 dBmV Figure 2-A



20 CHANNEL CROSS MODULATION BUILD-UP
DISCRETE TRUNK AMPLIFIERS WITH
TWO DIFFERENT BRANDS OF TRANSISTORS
+32 dBmV Figure 2-B

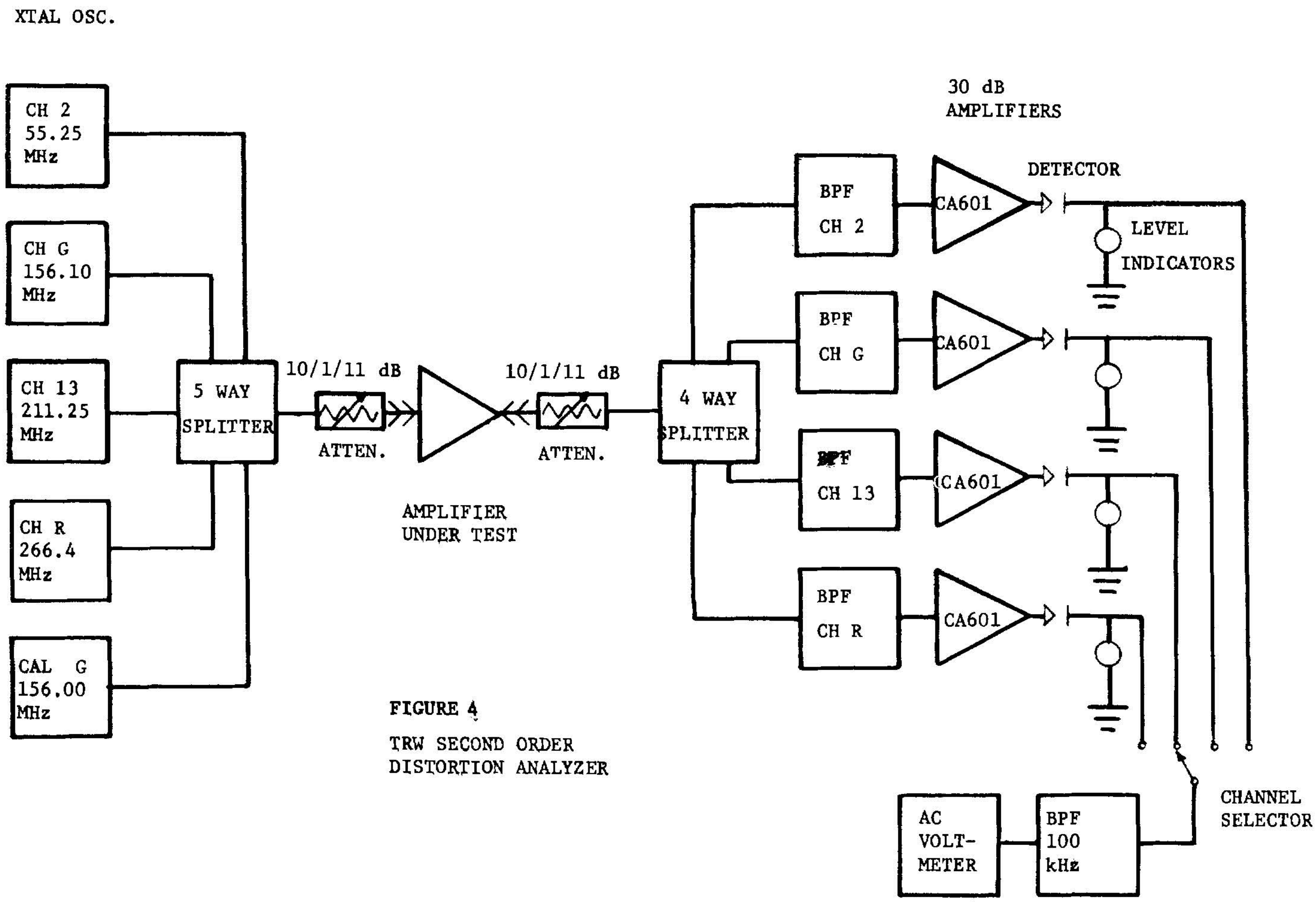


FIGURE 4

TRW SECOND ORDER DISTORTION ANALYZER

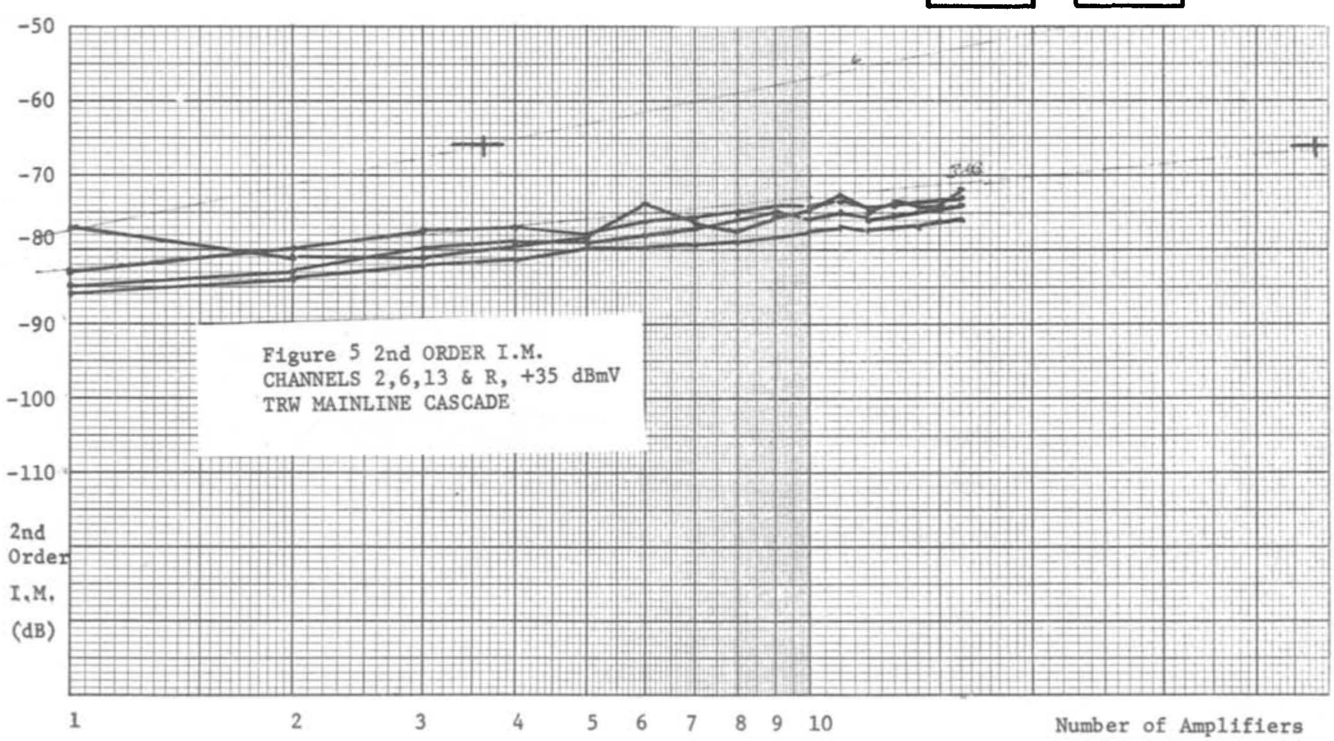


Figure 5 2nd ORDER I.M.
