Overload Stability Problem in Submarine Cable Systems

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Modern submarine cable systems usually provide bidirectional transmission over a single cable with repeaters which use a common amplifier for both directions of transmission. The signals for the two directions of transmission occupy separate frequency bands. Under normal loads, the amplifier is highly linear and there is negligible interaction of the signals in the two bands. However, when approaching overload, intermodulation in the repeaters may transfer appreciable power between bands. It has been discovered that this feedback, especially in the presence of large misalignments, can result in a system that maintains itself in overload. Such a system, once excited by a momentary signal or noise peak, generates sufficient intermodulation noise to keep itself overloaded, even in the absence of any further external signal. This paper describes the occurrence which drew attention to this phenomenon, presents an analytical approach used to predict stability margins for any given repeater, and describes the action taken to ensure the stability of the SF Submarine Cable System.

I. INTRODUCTION

Experience gained while laying the Oahu-Guam SD Submarine Cable System shows that a bidirectional single cable system whose repeaters have a common amplifier for both directions of transmission is potentially unstable. So far, this instability has occurred only when an abnormally high-gain repeater section is present. When the instability occurs, noise levels corresponding to repeater overload make communication in either direction completely impossible. The instability results from the feedback of intermodulated signals or noise in overloaded repeaters. Low-band power traveling in one direction through the system is partially converted to high-band power which propagates in the opposite direction, and vice versa. In this manner, a configuration of feedback loops develops. Loops in which repeaters are separated by less than nominal loss are especially critical.

II. THE FEEDBACK MECHANISM

The SD and SF repeaters consist of a common amplifier and directional filters. This configuration, shown in Fig. 1, is well suited to undersea applications because of the reduced number of components, greater reliability, and lower power drain compared with the more conventional twin amplifier arrangement. With typical pre-emphasis, the low-band signal levels at the amplifier output are about 10 dB below those of the high band. Thus, the low-band signals comprise a small portion of the total multichannel repeater load.

The common amplifier configuration has a severe limitation when one considers the effect of a very large overload. Assume that the high-band signal, which enters port A of Fig. 1, overloads the amplifier. This will produce, by intermodulation, not only a distorted output at B, but will also return power in the low band at A. Thus the repeater, through its nonlinearity, partially redistributes and reflects the spectrum of the incident power.

The simplest type of system overload instability occurs when a single high-gain repeater section is present as shown in Fig. 2. Assume that no signal is being transmitted by either terminal so that the load results entirely from noise generated by the repeaters. Because of the low loss equalizer section, repeaters $n + 1$ to N will be loaded mainly with low-band power, while repeaters n to 1 will be loaded mainly with high-band power. If sufficient loss is removed from the equalizer, the repeaters on one side of the equalizer will become overloaded with noise generated by repeaters on the opposite side and a self-sustaining overload results.

III. SD SYSTEM EXPERIENCE

3.1 *Wake Island*

The conditions shown in Fig. 2 were present for several days while the Oahu-Guam SD Submarine Cable System was being laid. This system has intermediate stations at Midway and Wake Islands which allow channels to be bridged onto the system at these two points. A modified ocean block equalizer is included in the through circuit at the intermediate stations. In the normal setting, this equalizer's loss is equal to 10 nm of cable.

While the second shipload of cable was being laid, a dc fault occurred which was apparently in the immediate vicinity of Wake Island. At that time 144 of the 200 repeaters had been laid. Wake Island is

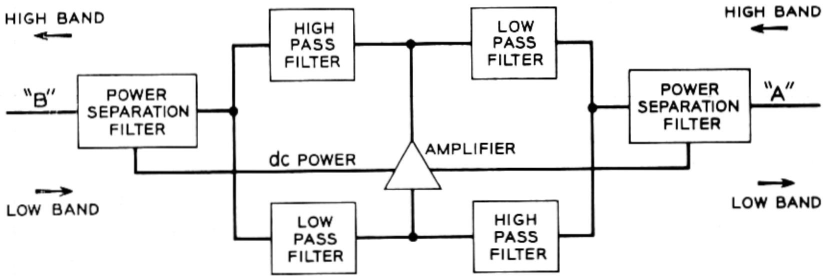

Fig. 1 — SF and SD repeater configuration.

between repeaters 121 and 122 counting from Oahu. To eliminate the Wake Island equalizer as a possible source of the dc fault, it was completely bypassed resulting in an excess gain equal to the loss of 10 nm of cable. After the equalizer was bypassed, system power was turned back up and the dc fault was no longer present. In the meantime, four additional repeaters had been laid without power.

