PHASE PHIDDLING

I. Switzer
Switzer Engineering Services Limited
5840 Indian Line
Mississauga, Ontario, Canada L4V 1G2

HISTORICAL

The system of harmonically related carriers (HRC) used on the St. Catharines system is based on studies begun in early 1970. A paper presented at the June, 1970 convention of the National Cable Television Association, in Chicago, reported on applications of phase lock loop (PLL) technology in cable television. Maclean-Hunter had successfully used PLL techniques to overcome some "direct pick-up" problems in CATV systems. The paper reported these results and speculated on further applications of PLL in CATV. One of the applications considered was the third order intermodulation problem (triple beat) in CATV systems. The paper suggested that PLL techniques could be used to generate carrier systems with uniform spacings. Third order intermodulation products would then be "zero beat" and their visibility would be significantly reduced. Not much was known about the problem at the time and the speculative discussion in the 1970 paper erred on the conservative side in assessing the importance of third order intermodulation in CATV systems. Third order intermodulation has since been shown to be more important in CATV system picture degradation than was suspected in the 1970 paper.

By the summer of 1971 these concepts had been developed at Maclean-Hunter into a more comprehensive system. The importance of third order intermodulation was now more widely and better understood. A paper making firm proposals for coherent carrier systems for CATV was prepared and read to the IEEE Broadcast Group Symposium at Washington, D. C. in September of 1971. This paper proposed coherent carrier systems and concluded with a recommendation for a "Complete System" using harmonically related carriers. This paper, although read to the Washington symposium, was not published and was considered the draft for a more detailed paper which was presented to the National Cable Television Association at their May, 1971, convention in Chicago. At this time there was still no practical experience with coherent systems.

The company was first able to experiment with a set of harmonically related carriers in the Fall of 1972. A twenty channel set of HRC modulators had been built for use as the "base band" in an experimental wide band, multi-channel microwave system. Carriers ranged from 6 MHz to 120 MHz. Laboratory tests with this set of TV carriers confirmed expectations with respect to suppression of visibility of intermodulation beats but raised some questions about the amount of cross modulation in an HRC system. This led to the writing of an unpublished paper "SUPERPOSITION OF COHERENT CARRIERS" in the fall of 1972. This paper suggested that prudent control of the relative phase of coherent carriers at the head end would result in reduction of overall distortion in a broad band CATV system. The harmonically related carriers were considered as the solution of a Fourier analysis problem. The repetitive waveform resulting from the superposition of these harmonically related carriers could have high peak-to-peak excursions of amplitude or the peak-to-peak amplitude could be reduced even though the RMS value of the composite repetitive waveform remained constant.

An attempt was made to obtain an analytical expression for optimum phase relationships for minimum peak-to-peak amplitude. Assistance was obtained from mathematicians at Rand Corporation. No analytical solution could be found. Literature searches subsequently confirmed the probability that analytical expressions were probably too difficult. One of the Rand computers was programmed to explore optimum phase relationships and some usefull tabulations were obtained.

At this time Maclean-Hunter had formed a partnership with California interests to establish a company to design and manufacture equipment for CATV "head-end" application. Both conventional and "coherent" type products were developed and marketed.

By September 1973 about twelve HRC systems had been built and installed in CATV systems in the United States. These installations were made to facilitate PAY-TV experiments which needed mid-band transmission capacity in CATV systems which had excessive second order distortion. Use of HRC head-ends enabled use of mid-band channels without time consuming and costly system amplifier replacement. Maclean-Hunter felt that an experiment under Canadian conditions and control was desirable and consequently installed an HRC system at St. Catharines, Ontario, beginning HRC operation on August 28th, 1973.

This paper reports experience with the St. Catharines system.

EXPERIENCE

The St. Catharines system at this time is carrying twenty television channels and two pilot carriers (Table 1).

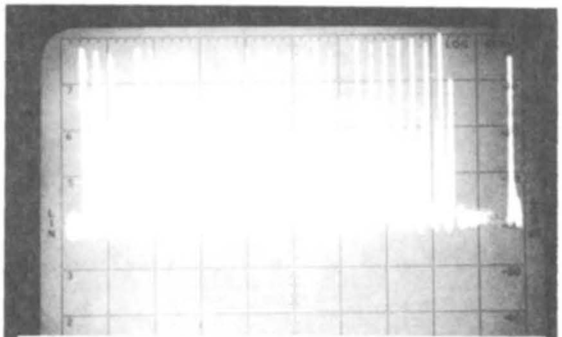


FIGURE I Spectrum Analyzer Display
Head-End 20MHz/div BW 300 KHz

The visual carriers and pilot carriers are derived by phase-locking to the selected component of a harmonic comb generated by a 6 MHz pulse generator. The pulse generator is driven by a crystal controlled oscillator.

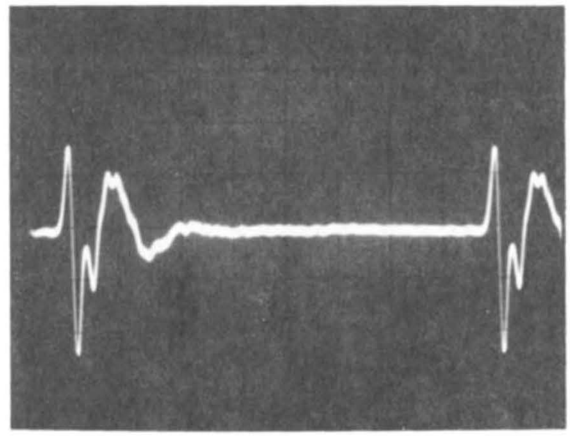


FIGURE 2

6 MHz pulse displayed on HP-183 oscilloscope with 250 MHz vertical amplifier

.02 usec/div 0.1 volts/div

TABLE 1

Channel	Visual Carrier MHz	Harmonic (N)	Nominal Deviation from Broadcast Freq.
2	54.000	9	- 1.25 MHz
3	60.000	10	- 1.25
4	66.000	11	- 1.25
PILOT	72.000	12	
5	78.000	13	+ .75
6	84.000	14	+ .75
A	120.000	20	
B	126.000	21	
C	132.000	22	
D	138.000	23	
E	144.000	24	
F	150.000	25	
G	156.000	26	
H	162.000	27	
7	174.000	29	- 1.25
8	180.000	30	- 1.25
9	186.000	31	- 1.25
10	192.000	32	- 1.25
11	198.000	33	- 1.25
12	204.000	34	- 1.25
13	210.000	35	- 1.25
PILOT	240.000	40	

+ FM radio carriers

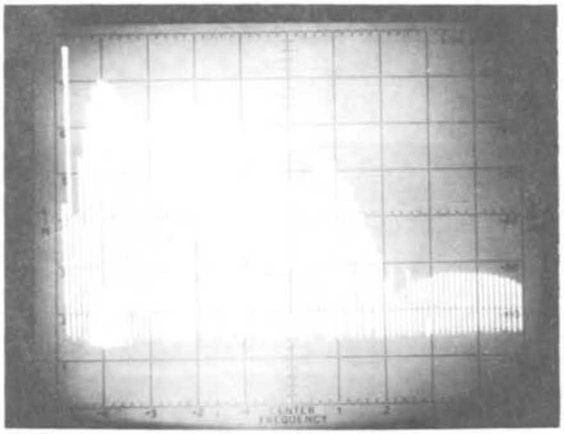


FIGURE 3

Spectrum of 6MHz pulse 50 MHz/div BW 100KHz
level ref + 42 dbmv

The "coherency" of the carriers can be observed by displaying the "synchronizer pulse", i.e. the controlling 6MHz pulse and individual system carriers on a suitable dual channel, high frequency oscilloscope. The following photographs taken on an H-P 183 oscilloscope with dual 250MHz vertical channels compare individual carriers with the synchronizing pulse. All displays were triggered by the 6MHz synchronizing pulse.

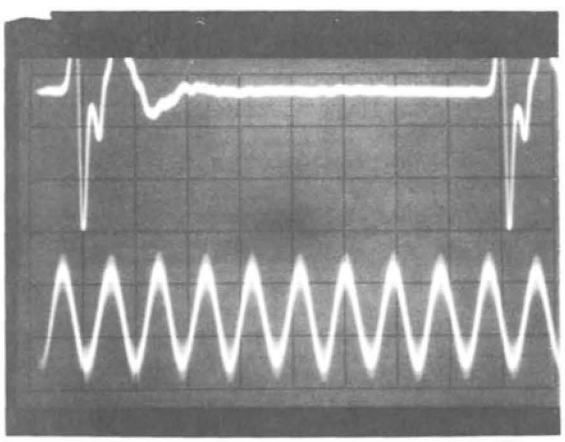


FIGURE 4

HRC Channel 2 .02 usec/div

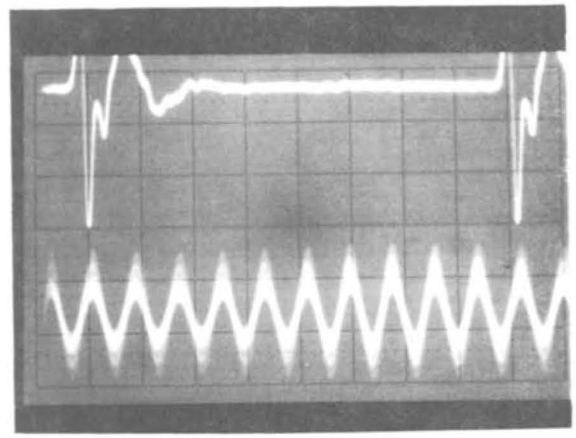


FIGURE 5

HRC Channel 3 .02 usec/div

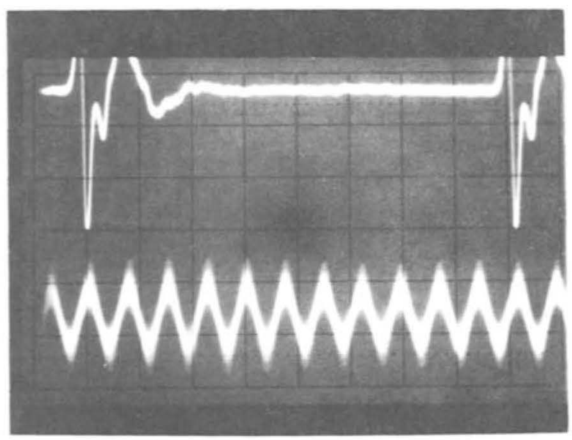


FIGURE 6

HRC Channel 4 0.02 usec/div

As expected, the display of HRC channel 2 shows nine complete cycles of RF carrier in each synchronizing pulse period. Channel 3 carrier shows 10 complete carrier cycles. Similarly channels 4, 72MHz pilot and channel F show N complete carrier cycles, N being the channel harmonic number. Amplitude "jitter" in the carrier traces is due to the amplitude modulation on the carriers.