CHANNELS 2,6,13 & R, +35 dBmV
TRW MAINLINE CASCADE

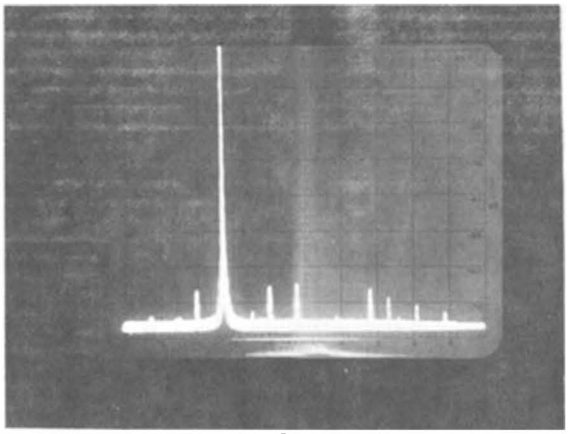


Figure 6. Amplifier No.8

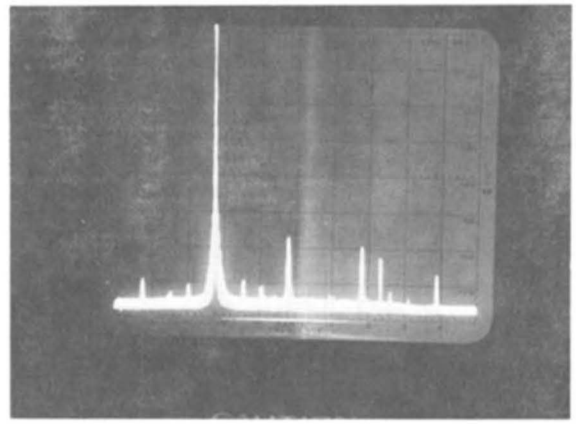


Figure 7. Amplifier No.16

Channel 13 Spectrum, 32 Active Carriers @ +45dBmV
10dB/div. vert., 1MHz/div. Horizontal.