Following power turn up, laying continued, but after a short time the system became noisy to the extent that order wire communication between the ship and Oahu was impossible. Power was turned down and when it was raised again the noise was no longer present. This was repeated several times. However, soon after repeater 156 was laid the noise reappeared and subsequent efforts to squelch it by lowering and raising power were unsuccessful. Then it was decided to install the spare equalizer on Wake Island. After this was accomplished, no further noise developed and the laying was completed. Subsequent examination of the original equalizer revealed no imperfections. The location or cause of the temporary dc fault has never been established.

3.2 *Description and Explanation of Noise Conditions*

The noise which existed after bypassing the equalizer appeared to result from repeater overload. The noise covered both bands and no

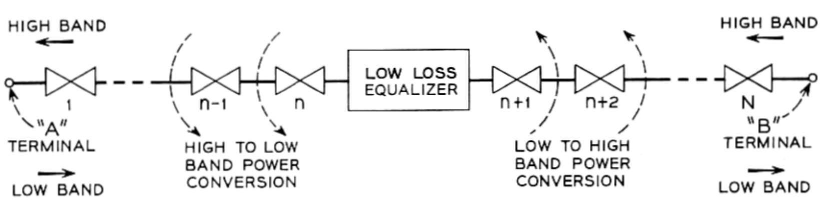

Fig. 2 — Interband power flow during self overload.

discrete frequencies were observed. At the time, the noise condition was believed to be related to the previously observed dc fault. Several months elapsed before the phenomenon was attributed to the excess gain resulting from by-passing the equalizer.

The excess gain between repeaters 121 and 122 was about 25 dB in the high band and 17 dB in the low band. Thus, any large burst of noise generated in the high band west of Wake Island tended to overload those repeaters east of Wake. They, in turn, generated modulation noise, some of which fell into the low band. This low-band noise was transmitted west, encountered excess gain, and tended to overload the repeaters west of Wake, regenerating the high-band noise. Thus, a potential feedback loop was established through the intermodulation of noise. With the excess gain present and a sufficient number of repeaters west of Wake converting power from low to high band, normal background noise alone was sufficient to initiate a self-sustained overload.

Evidently the stability of the system was marginal with the excess gain of 10 nm of cable at Wake and 22 repeaters laid west of Wake. When 34 repeaters had been laid west of Wake the system was definitely unstable. This means that 34 repeaters shifted enough power from the low to the high band so that, when this shifted power was subjected to the 25 dB of excess gain at Wake Island, it reached a level high enough to cause a significant shift of power into the low band by the repeaters between Wake Island and Oahu. This low-band power, enhanced by the 17 dB of excess gain at Wake, was sufficient to "close the loop" and the overload was self-sustaining. The repeaters that had not yet been laid did not contribute significantly in the process because of the excess loss of the relatively warm cable aboard ship. This excess loss attenuated the low-band power that caused the power shift as well as any high-band power that might have been generated.

3.3 *Two-Repeater Experiment*

To test the preceeding hypothesis, an experiment was conducted using two SD pilot model repeaters connected to each other with an adjustable cable shape equalizer. It was found that by reducing the loss between the repeaters to an amount equivalent to 2.5 nm of cable a "sing condition" could be established with the repeaters sustaining each other in noise overload. The reduction to 2.5 nm in the experiment rather than the 10 nm at Wake Island was necessary because in the experiment only two repeaters shifted power between bands. Thus, the Wake Island experience was very valuable in revealing a source of instability which is inherent in an equivalent four-wire system using a common amplifier for both directions of transmission. An intensive study of this problem was begun to evaluate the stability of the SF system which was then in the final design stage.

IV. SF SYSTEM STABILITY ANALYSIS

4.1 *Repeater Characterization*

Although the SD overload condition was analyzed and the result agreed with the experimental evidence, it was obvious that a direct application of those methods would not be valid for predicting the stability of a normal system where no large abrupt changes in repeater levels occur. The fundamental problem is one of characterizing the repeater input-output relations under severe overload conditions. The SF repeater overload performance was determined by noise loading both bands simultaneously and measuring the apparent compression or expansion of the power in each band as a function of the average driving power in each band. The instrumentation of the repeater measurements is shown in Fig. 3.