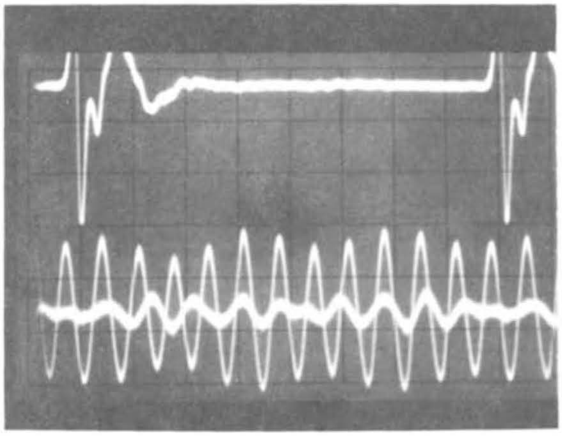


FIGURE 7

HRC Pilot 72 MHz 0.02 usec/div

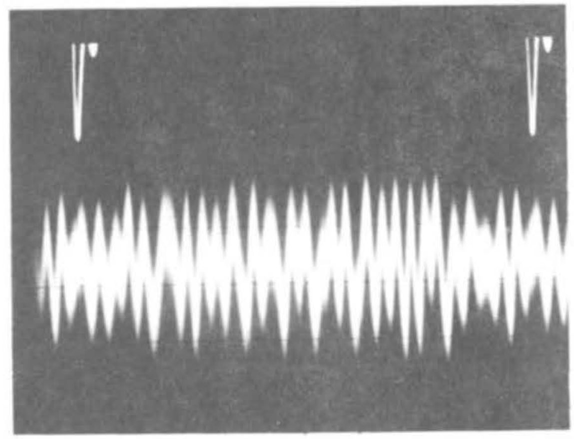


FIGURE 9

0.02 usec/div

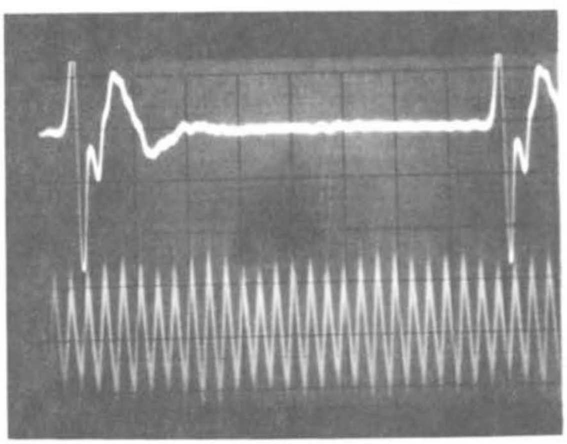


FIGURE 8

HRC Channel F 0.02 usec/div

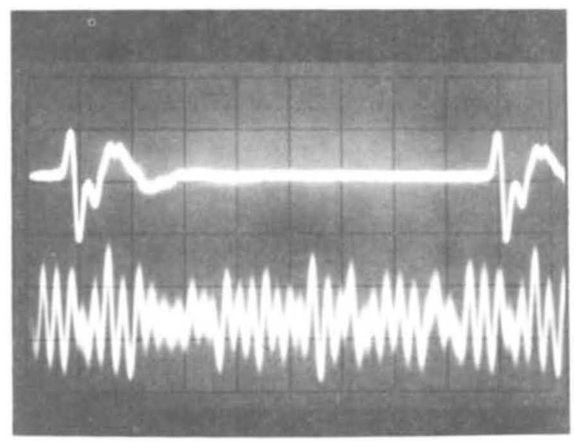


FIGURE 10

0.02 usec/div

Figures 9, 10 and 11 show the composite output of the head end as observed at the head end test point, including all twenty picture channels, two pilot carriers (coherent) and a number (approximately fifteen) FM radio channels. Figure 9 shows a nearly optimum phase relationship between visual carriers. "Peaks" and "valleys" seem evenly distributed within the period of the 6MHz synchronizing pulse. Figures 10 and 11 show less optimum phase relationships between carriers. A more detailed discussion of experiments with the relative phase of carriers will be found later in this report.

PROBLEMS

The major problem that was anticipated was that of expecting receivers to tune the new HRC channels without the use of set-top converters. It was, of course, expected that set-top converters would be used to tune the supplemental channels. Table 1 lists the carrier frequencies used. Most broadcast channels were shifted a nominal 1.25MHz lower. Channels 5 and 6 were shifted 0.75 MHz high.

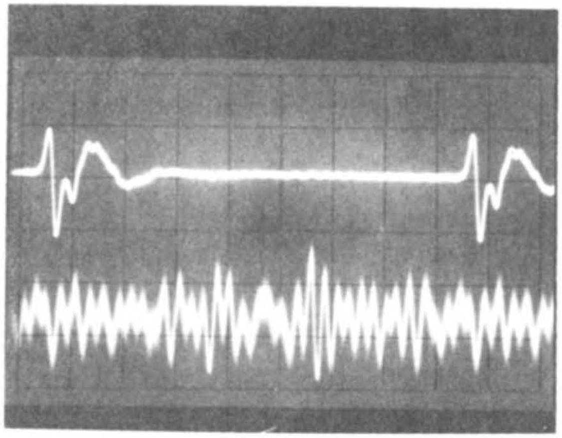


FIGURE 11

0.02 usec/div

Experience in American systems that had converted to HRC indicated that about 20% of subscribers would be unable to readjust their own fine tuners and would require assistance from the cable company. American experience also indicated that only about 1% of all receivers would lack sufficient fine tuning range to accomodate the new carriers. The changes were extensively advertised in the newspapers and in a special mailing to all subscribers with detailed explanations on the fine tuner changes required. A videotape showing a typical tuner arrangement was shown frequently on the community service channel (channel 8) on cable.

Switch-over to HRC channels on August 28th, 1973, still required a very large number of service calls. Additional staff had been brought in from other CATV systems and staff worked overtime to make service calls to help subscribers readjust their fine tuners. Set-top converters were provided on a loan basis for those subscribers whose receivers would not retune to the new channels. Most receivers had sufficient fine tuning range. Some receivers required adjustment of fine tuner range with a tuning tool through the front of the receiver. A very small number (less than 100) of receivers were readjusted in this way. It should be borne in mind that the St. Catharines system has about 14,000 subscribers.

The direct-pick-up problem was seriously underestimated. Some problem had been anticipated since St. Catharines is only about 30 miles from a maximum parameter station on channel 11+. This proximity had caused some marginal direct pick-up problems with conventional operation but the situation had not been considered serious. With HRC operation the direct pick-up was no longer coherent but was 1.26MHz into the HRC channel, i.e. 1.260MHz above the HRC-11 carrier. We have since determined that this beat has a threshold about 15 db less favourable than the coherent beat (worst case). After most subscribers receivers had been retuned for HRC channels the direct pick-up problem remained the most serious problem. A very few receivers, particularly succeptible to direct pick-up, showed some direct pick-up beat on other channels as well, notably on channels 7 and 9, both about 40 - 45 miles distant. This number was very small and has not been considered significant at all.

The initial approach to the direct pick-up problem on channel 11 has been to "unlock" HRC channel 11 and shift it slightly to take advantage of the "interlace" provided by "channel offset". The visibility of the direct pick-up beat was reduced about 10 db my moving HRC-11 so that the pick-up beat fell halfway between H sidebands. The 1.260MHz beat falls just above the 80th H sideband of the HRC-11 carrier. The HRC carrier was shifted slightly downward so that the beat fell halfway between the 80th and 81st H sidebands. This required a shift of about 6.6KHz. The adjustment was made visually for minimum visibility of beat. At first this was not completely effective since there was considerable direct leakage of channel 11 into the cable system. Sources of leakage were found and corrected and this leakage has been held to a minimum. Figure 12 shows the extent of this leakage and shows the offset of HRC-11.

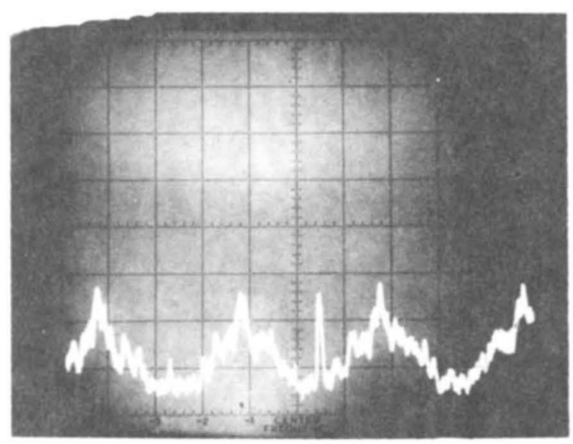


FIGURE 12

Leakage of channel 11 into system 5KHz/div BW 300Hz video filter 10Hz level reference HRC-11 carrier

This spectrum analyzer photograph was taken at the cable system office. The offset is only approximate due to drift of the "unlocked" HRC-11 carrier. The leakage into the system at this point is about 54 db below desired carrier level. HRC-11 frequency was subsequently adjusted to more optimum "mid-point".

The "unlocked" operation of HRC-11 causes a few undesired beats in the system. Figure 13 shows HRC-4 observed at the same location showing beats due to the HRC-11 offset. These beats disappear when HRC-11 is locked to the synchronizing comb.

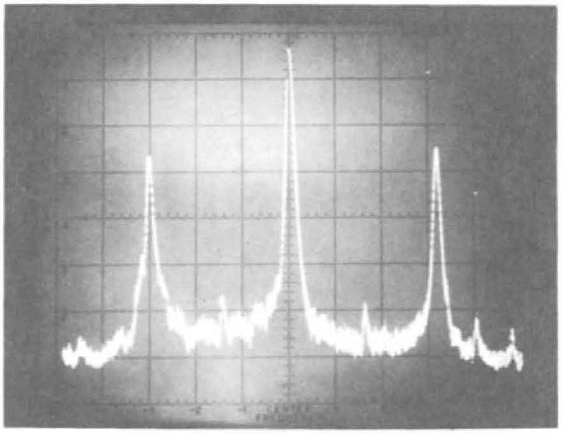


FIGURE 13

HRC-4 showing beats from "unlocked" HRC-11
5KHz/div BW 300Hz video filter 10Hz

At the time of the installation of the St. Catharines HRC system we had devised a solution for the direct pick-up problem from channel 11 which involved locking the system to the channel 11 transmitter. It was not possible to get the necessary equipment designed and constructed in time for the St. Catharines test and the risk of direct pick-up had to be accepted.