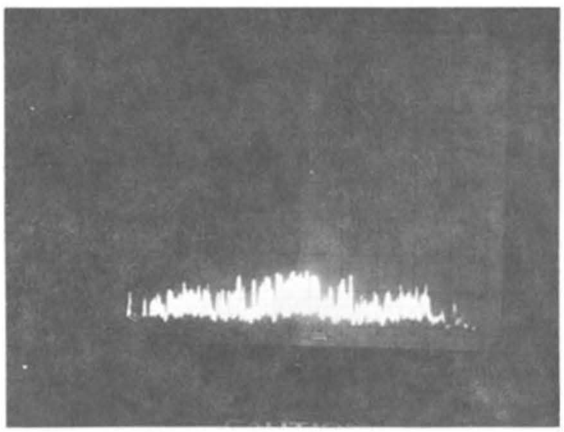


Figure 13. CH2

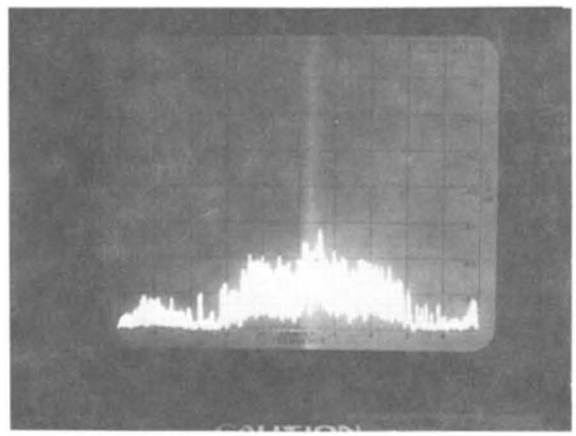


Figure 14. CH13

Beat build-up from 32 carriers @ +45dBmV, Amplifier No.16
10dB/div. vert., 5kHz/div. Horizontal.