Such a characterization is obviously not rigorous in that it neglects the spectral distribution of either the input or output noise power. The input was band-limited white noise. Figures 4 and 5 show the three dimensional characterization. The nonlinear behavior is described simply as an apparent compression or expansion of the signal relative to the transmission of a truly linear repeater. Compression indicates a reduction in gain while expansion, which is the source of instability, is an apparent increase in gain.

Figures 4 and 5 show that the power transferred from low to high band is much greater than the power flow from high to low band. Since the mechanism of interband power flow is intermodulation noise produced by one band falling into the other, it seems reasonable that the band with greater feedback would undergo least expansion. The difference in feedback between the two bands is about 12 dB, which is roughly the same as the difference between the maximum high- and low-band expansion.

4.2 *Analytical Model*

In line with the empirical nature of the repeater characterization, the analysis of system stability is based upon an iterative scheme.

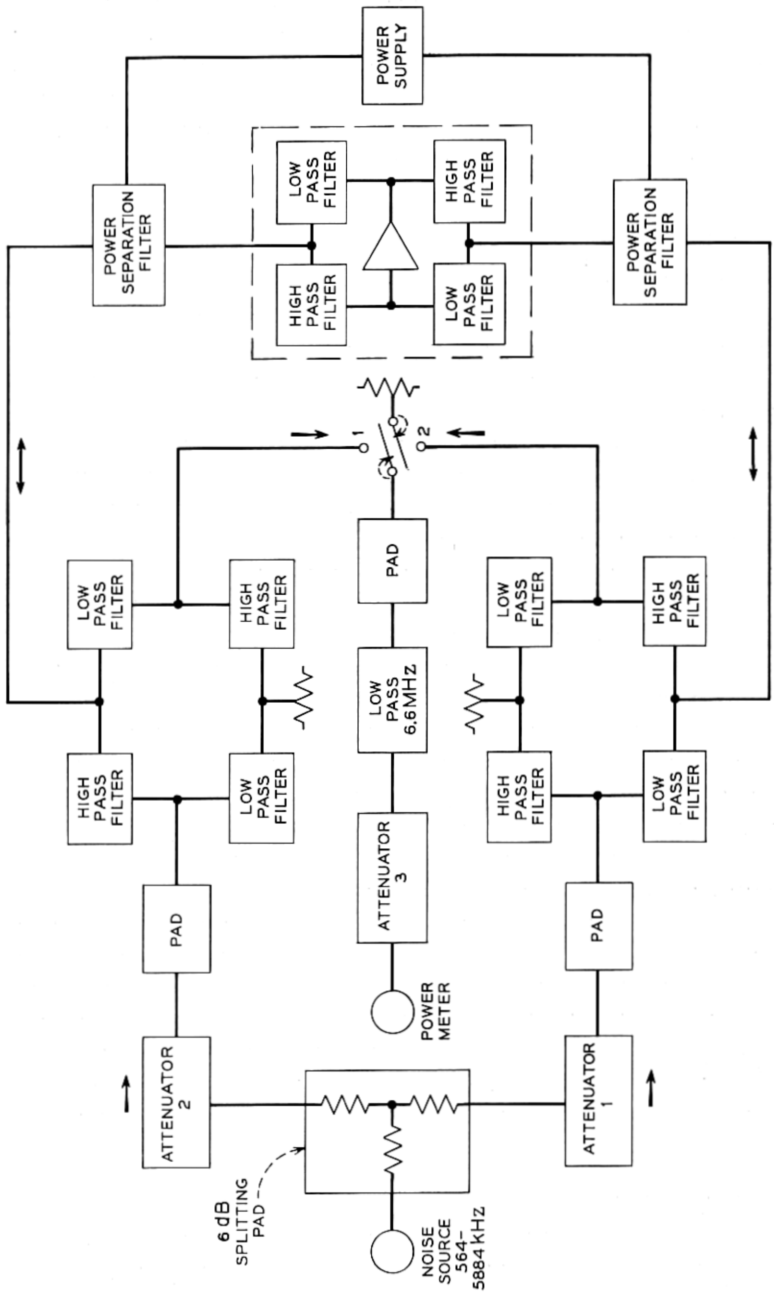

Fig. 3 — Instrumentation of repeater measurements.