A system for relieving this direct pick-up problem has been devised and is being engineered and constructed for installation in St. Catharines within the next few months: -

Limited PLL lock-in range does not allow shifting the synchronizing pulse frequency to cause the direct pick-up beat to fall midway between H scan lines. A special phase-lock loop is being built to cause the beat to fall midway between V scan lines, as follows:-

For colour television the following "standards" apply:

Colour subcarrier	=	3.579545 MHz
H = C/455 X 2	=	15734.26374 Hz
V = H/525 X 2	=	59.94005 Hz

Midway between H sidebands would require beat to be:

$80\frac{1}{2}$ H = 1.2666082 MHz

This requires a shift of about 6KHz in HRC carriers and would require new VCXO's in all signal processors. The nearest beat frequency which falls halfway between V sidebands is:

80 H + $21\frac{1}{2}$V = 1.26002981 MHz

This requires only a 30Hz shift and will not affect the present VCXO's. A phase lock loop will control the 6MHz synchronizing oscillator so that the beat between HRC-11 and the broadcast channel 11+ will always be 1.26002981MHz with a tolerance of +- 0.1Hz. Effectiveness depends on the stability of the colour synchronizing generator at the channel 11 broadcast station but this is considered to be a good quality generator. The channel 11 transmitter has been observed, however, to drift +- 40Hz within a period of a few minutes. This suggests that a precise offset operation requires locking our master oscillator so that the beat between the two carriers (broadcast 11+ and HRC-11) is maintained at a very precise frequency relative to the line scanning frequency. It is expected that this system will allow coherent operation of HRC-11 with minimum direct pick-up problems.

Alternative Technique for Controlling "Direct Pick-Up" at St. Catharines

The technique we would have preferred to use to reduce direct pick-up at St. Catharines would be to lock the HRC-11 channel to the local broadcast channel 11. The HRC carriers need not be harmonics of precisely 6.000000MHz. The fundamental frequency may vary somewhat as long as the system carriers remain harmonics of the fundamental. Variations from 6.000000MHz merely affect the spacing between channels, most importantly the spacing between lower adjacent sound and the next higher visual carrier.

In this case it would be helpfull if the fundamental frequency was adjusted so that its 33rd harmonic (HRC-11) co-incided with the local broadcast channel 11. In fact the fundamental master oscillator would be derived by locking an oscillator to the local channel 11 and then counting down, digitally, to obtain the master fundamental frequency. Since the local channel 11 is actually channel 11+, nominally 199.260MHz, the master oscillator would be 199.260/33 = 6.038182MHz. This oscillator frequency would be floating up and down as the local channel 11+ transmitter shifts in frequency around its nominal assigned frequency. Table II lists the HRC carrier frequencies in this case and their deviations from nominal broadcast frequencies.

Note that the high band channels are quite close to nominal broadcast frequencies. Channel 11 is identical and locked to a local broadcast channel. The other high band channels are within 150KHz of nominal broadcast channels, well within fine tuning and AFT ranges on virtually all receivers. The low band channels are improved for channels 2, 3 and 4, but channel 6 may have more problems since it is shifted up in frequency toward any FM traps that may be present in the RF stage of the receiver tuner.

TABLE II

Channel	Visual Carrier MHz	Harmonic (N)	Nominal Deviation from Broadcast Freq.
2	54.344	9	- 906 KHz
3	60.382	10	- 868
4	66.420	11	- 830
5	78.496	13	+ 1246
6	84.535	14	+ 1285
A	120.764	20	
B	126.802	21	
C	132.840	22	
D	138.878	23	
E	144.916	24	
F	150.955	25	
G	156.993	26	
H	163.031	27	
I	169.069	28	
7	175.107	29	- 143
8	181.145	30	- 105
9	187.184	31	- 66
10	193.222	32	- 28
11	199.260	33	0
12	205.298	34	+ 48
13	211.336	35	+ 86
J	217.375	36	
K	223.413	37	

etc........

The spacing between lower adjacent sound and desired visual carrier becomes 38KHz greater than nominal. A broadcast situation might have a - offset channel adjacent to a + offset and allowing for the 1KHz tolerances allowed in visual and intercarriers might have this spacing at 23KHz greater than nominal 1.500MHz. This 38KHz increase is an additional 15KHz. This might reduce the effectiveness of adjacent channel traps in some receivers. Our experience is that this effect is not significant and that this not a practical obstacle to implementation of this channeling variation. Many cable systems already have adjacent channel sould spacings of greater than 1.523 MHz due to inaccuracies in their carrier frequencies on cable. These inaccuracies usually occur in UHF channels being converted to VHF channels for cable distribution. Local oscillators of 600MHz or so are quite common in UHF to VHF conversions and a 30KHz error represents only .005% and many of the local oscillators used in cable systems do not meet .005% tolerance. The new FCC standards require tighter tolerance but the fact is that systems have operated with rather slack tolerances for many years, and it may turn out that .005% tolerances are difficult to achieve in UHF conversions. We deliberately introduced a 1.538MHz adjacent spacing into a pair of the channels on the Maclean-Hunter Cable system and could find no evidence of increase in adjacent channel interference problems on these two channels during a test period of several months.

The direct pick-up problem is less serious in a system which uses converters on all channels. Such a system has no practical problem in tuning HRC channels since all the set-top converters we have seen can easily be adjusted to HRC channels instead of broadcast channels. Such a system should also be immune from direct pick-up problems and operation on either broadcast or HRC channels would require maintenance of a high degree of system integrity. In such cases there would seem to be little effect on the subscriber from system use of HRC channels, and the cable system might prefer to use a system based on a precise 6.000MHz master oscillator.

SYSTEM PERFORMANCE

Rigorous system performance measurements are still being made, but some preliminary measurements are available. These measurements were made at the system office, which is about 2/3 of the way along the maximum system extension. The transportation trunk from the head end to the beginning of distribution had been replaced with push-pull amplifier equipment (20 amplifiers in cascade). The remaining route to the office consists of nine trunk amplifiers, a bridging amplifier and four line extenders, all single ended design. The distribution amplifier within the office is push-pull design, conservatively operated.

Some systems performance measurements made on January 25th: (Cable Office, 45 Wright Street)

Noise: Figure 14 shows system noise as observed at the office. Channel 3 was chosen as a convenient test channel. The Global TV network is distributed on this channel and since its programming does not start until late afternoon, the standby carrier on this channel could be used as a test carrier.

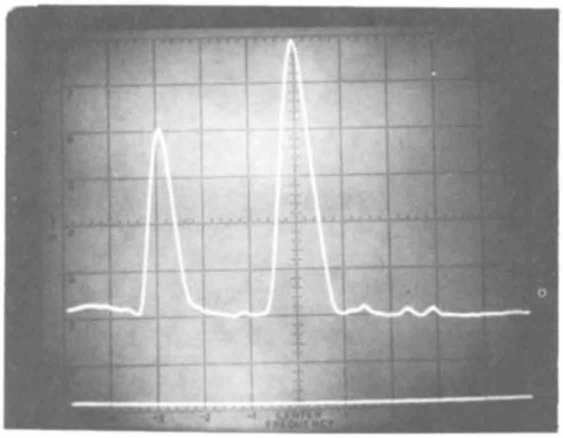


FIGURE 14

500 KHz/div BW 100KHz video filter 10Hz
Standby carrier on Channel 3 showing channel 2 sound. Double exposure shows spectrum analyzer noise level

Noise measurements were made with the spectrum analyzer. The noise bandwidth for the 100KHz IF filter had been measured using Hewlett-Packards recommended technique. Correction factor, including factor for detector and logarithmic display was calculated to be +18 db for the particular analyzer used. An IF bandwidth of 100KHz was used with a video filter of 10Hz (10,000 X) to give effective averaging of noise. Figure 15 shows the smoothness of noise display around the channel 3 standby carrier. Standby carrier had been adjusted for same peak carrier level as normally modulated carrier. This photo indicates carrier/noise ratio of 60 db displayed, correcting to 42 db for 4MHz noise bandwidth. Similar measurements at other parts of the spectrum show C/N ratios of from 44 db near channel 2 to about 41 db in mid-band to about 40 db in the high band.

Beats: Control of undesired beats is one of the main features of HRC operation. Figures 15 and 16 show the channel 3 standby carrier and the beats at this portion of the spectrum when the channel 3 standby carrier is removed from the system.

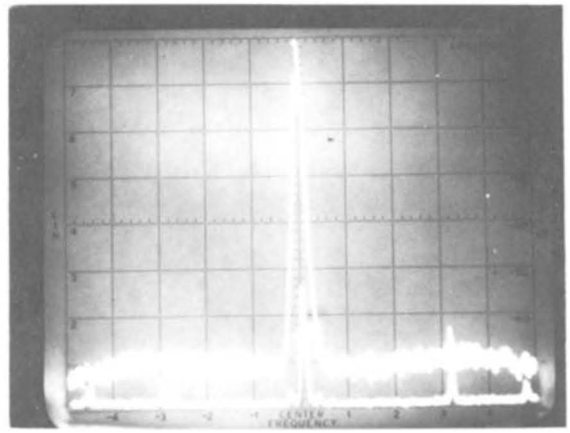


FIGURE 15

Channel 3 standby carrier (all channels coherent)
5KHz/div BW 300Hz video filter 10Hz
Double exposure showing beats present when carrier removed

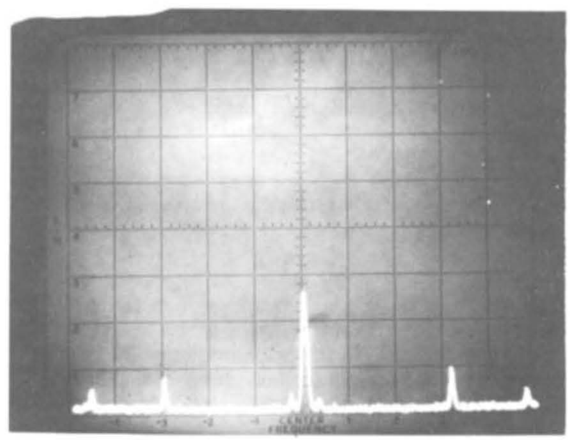


FIGURE 16

As in Figure 15 but showing beats only
(Channel 3 standby carrier removed)

The beats in Figures 15 and 16 arise from second order and third order causes. Because of the coherency of the system all the beats are co-incident and only the resultant sum of all the beats is observed. Phase cancellations of beats does occur. The observed resultant beat is 54 db below desired visual level and is, of course, at visual carrier frequency. The H sidebands, which are effectively cross-modulation, can be seen only when the channel 3 carrier is removed since they are at a level just below the noise in most observations.

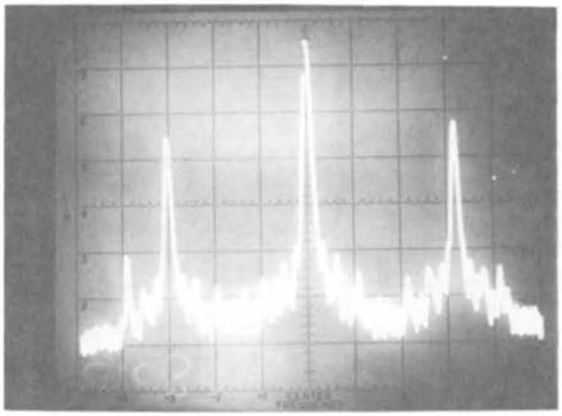


FIGURE 17

Normally modulated channel 3 (Global 6+)
5KHz/div BW 300Hz video filter 10Hz
Ref level adjusted for peak carrier showing H sidebands and -20KHz co-channel interference

Figure 17 shows that normal H sidebands are typically about -24 db relative to peak visual carrier. Observed H sidebands with carrier removed seem to be about 70 db below peak visual carrier indicating a cross modulation ratio of about 46 db. No cross modulation coult be visually observed in the pictures at this point. Figure 17 also shows an unwanted co-channel carrier (originated as channel 6-) at about 50 db below desired peak visual. This level of co-channel interference was not visible in the pictures.