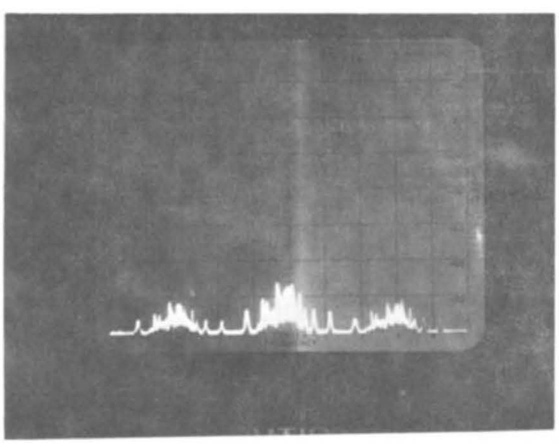


Figure 15. CH2

20 carriers @ +45dBmV

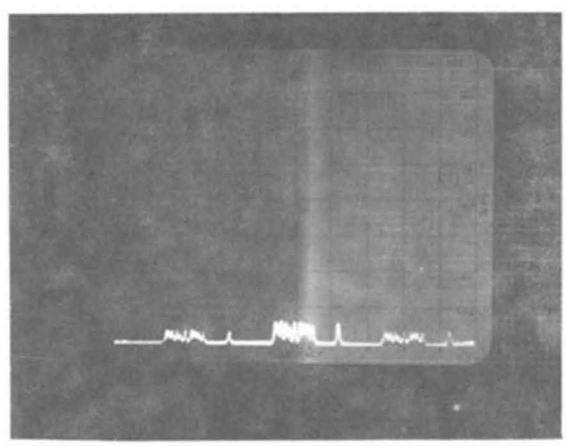


Figure 16. CH2

12 carriers @ +45dBmV

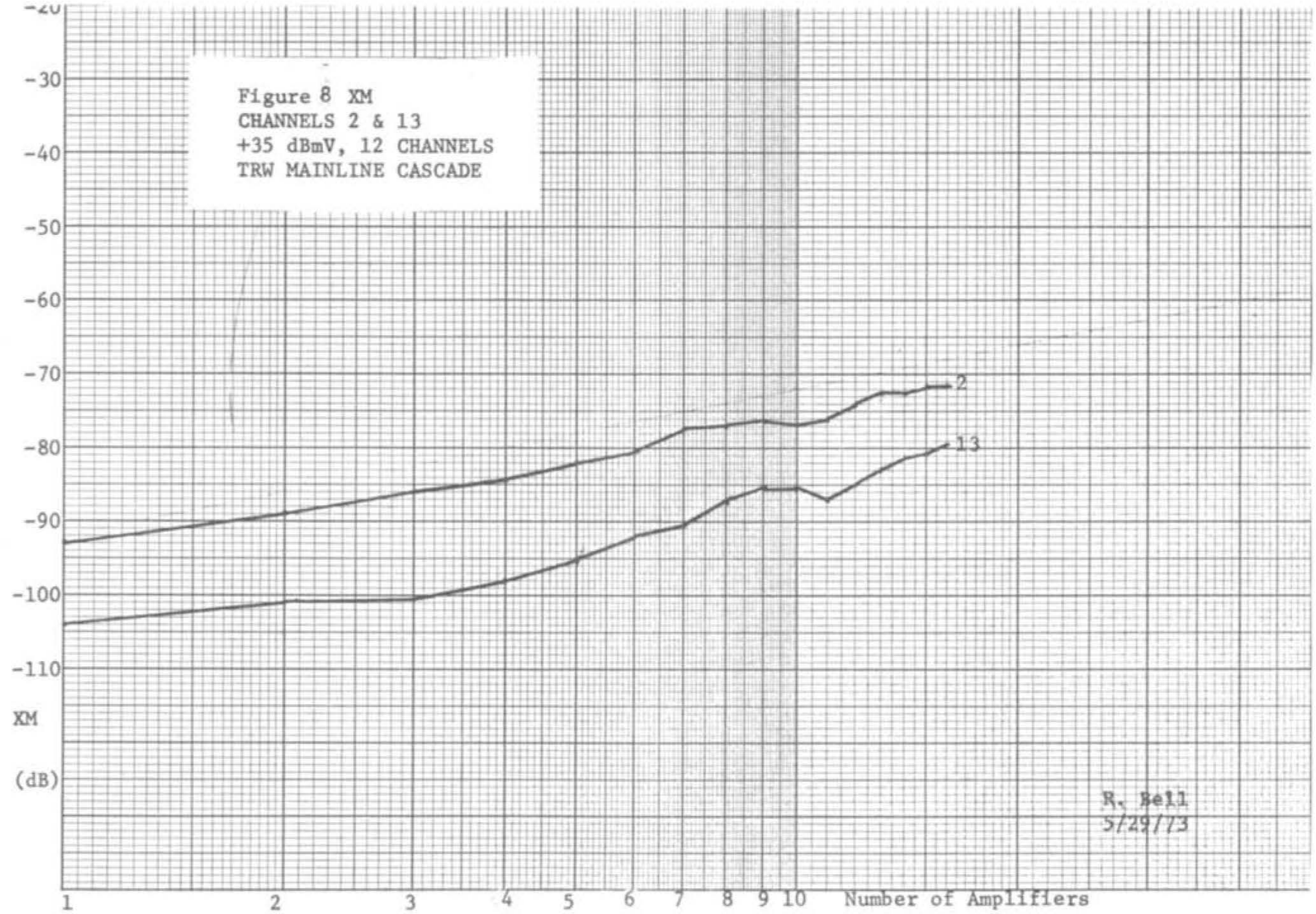


Figure 8 XM
CHANNELS 2 & 13
+35 dBmV, 12 CHANNELS
TRW MAINLINE CASCADE
-30
-40
-50
-60
-70
-80
-90
-100
-110
XM
(dB)
2
13
R. Bell
5/29/73
1
2
3
4
5
6
7
8
9 10
Number of Amplifiers