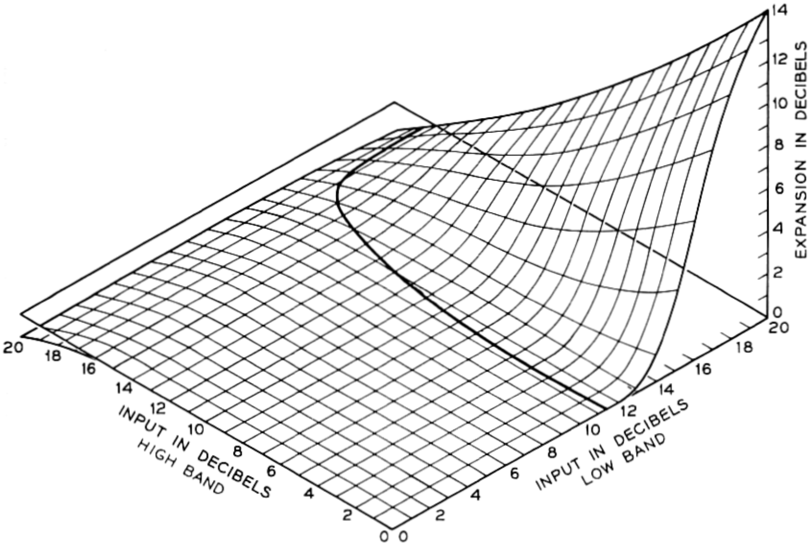

Fig. 4 — SF repeater high band expansion versus drive. (0 dB is input power for 0 dBm output power.)

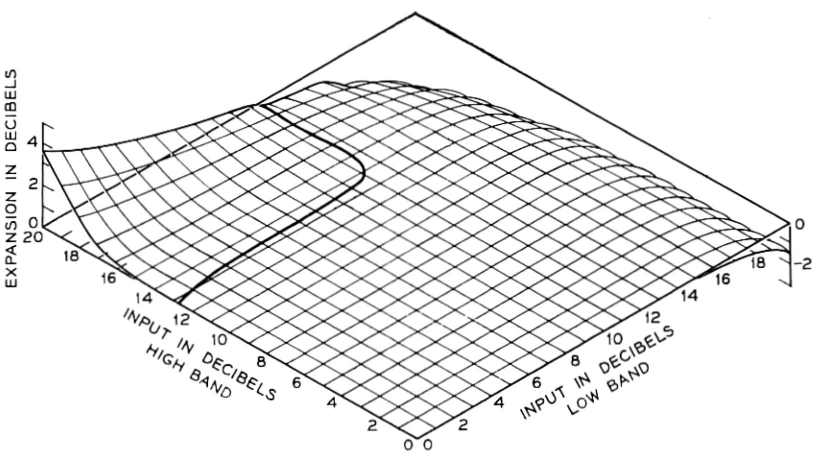

Fig. 5 — SF repeater low band expansion versus drive. (0 dB is input power for 0 dBm output power.)

Simply stated, the method seeks to determine whether a system would "recover" from a gross overload. By "recover" is meant that the signal levels at the repeaters would return to their normal value once the overloading signal is removed from the transmitting terminals. If any repeater remains overloaded in the steady state after the overloading signal is removed from both terminals, then clearly the system is unstable.

The quantities which must be determined numerically are the steady state values of output power in each band of every repeater, as indicated in Fig. 6.

Let $P_H(n)$ = high-band power delivered by repeater n,
$P_L(n)$ = low-band power delivered by repeater n,
$G_H(n)$ = excess high-band gain of nth repeater section, (that is, misalignment),
$G_L(n)$ = excess low-band gain of nth repeater section,
$F_H(P_L, P_H)$ = repeater high-band expansion with driving powers P_L and P_H in the low and high bands, respectively, and
$F_L(P_L, P_H)$ = repeater low-band expansion with driving powers P_L and P_H as above.