Figures 18 and 19 show the beats with a different phase arrangment at the head end. Figure 20 shows still another phase arrangement. Note that the level of beat has changed due to differing phase cancellation.

The cross modulation produced H sidebands could hardly be distinguished in the channel noise when observing the standby carrier so an attempt was made to improve this observation. The first lower H sideband was selected and maximum spectrum analyzer resolving power and "signal averaging" using the oscilloscope screen storage was attempted. A tunable preselector and amplifier were used to improve the spectrum analyzer noise figure and the spectrum analyzer gain was raised 20 db from previous observations. The H sideband can just be distinguished at about -50 db on the display, indicating -70 db from peak visual carrier, or equivalent to about -46 db cross-modulation.

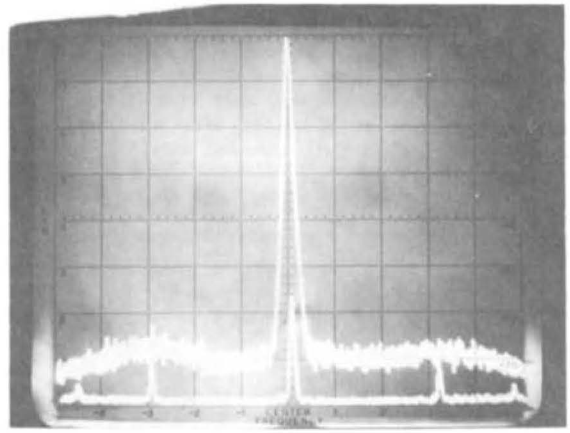


FIGURE 18

Double exposure with and without channel 3 standby
5KHz/div BW 300Hz video filter 10Hz

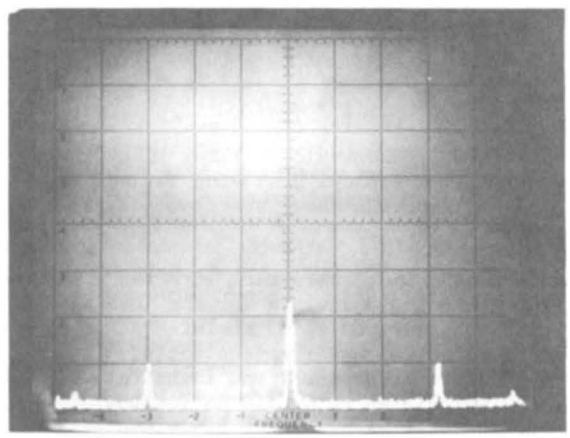


FIGURE 19

As figure 18 but single exposure - beats only

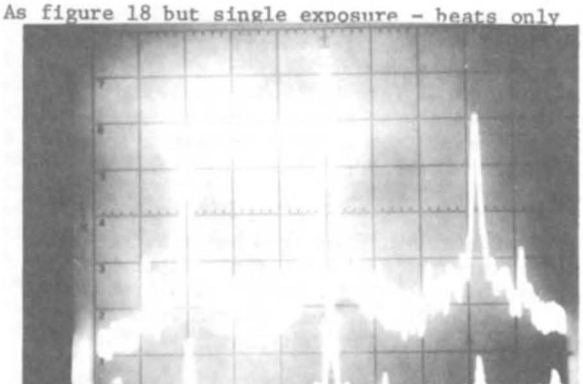


Figure 20 Double Exposure showing beats when channel 3 removed 5KHz/div BW 300Hz video filter 10Hz Carrier phases altered from Figures 18/19

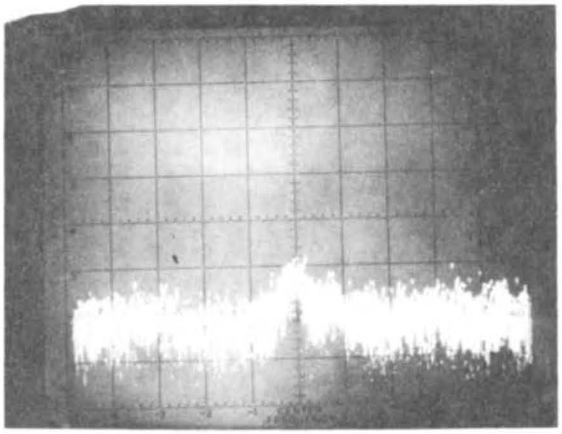


FIGURE 21

Lower H sideband channel 3 standby carrier
20Hz/div BW 10Hz video filter 10Hz
integrated by storage CRT

Intermodulation:

The systems freedom from intermodulation beats around the visual carriers was demonstrated by observing the channel 3 standby carrier with increasing resolution and decreasing dispersion. Figure 22 shows low level intermodulation products due to channel HRC-11 being non-coherent.

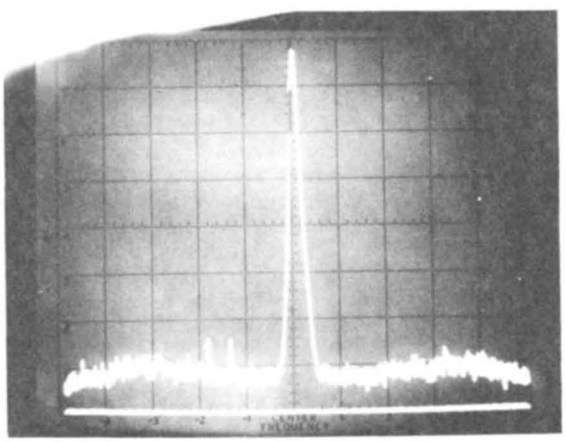


FIGURE 22

5 KHz/div BW 300Hz video filter 10Hz

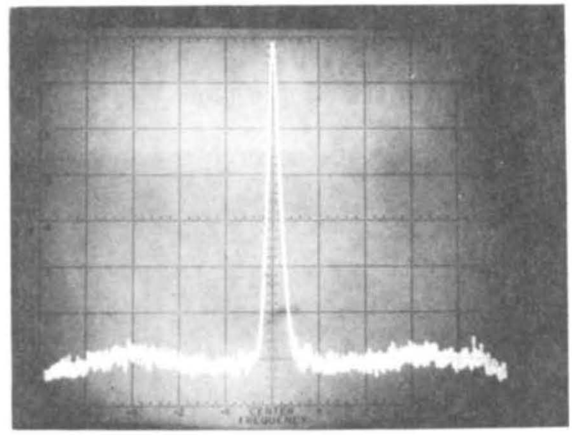


FIGURE 23

5 KHz/div BW 300Hz Video Filter 10Hz

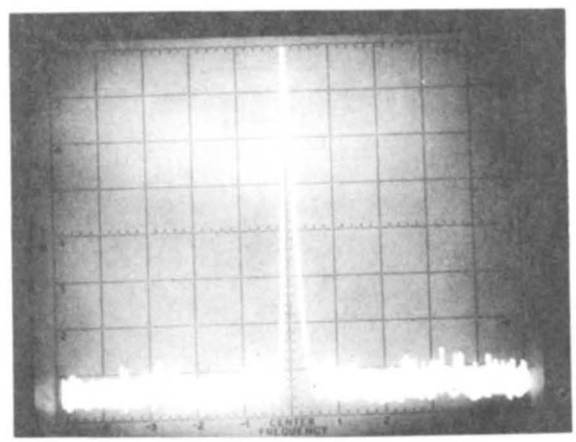


FIGURE 24

2 KHz/div BW 100Hz Video Filter 10Hz

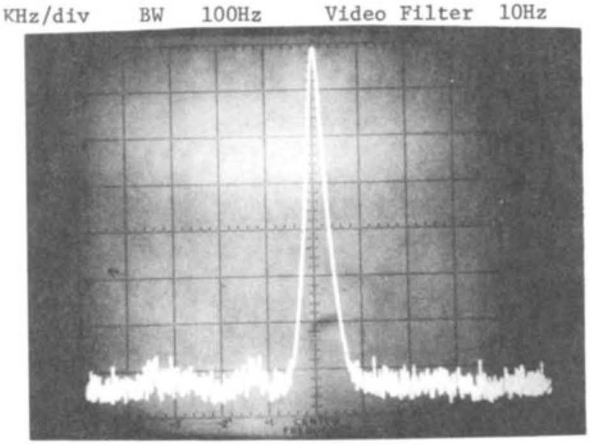


FIGURE 25

1 KHz/div BW 100 Hz Video Filter 10Hz

Locking reference (6MHz synchronizing comb) was then disconnected so that all visual carriers were non-coherent. Figure 26 shows that the channel 3 standby carrier has moved about 1.5KHz and several intermodulation beats appear.

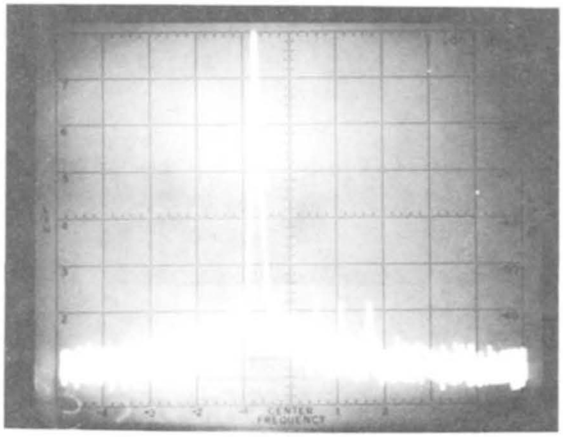


FIGURE 26

2KHz/div BW 100Hz Video Filter 10Hz

The channel 3 standby carrier was then removed and the beats examined in greater detail, Figure 27

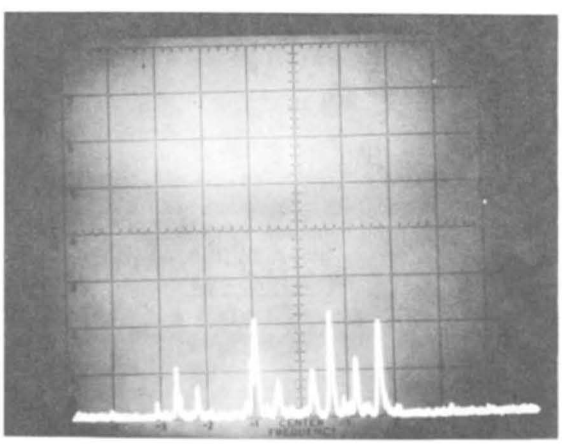


FIGURE 27

2KHz/div BW 100Hz Video Filter 10Hz

Hum Modulation:

Although not the subject of this particular discussion hum modulation was observed in terms of hum modulation sidebands on the channel 3 standby carrier. These are shown in Figure 28. Hum modulation appears to be about 1%.