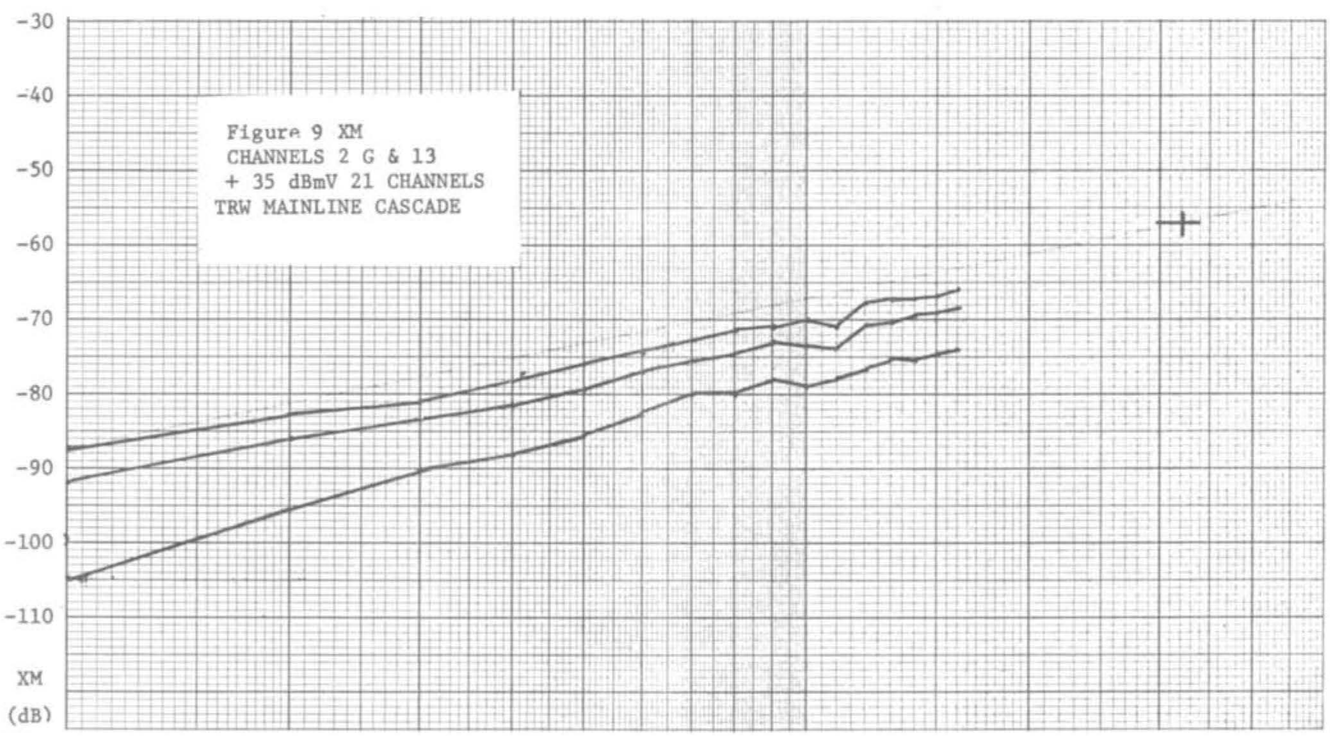


Figure 9 XM
CHANNELS 2 G & 13
+ 35 dBmV 21 CHANNELS
TRW MAINLINE CASCADE
-30
-40
-50
-60
-70
-80
-90
-100
-110
XM
(dB)