F_H and F_L, which were determined experimentally by noise loading a repeater, are plotted in Figs. 4 and 5. These functions describe the nonlinear input-output relationship of the repeaters. The two equations which must be satisfied are:

$$P_H^i(n) = P_H^{i-1}(n+1) + G_H(n) + F_H[P_L^{i-1}(n-1) + G_L(n), P_H^{i-1}(n+1) + G_H(n)]$$

$$P_L^i(n) = P_L^{i-1}(n-1) + G_L(n) + F_L[P_L^{i-1}(n-1) + G_L(n), P_H^{i-1}(n+1) + G_H(n)]$$

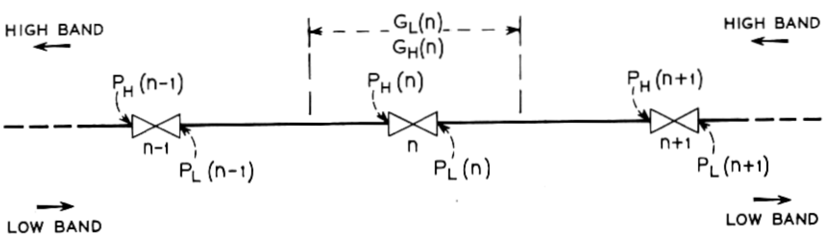

Fig. 6 — Quantities which describe the state of the system.

where the index i is the number of the iteration while n ranges over all repeaters.

These two equations simply say that the state of a repeater on the ith iteration is determined by the states of the adjacent repeaters on the $(i - 1)$th iteration. The initial conditions are set by assuming the system is linear and applying a large overload at the two transmitting terminals. The overload signal is then removed and the system "relaxed" by successive applications of the two preceeding equations to every repeater. When the maximum difference between the states of each repeater on two successive iterations is sufficiently small, say 0.1 dB, the process is halted and the equilibrium or steady state is assumed to be reached. Then if any repeater carries a load greater than that caused by the normally applied signals, an unstable condition exists.

This sequence of operations was programmed in FORTRAN on the IBM 7094 computer. The input data characterizing the repeater nonlinear behavior was in the form of two 20×20 matrices which covered the entire repeater power range of interest. Linear interpolation was used between input data points. Critical misalignment conditions were found by successive trials with different values of misalignment. Stability margins were determined by finding that amount of misalignment in the system which would just cause instability. The stability margins are, by definition, equal to this misalignment.

Various forms of misalignment (net gain or loss) can be assumed. The simplest is lumped gain at a particular point in the system. (This corresponds to the Wake Island experience.) By successive trials, that point in the system is found where the smallest amount of excess gain results in instability. That value of gain at this point is defined as the lumped gain margin. This situation does not correspond to an event that is likely to occur in practice. It is simply a figure of merit characterizing the stability of the system.

Another type of margin studied corresponds to within-block misalignment. Submarine cable systems are divided into ocean blocks. Each block has associated with it a block equalizer which is expected to compensate for most of the misalignment (net gain or loss) accumulated in that block. In the SF system, for example, a block consists of 20 repeaters, 192 miles of cable, and an equalizer. The within-block misalignment stability margin is the amount of misalignment that could occur in every block, equalized perfectly at every equalizer, and result in a system which is marginally stable. This situation corresponds more closely than the Wake Island experience to the type of misalignment encountered in practice. It has been found that excess loss within a block compensated by gain in the equalizer section is more critical than excess gain in a block compensated by loss in the equalizer section.

A third type of misalignment margin assumes a uniform gain across the whole system compensated only in the terminals. This situation corresponds to misalignment resulting from aging or temperature where equalization by the ocean block equalizers is not possible. For this condition, only excess gain can cause instability; excess loss tends to prevent instability.

4.3 *Computed SF Stability Margins*

Based on the measured repeater nonlinear performance and the preceeding analysis, these marginal stability conditions were computed:

(*i*) 10 dB excess gain per block completely equalized at the ocean block equalizer,

(*ii*) 6 dB loss per block completely equalized at the ocean block equalizer,

(*iii*) 6 dB of lumped gain in both bands at one ocean block equalizer and

(*iv*) 13 dB of uniform positive misalignment in both bands.

Although the expected misalignment was considerably less than these critical values, it was felt that the margins were dangerously low, especially for within-block loss compensated by equalizer gain. Block losses of 3 dB or more may be expected under normal conditions. There was also a large uncertainty in the amount of variation in the overload response of repeaters and the effect of aging. What a "safe" stability margin would be was not known. However, from SD system experience, we knew that its stability margin, about 15 dB lumped gain, was adequate. Consideration of these points led to the study of a practical means of improving the SF system stability margin.