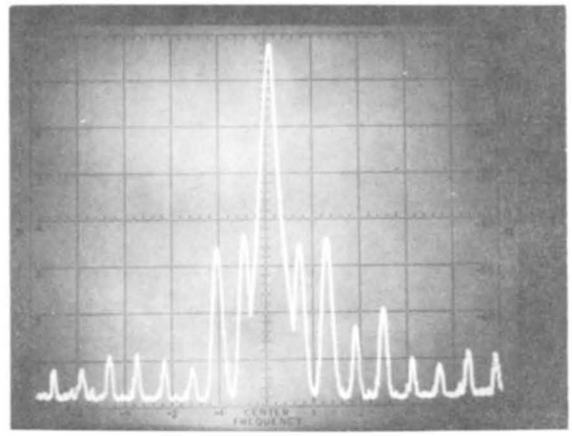


FIGURE 28

100Hz/div BW 10Hz Video Filter 10Hz

"Phase Phiddling"

A cable television system is a "very nearly linear system". The slight non-linearities give rise to intermodulation and cross modulation effects. The effect of the harmonic relationship of the carriers is to make intermodulation products zero-beat and therefore reduce the visibility of these non-linear effects. The high degree of linearity means that we can consider that the carriers in the system are "superposed", i.e. that they add algebraically in such a linear system. We can therefore consider that the simultaneous carriers can be considered as adding to give a sum waveform that can be displayed on an oscilloscope or oscillograph. In a non-coherent system the phase relationships of the carriers are quite random and the sum waveform is quite "random". There is no repetition of any particular waveform and an oscilloscope shows a "jumble". There is a high probability that voltage addition of all the carrier amplitudes could occur, although the power in the system at any point in time cannot exceed the sum of the power present in the individual carriers.

The superposition (addition) of coherent carriers can be considered to be the inverse of Fourier analysis - a sort of Fourier "synthesis". Any periodic function can be analyzed into a Fourier series - a series of sin, cos, or sin and cos terms of the fundamental and harmonics (depending on nature of symmetry of the periodic function). The physical implication is that any periodic function can be analyzed by Fourier methods into a series of harmonics with definite phase and amplitude relationships. A periodic function defined only in terms of the amplitude of its Fourier constituents is not uniquely defined. The phase relationships between the Fourier components must also be defined.

Waves which are harmonically related may be superposed (added) into a periodic waveform. The periodicity will be that of the fundamental. The exact nature of the periodic function resulting will depend on the amplitude and phase of the component waves.

The visual carriers of a cable television system may be considered to be a set of waves which are being added in a broad band distribution system. If these carriers are harmonically related they may be considered to be components of a Fourier "synthesis" which will yield a composite waveform with a period which is that of the fundamental on which the carriers are based. The resulting function will have a unique form dependant on the relative amplitudes and phases of the component carriers. The RMS value of the resulting function will depend only on the amplitudes of the component carriers and represents the addition of the power content of the component carriers. The peak amplitude of the resultant function depends critically on the phase relationships between the component carriers. Peak amplitude reached by the periodic function can be minimized by prudent selection of relative phases.

Carriers which are not coherent, i.e. not locked to a common "fundamental" frequency, will have random relative phases and will add in such a way that the sum waveform often reaches a peak which is the sum of the peak amplitudes of the component carriers. Carriers which are coherent have controlled phase relationships. Such carriers can be phased so that their additive peak amplitude is substantially less than the sum of the individual peak amplitudes.

The behaviour of an amplifier when the input is a set of coherent carriers may be described in terms of its response to the "sum" waveform. If the "sum" waveform has reduced peak amplitude excursions we can consider that the amplifier output will have reduced distortion because of reduced excursions along the amplifier transfer curve. The amplifier will always be working on a more linear part of the transfer curve rather than experiencing frequent large peak amplitude excursions along the transfer curve. We propose that the effect of this would be to allow derating of CATV amplifiers for increasing number of channels by a "power addition" law rather than by "voltage addition" law. We doubt that exact "power addition" is actually achieved but we do believe that we are achieving benefits somewhere between "power addition" and "voltage addition".

The potential benefits may be estimated from this table of "derating factors" relative to 12 channel loading, based on "power addition", "voltage addition", and a "14 log" law estimated to be about half way in between.

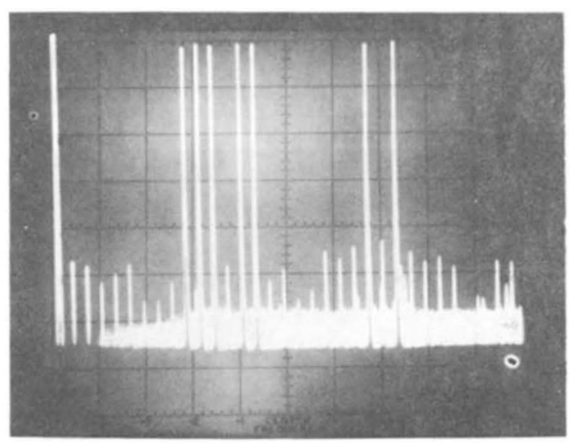
N Channels	Power Addition 10 log N/12	14 log N/12	Voltage Addition 20 log N/12
15	1.0 db	1.4 db	1.9 db
20	2.2	3.1	4.4
25	3.2	4.5	6.4
30	4.0	5.6	8.0

The effect of "phase phiddling" on distortion has been demonstrated in the laboratory and in limited field tests. The following is typical of laboratory demonstrations:-

Seven HRC carriers were generated (unmodulated) as follows:-

Channel	Frequency	N
HRC-2	54.000	9
-3	60.000	10
-4	66.000	11
-5	78.000	13
-6	84.000	14
-C	132.000	22
-E	144.000	24

This set of carriers was amplified by a high quality single ended MATV type amplifier to introduce a moderate level of distortion. Input signal level (flat) was adjusted so that output distortion products were typically 45 db below carriers for second order and about 55 db below carriers for third order intermodulation products.

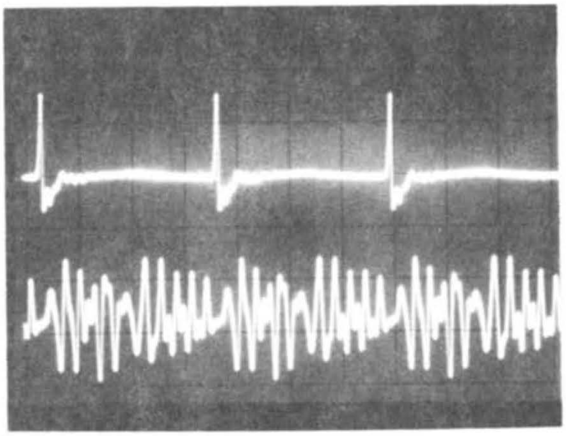


7 Channels 10 db/div 20MHz/div

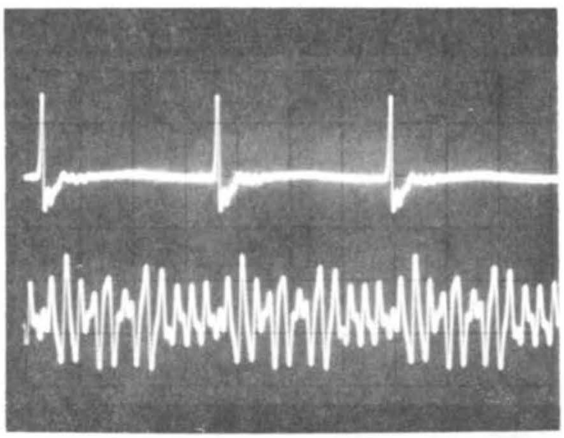
The intermodulation products at 72.000MHz were chosen for study. Channels C and 3 produce a second order product at 72.000MHz so channel C was removed to allow study of the underlying third order products.

The phase of the six remaining carriers was than adjusted for maximum amplitude of the displayed third order products. We had previously found that a single distortion product (intermodulation) which is the result of only two carriers intermodulating is not sensitive to the phase of the contributing carrier. Dr. J. Shekel, of Jerrold, was kind enough to contribute an analysis to this effect and we have verified this experimentally. Removal of the single second order distortion product at 72.000MHz allowed us to observe the third order products "underneath". The observed third order product is the vector sum of seven contributing third order products.

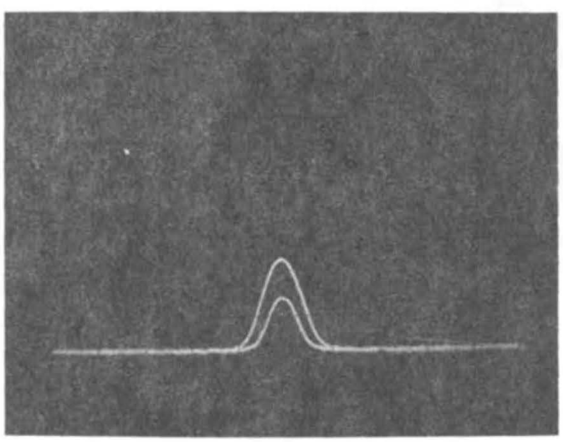
Carrier phases were adjusted to produce maximum amplitude of the 72.000 MHz product. Corresponding sum waveform and intermod amplitude are displayed below:



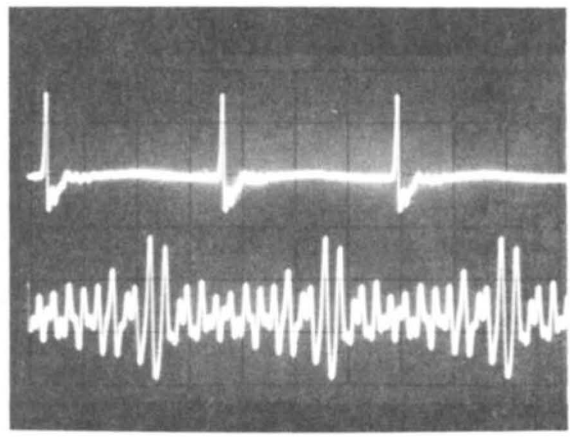
"Sum" Channels 2,3,4,5,6,C,E .1V/div .05 usec/div



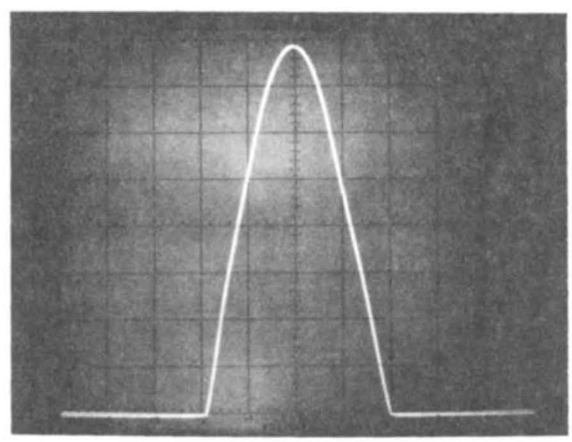
"Sum" Channels 2.3,4,5,6,E .1V/div .05 usec/div