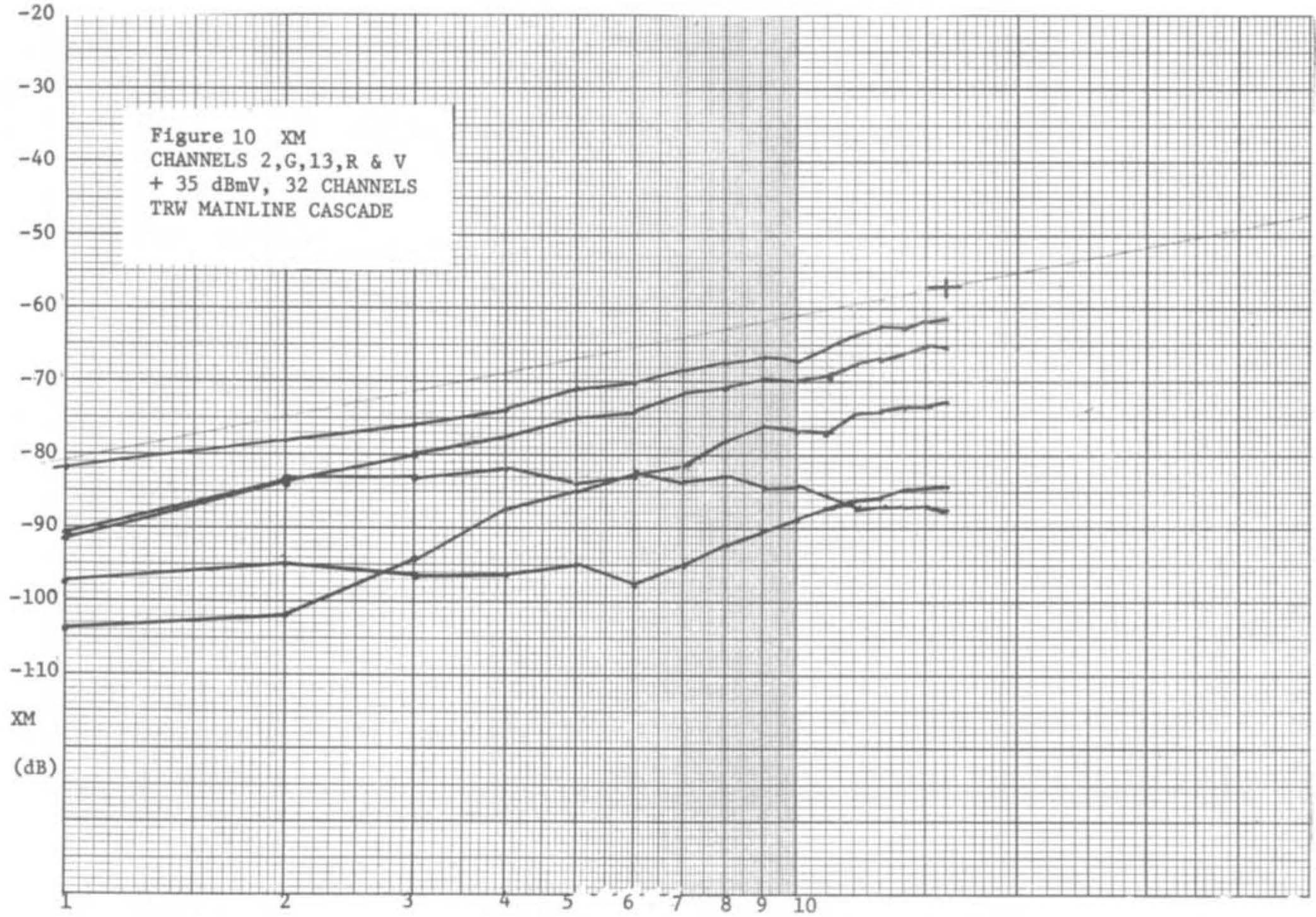


Figure 10 XM
CHANNELS 2,G,13,R & V
+ 35 dBmV, 32 CHANNELS
TRW MAINLINE CASCADE

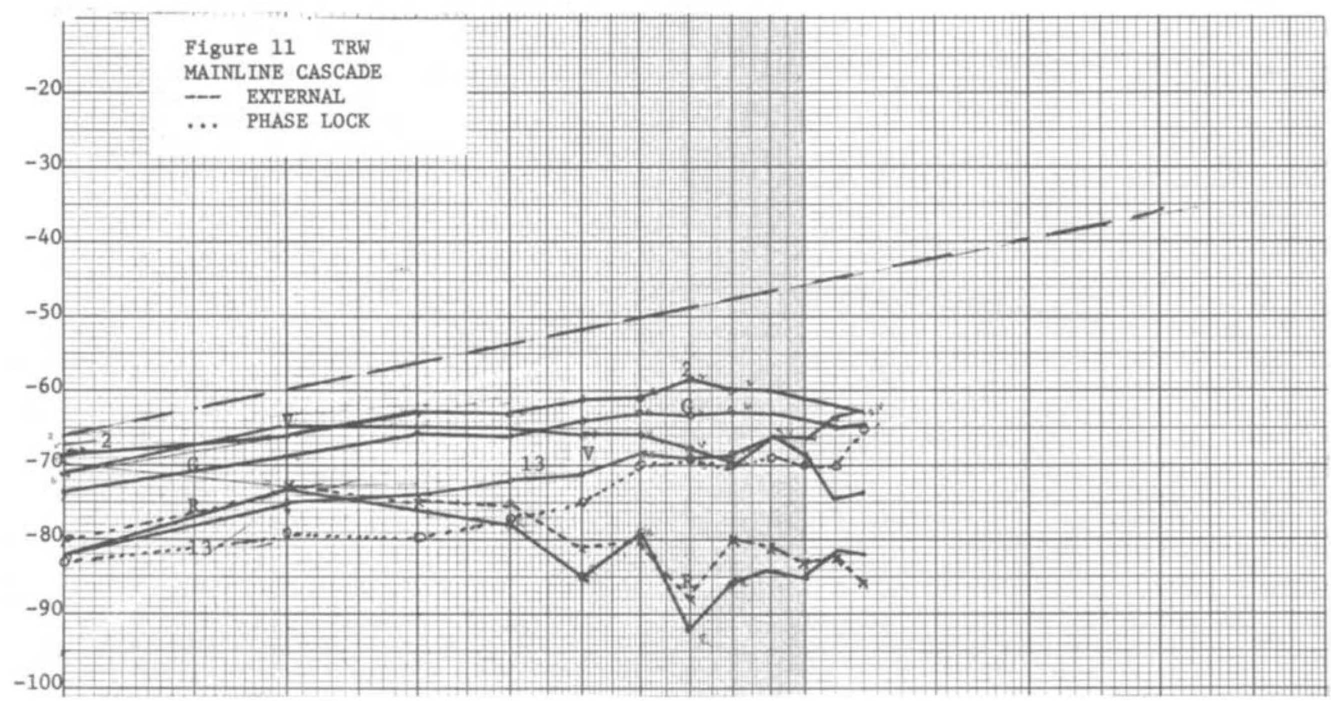


Figure 11 TRW
MAINLINE CASCADE