4.4 *Improving the SF Stability Margin*

Two different approaches were taken to improve the stability margin. The first was to modify the repeater feedback. No improvement resulted, probably because in the process the repeater feedback phase was changed from its optimum 90° value. The second attempt involved using a diode limiter to prevent the low band signal from severely overloading a repeater.

Figure 4 shows that if the low band repeater output power remains below about 12 dBm, then no power is transferred from the low band to the high band and the feedback loop is opened. Since a limiter by itself generates intermodulation noise, it must be placed somewhere in the transmission path where the two bands are physically separated and are isolated by filters. Otherwise the limiter itself would transfer power between bands.

The limiter was placed in the low band branch of the ocean block equalizer as shown in Fig. 7. Since the average low band signal power at the repeater output is about −10 dBm, limiting the maximum rms repeater low band output power to about 12 dBm involves very little signal-to-noise penalty. System stability studies assuming diode limiters in each ocean block equalizer indicated that it would be possible to increase the stability margin by at least 6 dB with a resulting noise contribution of less than 20 dBrnC0 on a 3500 nm system. Figure 8 compares the measured low band compression of the limiter with that of a repeater. The driving signal was white noise, band limited to cover only the low band.

V. CONCLUSIONS

Equivalent four-wire transmission systems which use repeaters with a common amplifier for both directions of transmission are po-

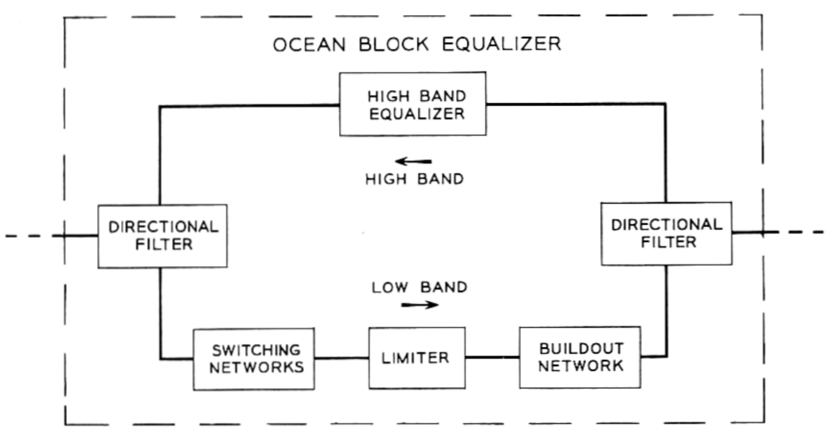

Fig. 7 — Location of low-band limiter.

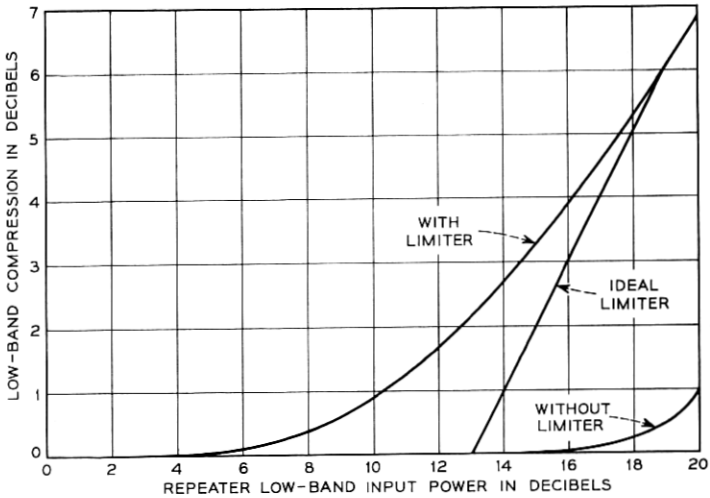

Fig. 8 — Effect of limitation on low-band compression. (0 dB is input power for 0 dBm output power.)

tentially unstable. Although this instability has never yet been experienced under normal operating conditions, it has occurred when an unusual amount of excess gain was present. A method of calculating a first order approximation of the stability margin has been described. This method has been used in evaluating the stability of the SF Submarine Cable System. The nonlinear stability problem appears to become more acute as system bandwidths increase. This effect may limit, or even possibly preclude, the use of a common amplifier in future broadband submarine cable repeaters. Although only the surface of this problem has been probed we hope that publishing these results will stimulate a deeper investigation.

VI. ACKNOWLEDGEMENTS

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