Double Exposure 20KHz/div BW 10KHz video filter 10Hz 10 db/div showing third order IM under 2nd order product

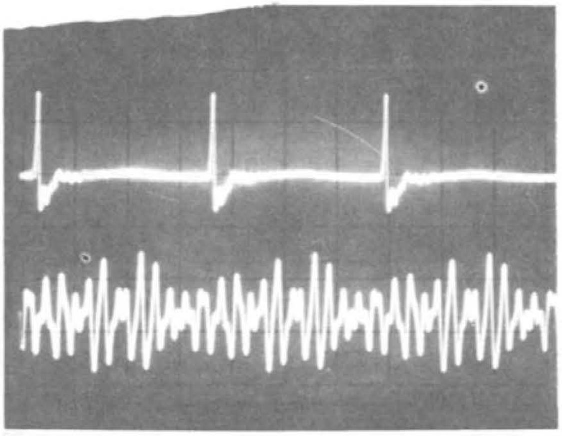


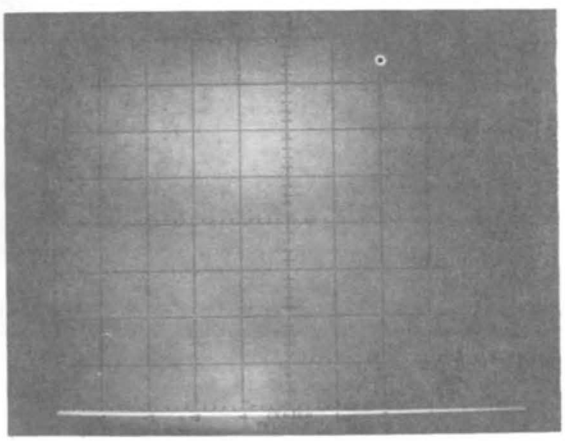
Sum waveform for maximum IM at 72MHz
0.1 v/div .05 usec/div



Amplitude of IM at 72MHz 2db/div 20KHz/div
ref - 54 dbm

Carrier phases were then adjusted for minimum IM product at 72.000 MHz. This product was reduced by more than 16 db dropping out of sight on the 2 db/division spectrum analyzer display. The sum waveform shows reduced peak to peak amplitude .





Since channel E did not contribute to the 3rd order product at 72MHz we tried removing it. Removal of E reduced the third order product by 1 db. Phase adjustments on E alone produced a similar 1 db change, whereas the phase of the other 5 channels had far greater effect on the amplitude of the IM product at 72MHz.

The intermod product at 48MHz was also observed to see whether it decreased in amplitude along with the product at 72 MHz:

	IM Product	Level	N (products)
"Worst Case"	72.000 MHz	-56 dbm	7
	48.000 MHz	-61 dbm	3
"Best Case"	72.000 MHz	-83 dbm	7
	48.000 MHz	-70 dbm	3

The 48.000MHz product decreased in amplitude but not as dramatically as the 72.000MHz product for which the adjustments were optimized.

EXPERIMENTAL PHASE ADJUSTMENTS

Some experiments with head end carrier phase adjustment were conducted in late November 1973.

A technique was developed for observing and adjusting the "relative phase" of the visual and pilot carriers at the head end. The concept of "relative phase" of carriers of differing frequency was taken to mean their relative phase at periods of the fundamental frequency from which the coherent carriers were derived. The main head end test point was designated as the visual carrier reference point and one of the "synchronizing pulse" test points was designated as another reference point. Test cables of convenient length were cut and marked to connect these test points to the dual channel high frequency oscilloscope. The oscilloscope (H-P 183 with dual channel 250MHz vertical amplifiers) was triggered by the 6MHz sync pulse. The individual channel processors were then all disconnected from the mixing networks and then reconnected one at a time for individual observation beginning with channel HRC-2. The length of the jumper cable from the channel HRC-2 processor to the mixing network was then adjusted until the first "peak" of the sync pulse coincided with a "valley" of the visual carrier. This is illustrated for the 72MHz pilot carrier in Figure 29. This was considered "zero phase". Figure 30 is an expanded version of Figure 29. In Figure 31 a half-wave length of cable has been added to the mixing jumper to show the 180 degree phase reversal case.

HRC-2 was then disconnected and HRC-3 was connected and a similar adjustment of mixing jumper made. Similarly all 21 visual carriers and the two pilot carriers were adjusted to "zero phase" with the sync pulse. Being "in phase" with the same pulse now meant that they were "in phase" with each other, meaning that there was a time during the period of the 6MHz sinc pulse when all the carriers would have co-incident peaks. This was expected to be a "worst case" condition. Figure 32 shows the composite of all these carriers in the coincident with the sync pulse. Switches were then installed in each channel mixer jumper to allow easy addition of half wave length of cable. Channels could then be quickly shifted 180 degrees in phase.

Some practical problems have arisen in detailed evaluation of effectiveness of this phase adjustment. The coincident phase adjustment made in late November was very tedious. It required adjustment of one channel at a time, while the system was out of service (early morning hours). Several problems were apparant very soon, mostly from the fact that phase stability and adjustability had not been considered in the design of the head end equipment at St. Catharines. It had been spec'd for coherency, i.e. ability to phase lock to desired harmonic comb components, but not to maintain any specified phase relationship with that comb component.

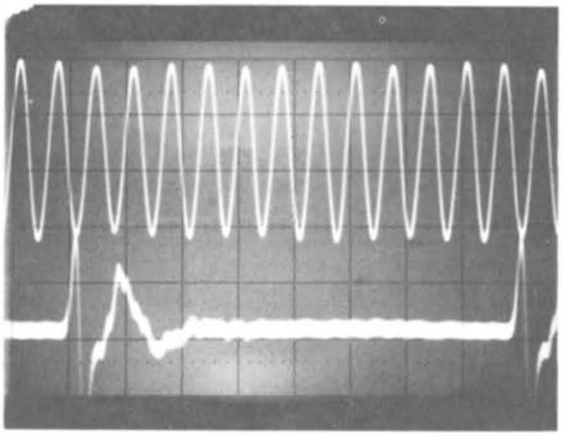


FIGURE 29 0.02 usec/div

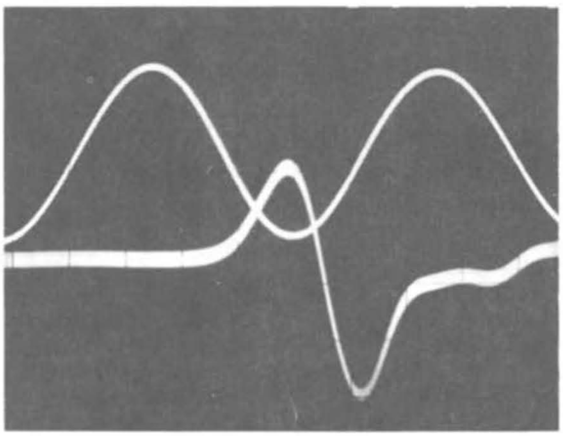


FIGURE 30 0.002 usec/div

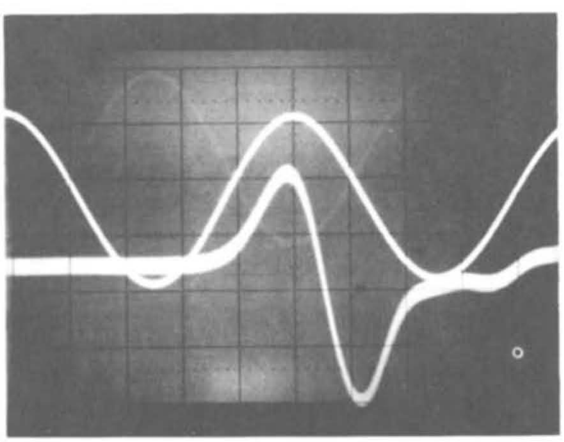


FIGURE 31 0.002 usec/div

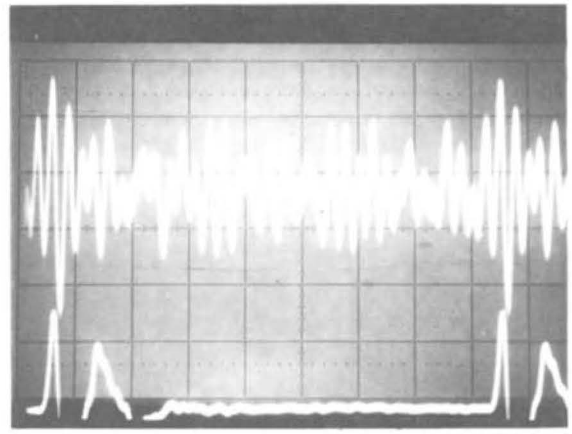


FIGURE 32 0.02 usec/div

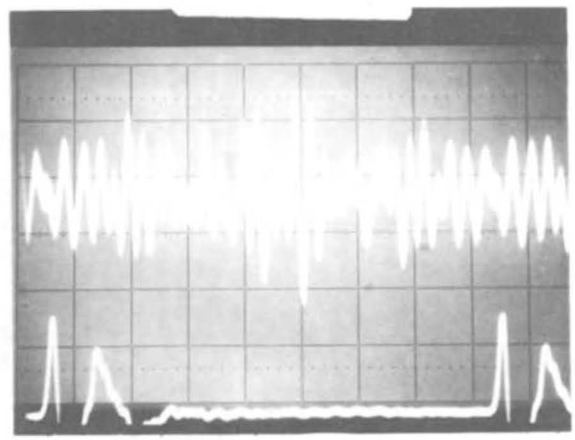


FIGURE 33

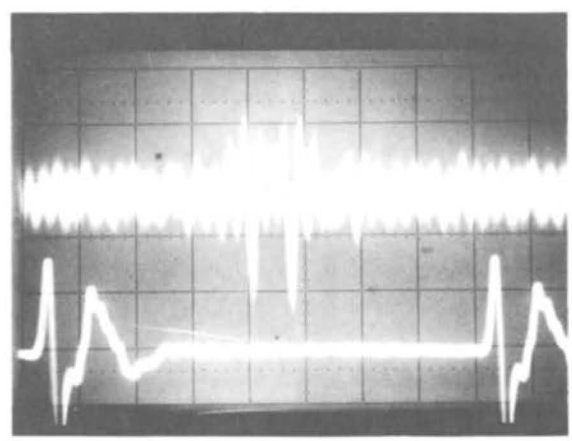


FIGURE 34 0.02 usec/div

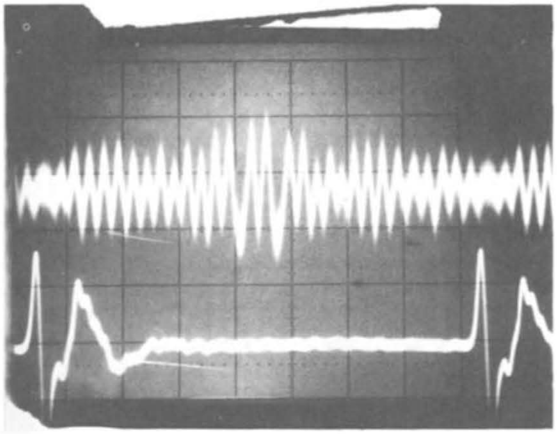


FIGURE 35   0.02 usec/div

We found that the standby carriers had different "phase" than the normal carrier. We also found that "relative phase" drifted with time. Adjustment of phase locking controls or any of the tuned circuits in the equipment also changed the relative phase. We therefore found it difficult to reproduce the coincident phase condition or any other specific relationships. Having observed the "worst case" coincident phase and photographed it we could now recognize it if it should occur again. We are getting the impression that the range of "optimum" adjustments is quite broad and that as long as the worst case "coincident phase" is avoided we are probably realizing near maximum benefits.