--- EXTERNAL
... PHASE LOCK

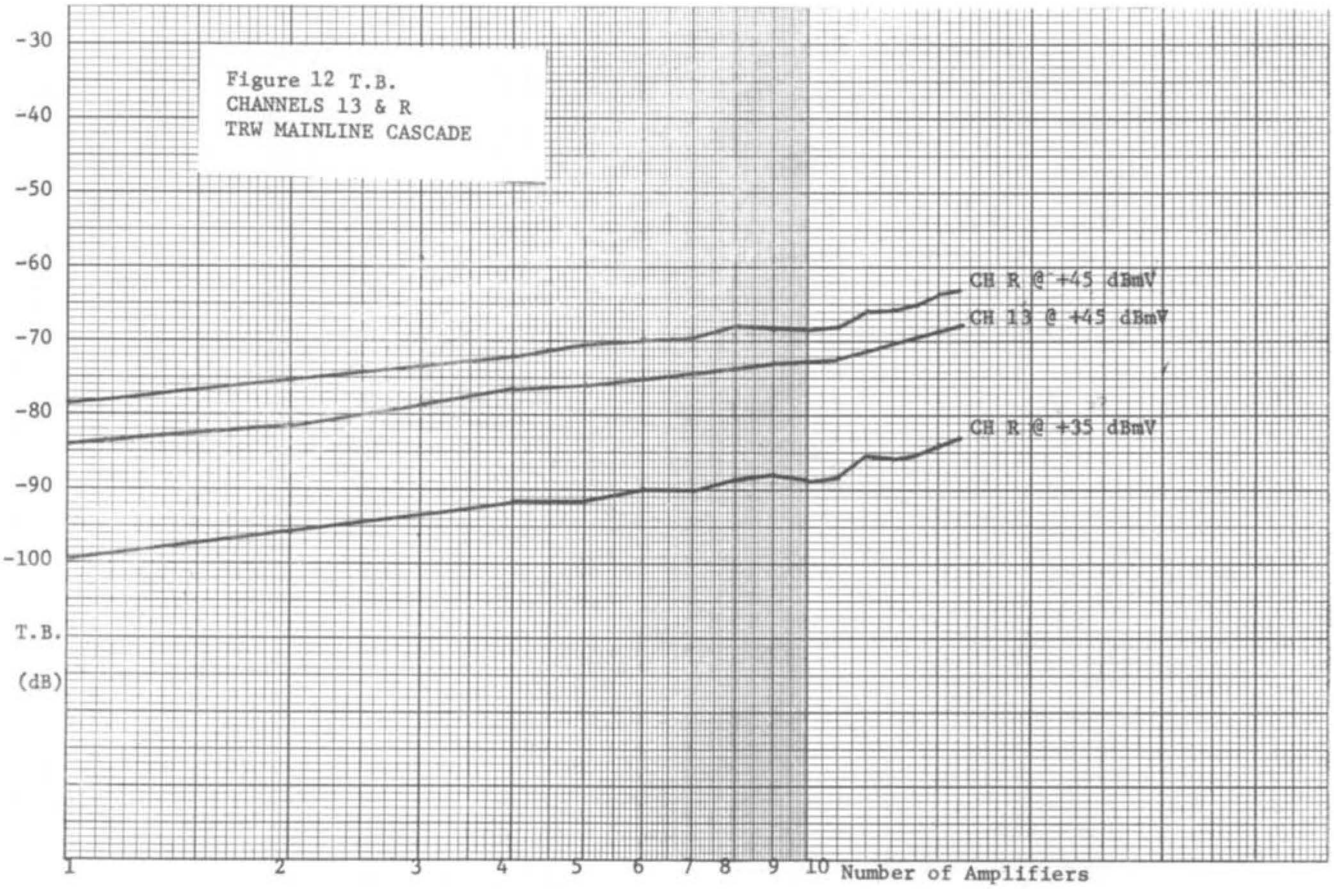


Figure 12 T.B.
CHANNELS 13 & R
TRW MAINLINE CASCADE
CH R @ +45 dBmV
CH 13 @ +45 dBmV
CH R @ +35 dBmV
-30
-40
-50
-60
-70
-80
-90