The new generation of coherent head end equipment for subsequent application will be designed for stability and ease of phase adjustment to overcome the experimental difficulties we have experienced with this installation.

ADDITIONAL COMMENTS

The new amplifiers installed in the transportation trunk use modulated pilot carriers. The pilots, at 72 and 240 MHz were coherent but were initially modulated at 30KHz. The 30KHz modulation was occasionaly visible as a slight beat in system pictures. Modulation was changed to 23.601 KHz (3/2 X H). This "interleaves" any visible beat that is produced. The "beat" or cross modulation from the pilot was slightly visible when ordinary cross-modulation was not visible because of the high modulation index and spectral nature of the modulation. The pilot modulation sidebands are very high in level compared with individual sidebands in normal TV modulation, see figure 36. The 23.601KHz modulating frequency has remedied this problem.

Interference potential to other services has been considered, particularly to the aircraft distress frequency, 121.5MHz. HRC carrier frequencies are closely controlled. HRC-A at 120.000MHz is 1.500MHz below the distress frequency. Relative energy density of a typical television channel is shown in figure 37, which is a spectrum analyzer display with 30KHz bandwidth but no video filtering. Sweep was slow enough to display peak energies due to picture components. Energy 1.5MHz above the carrier, at 121.5MHz is about 40 db down from the visual carrier. Radiation at 121.5MHz would be at a level about 40 db below that expected from carriers in the system. If as much as 1 volt of carrier was available for radiation in a system fault condition this would make available about +10 dbm of power for radiation at carrier frequency. At 121.5MHz the available power could be considered to be about 40 db less than this or about -30 dbm, or -60 dbw (1 microwatt). This is a very low level of energy and not likely to cause any interference to an aviation receiver system.

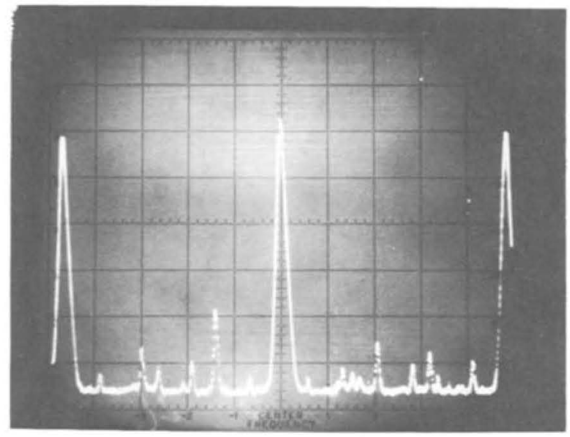


FIGURE 36 5KHz/div BW 300Hz video filter 10Hz showing modulation sidebands on 72MHz pilot carrier and beat from offset HRC-11

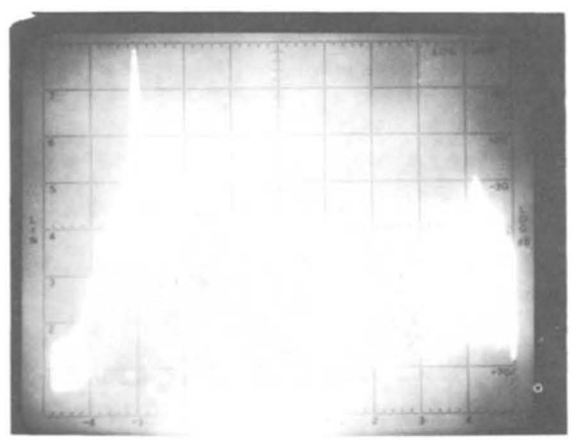


FIGURE 37   500 KHz/div BW 30KHz

SUPPLEMENTAL MEASUREMENTS

Additional oberservations were made at a subscriber's home close to the end of the system (6 Colton Street). System at this observation point has 20 push-pull trunk amplifiers, 24 single ended trunk amplifiers, 1 single ended bridging amplifier, 2 single ended line extenders. A good quality single-ended amplifier with flat band-pass characteristic was used in the subscriber's home to boost levels to overcome spectrum analyzer noise. Figure 38 shows system carrier levels at this subscriber drop. The 240MHz pilot carrier has been attenuated by the single ended equipment.

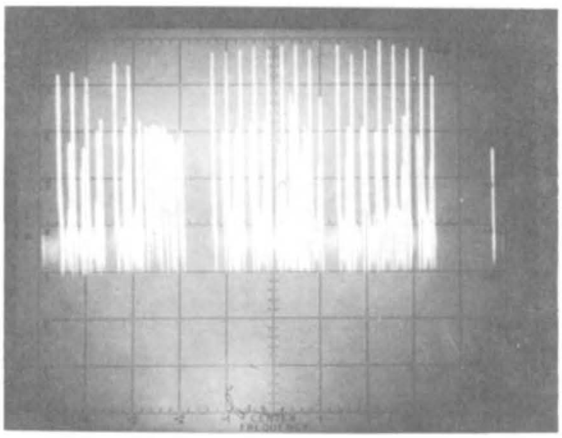


FIGURE 38 20MHz/div BW 300KHz ref level +6.5dbmv subscriber drop 6 Colton Street

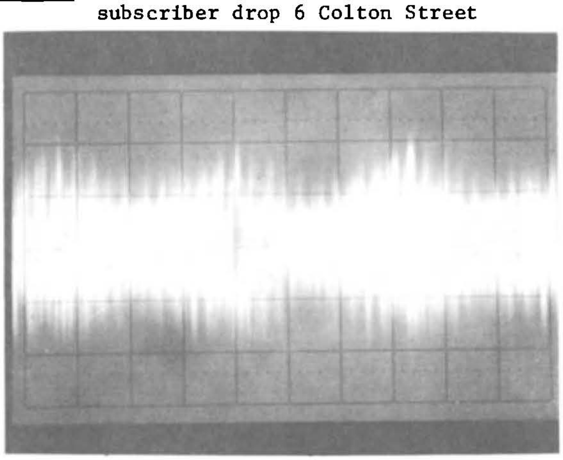


FIGURE 39 0.5 usec/div subscriber drop 6 Colton Street

Figure 39 shows the composite waveform at the subscriber terminal. This photograph is "inconclusive" because of the trouble in triggering since there is no 6MHz system reference signal readily available at this point in the system to provide reliable scope triggering. The photo does suggest that there may be undesirable co-incidence of carrier peaks.

Group delay distortion on a "broad band" basis can cause the phase relationships established at the head end to change along the system. This effect was anticipated in the preliminary technical paper, and if necessary we plan to use passive, all pass, delay correction networks in the system.

Noise measurement at channel 3 was made. Figure 40 shows the carrier to noise ratio at the output of the head-end processor on HRC-3. A C/N ratio of about 52 db is indicated.

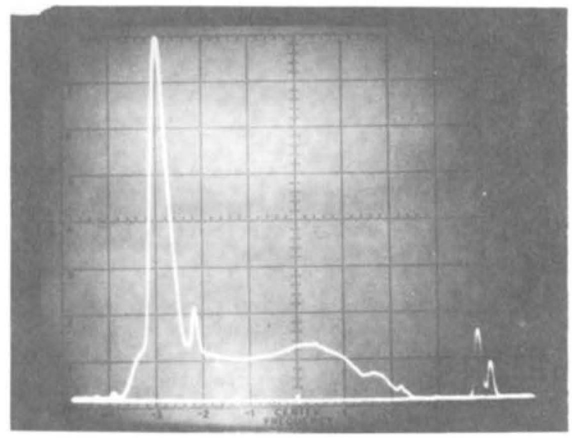


FIGURE 40 HRC-3 Standby at head-end 1MHz/div BW 100KHz video filter 10Hz showing C/N correction to 4MHz noise BW= +18db

Figure 41 shows the noise at the subscriber location. The channel 2 aural carrier has been attenuated somewhat and the channel 4 visual carrier has been severely attenuated by the preselector filter used to prevent overloading of the spectrum analyzer. The C/N ratio is indicated to be about 39 db.

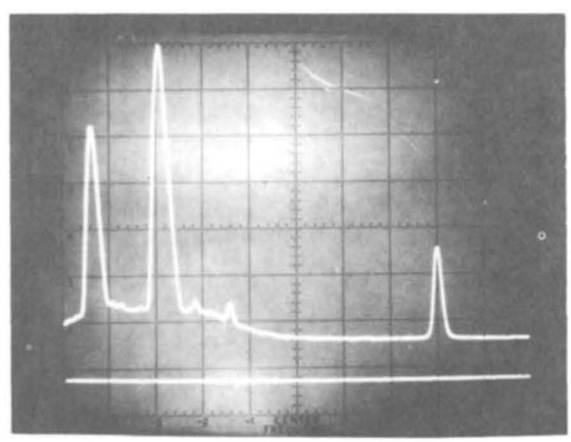


FIGURE 41 HRC-3 standby 6 Colton Street 1 MHz/div BW 100KHz video filter 10Hz correction to 4MHz noise BW = + 18db

Leakage of air channel 11+ into the system was checked. Figure 42 shows this leakage. The photo was made during the readjustment of the offset of HRC-11 for minimum beat visibility and does not represent the optimum position of the beat. This photo should be considered as representing levels only. Reference level is -17.5 dbmv, indicating the channel 11+ leakage to be about -48 dbmv or about 55 db below HRC-11 at this subscriber location. This is considered an acceptable leakage level since this signal/beat ratio would not be visible. Any visible beat would be due to direct pick-up in the receiver connected to the system at this point.

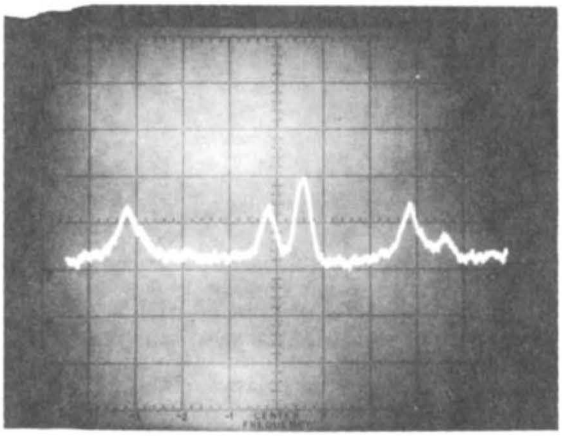


FIGURE 42 Channel 11+ leakage into system
6 Colton Street
5KHz/div BW 1KHz Video Filter 10Hz
ref level -17.5dbmv

Figure 43 shows intermodulation beats in HRC-3 standby due to HRC-11 being unlocked, i.e. not coherent. HRC-11 is being operated so that the direct pick-up beat from air channel 11+ falls halfway between H sidebands. The intermodulation beat caused in other channels then shows up as beats above and below the desired carrier. In this case the undesired beat is about 47 db below desired carrier. The beat is not visible on TV sets because of the H/2 offset. Figure 44 shows beats from other channels into the offset HRC-11 at a similar level.