-100
T.B.
(dB)
1
2
3
4
5
6
7
8
9
10 Number of Amplifiers

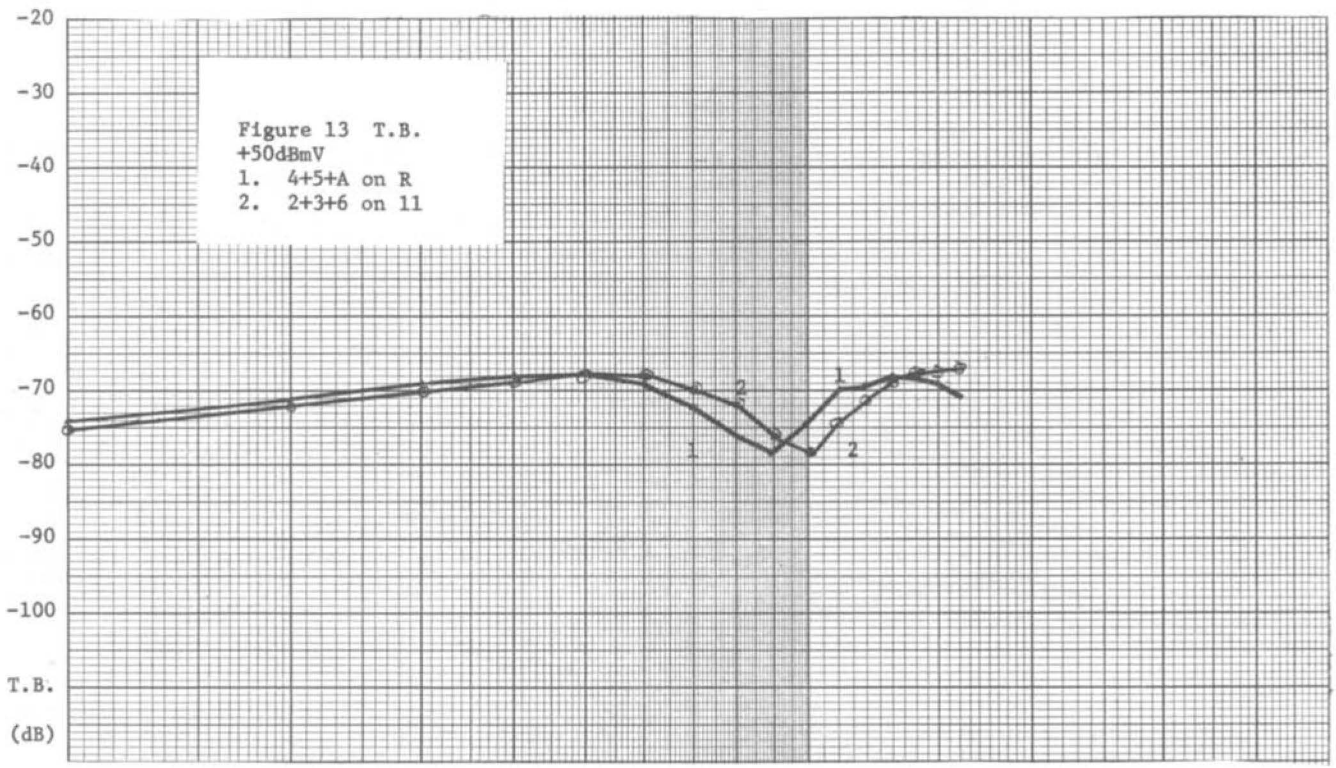


Figure 13 T.B.
+50dBmV
1. 4+5+A on R
2. 2+3+6 on 11
-20
-30
-40
-50
-60
-70
-80
-90
-100
T.B.
(dB)