We tabulated all the second order beat products that would fall into HRC-3 due to the added mid-band channels. Since all the beat products fall directly on each other the spectrum analyzer cannot distinguish any single beat. The many third order beats which are generated also fall on each other but are much lower in level than the second order beats. The beat which is seen when the carrier is removed is the resultant (vector sum) of all the beats which are generated. There are ten second order beats, all "differences" which fall on HRC-3.

Only the D - 5 and the E - 6 beats would be harmfull in a "conventional" system since the rest of the beats fall at the band edge where their effect would be minimal. Channel HRC-3 was chosen as an example because of its convenience for testing during system operation. It is not the worst case channel for second order beats. It is available because Global starts programming late in the afternoon and it is tunable on the high resolution H-P spectrum analyzer which makes possible a degree of precision not easily achieved for measurements above 110MHz.

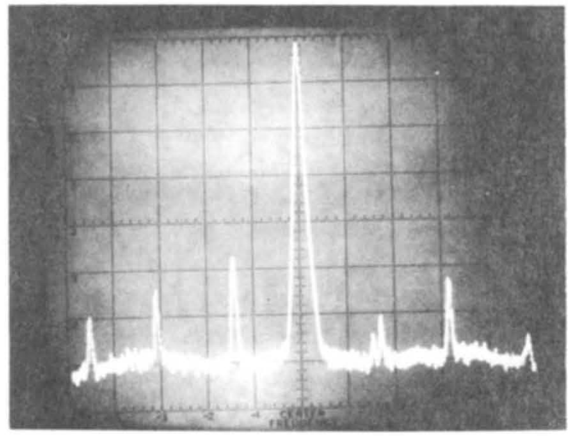


FIGURE 43 Intermod beat into HRC-3 standby
due to unlocked, offset HRC-11
5KHz/div BW 300Hz Video Filter 10Hz

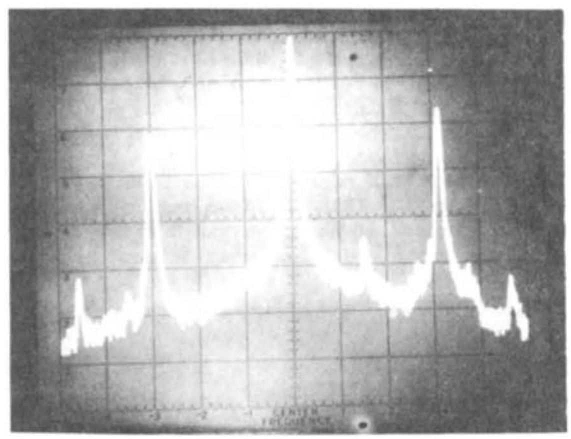


FIGURE 44 Intermod into HRC-11 due to unlocked
offset operation of HRC-11
5KHz/div BW 300Hz Video Filter 10Hz

Beat Product	Freq. in "conventional" system	Freq. of video beat in conventional system
13 - F	60MHz +-20KHz	band edge
12 - E	"	"
11 - D	"	"
10 - C	"	"
9 - B	"	"
8 - A	"	"
A - 3	"	"
B - 4	"	"
C - 72MHz pilot (73.5)	59.75MHz +-	CH 2 sound
D - 5	62 MHz +-	0.75 MHz
E - 6	62 MHz +-	0.75 MHz

Figure 45 is a triple-exposure showing channel HRC-3 in normal picture modulation, standby, and removed. This shows the level of beats under the carrier and also gives some further noise information. Some of the noise observed in standby carrier is due to the head end processor and that the system noise, with the head end processor disconnected is a further 6 db down.

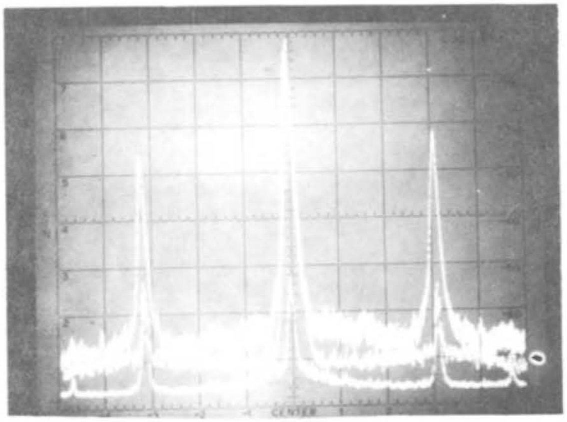


FIGURE 45 5 KHz/div BW 300Hz Video Filter 10Hz

Figure 46 shows the HRC-3 standby carrier at 6 Colton Street and figure 47 shows the intermod beats under the carrier, i.e. carrier removed. The carrier beat is about 48 db below desired vidual. Being zero beat (HRC-11 was locked in for these observations) there was no visible effect on the screen due to carrier beats. The H sidebands associated with the carrier beats are about 55 db below desired visual carrier but only about 30 db below the normal H sidebands in a normally modulated picture channel. This could be interpreted as -30db cross modulation if the observed H sidebands are considered to be undesired modulation.

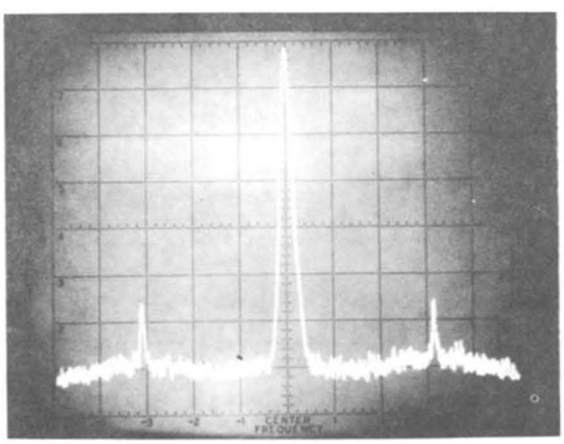


FIGURE 46 HRC-3 standby 6 Colton Street
5 KHz/div BW 300Hz Video Filter 10Hz

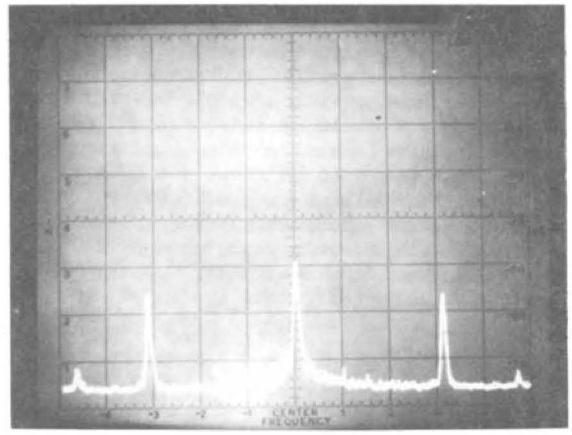


FIGURE 47 Standby carrier removed
5 KHz/div BW 300Hz Video Filter 10Hz

All carriers were then unlocked to show effect of non-coherent operation. Figures 48 and 49 show the resultant beats. The frequency spread is due to the head-end processors dropping out of phase-lock. Restoration of the reference signal then pulls them back to locked, coherent operation. Note that there are four beat products at a -48 db level and additional beats at lower levels. If these individual beats had added "in phase" on a voltage basis they might have produced a beat some 12 db higher when they are "brought together" by coherent operation. Even with power addition as a worst case the sum of these four beats might have been 6 db higher than each individual beat. Figure 47 shows that the resultant of all the carrier beats is no greater than any of the individual beats. Obviously an advantageous cancellation of beats has taken place, or at least a partial cancellation.

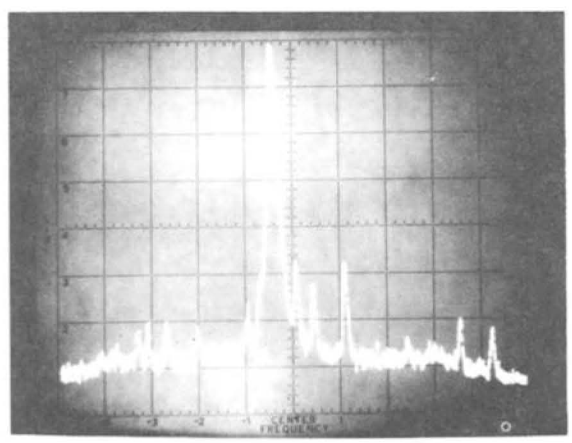


FIGURE 48 HRC-3 standby all carriers unlocked
5 KHz/div BW 300Hz Video Filter 10Hz

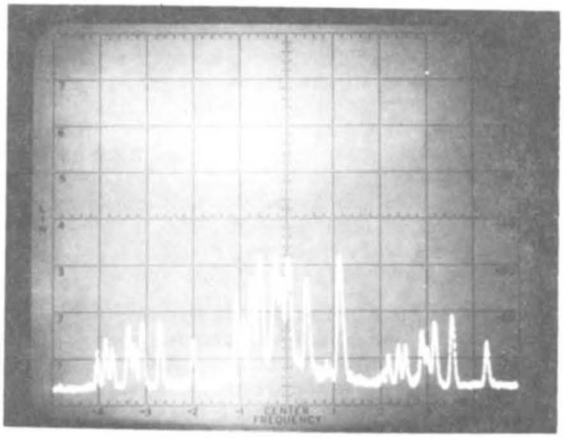


FIGURE 49 Carrier removed
All other carriers unlocked
5KHz/div BW 300Hz video filter 10Hz

The proper way to "add" beats at different frequencies as in figures 48 and 49 is not really known. These beats are spread over a 50KHz span around the carrier. We have made similar observations of "dispersion" of individual third order beats around a carrier in conventional systems. How does the eye sum the consequent video beats as seen on a TV receiver? Is the visual effect of a number of dispersed beats the same as from a single beat which is the power sum of the individual beats? One paper presented at the 1973 NCTA convention (Arnold - "REQUIRED SYSTEM TRIPLE BEAT PERFORMANCE") suggests that a "Power Law" is applicable. In a 24 channel example the individual third order intermod beat would have to be 76 db down from desired carrier so that the sum effect of the 198 triple beats falling on the worst case channel (9) would meet the visibility threshold requirements he sets out.

The "apparant" 30 db cross modulation observed in figure 45 is alarming when viewed on the spectrum analyzer, yet the pictures visually observed on a test receiver and the subscriber's receiver were judged of "good quality" with no visible cross modulation. At the date of this writing (March 1st, 1974) we have not been able to explain this apparant inconsistency.