SF System:

An Overview: Requirements and Performance

By CLEO D. ANDERSON and ROBERT L. EASTON

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This article describes the considerations which led to choice of the SF System design objectives and gives an overview of the system. It further discusses various system parameters and the techniques of laying and adjusting the system for optimum signal-to-noise performance. Finally, the article shows performance results of the recently completed TAT-5 System which extends from Rhode Island to Spain. These results show good agreement with calculated system performance.

I. INTRODUCTION*

At the time of the first transatlantic SD System installation in 1963, it was already clear that a new system with considerably more capacity would be required to meet the traffic demands of the early 1970s. Economic studies indicated that the large potential demand expected by that time would justify the greatest bandwidth achievable from available technology and consistent with high reliability.

Both the SB and SD Systems used vacuum tubes as the active device. As a result, the maximum terminal voltage which could be applied to power the systems without unduly affecting the reliability of the high voltage undersea components was a determining factor on the maximum feasible number of repeaters. This maximum limit, in turn, limited the bandwidth of these systems. The availability of transistors with their lower power requirements removed powering voltage as an important constraint. Instead, the need to obtain sufficient feedback to suppress the effect of device variations and nonlinear distortion played a dominant role in setting limits on achievable channel capacity. Halving the

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* This article touches on all aspects of the SF System. For greater detail on any portion of the system or its installation, the reader is referred to the appropriate subsequent article.

repeater spacing from 20 nm to 10 nm* made it possible to quadruple the bandwidth. Increasing the cable diameter from 1.0 inch to 1.5 inches similarly increased the possible bandwidth by 50 percent. The combination of larger cable and reduced repeater spacing resulted in the SF System, with nearly six times the capacity of its predecessor, the SD System. The equivalent-four-wire configuration and the 192 nm spacing between ocean block equalizers were retained from the SD design. This article describes the general design and performance of the SF Submarine Cable System.

II. SYSTEM DESIGN CONSIDERATIONS

2.1 *Load Assumptions*

The design channel load statistics for the SF System are the same as those used in the SD System. These values and the resulting broadband load for the nominal 720 channels are shown in Table I. Although the per-channel-mile cost of the SF System is one-third that of the SD System, it still is economically sound to design for 3-kHz spaced channels and for a TASI load.

TABLE I—SF SYSTEM DESIGN LOAD STATISTICS

Average talker volume	−10.8 vu
Standard deviation	5.8 dB
Activity factor with TASI	0.75
Rms load per channel	−9.6 dBm0
Rms load per group	2.4 dBm0
Rms load per SG	9.4 dBm0
Rms system load per band (720 channels)	19.0 dBm0
Peak factor	13.9 dB
Instantaneous peak load per band*	32.9 dBm0

* This is the load which is exceeded only 0.01 percent of the time during the highest 1 percent of the busy hour.

2.2 *Noise Objectives*

2.2.1 *Thermal and Modulation Noise*

The uncompandored noise objective for a 3500-nm† SF System is set at 43 dBrnC0 over the life of the system. This means that the great majority of voice channels are to contain a total of thermal and modula-

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* In this and subsequent articles in this issue, the abbreviation nm indicates a length of 6087 feet or 1855.3 meters—that is, 1 nautical mile.

† Noise objectives are given for 3500 nm ≈ 4000 statute miles usually used in specifying long haul objectives. This is not to be confused with the maximum design length (used to set high voltage requirements on system components) which is 4000 nm.

tion noise whose value does not exceed 43 dBrnC0 when all channels are carrying the design load described in the previous section. The value of 43 dBrnC0 corresponds to 3 picowatts/km and exceeds the objectives usually assumed for long haul land systems (40 dBrnC0 by the Bell System and 1 picowatt/km by CCITT). It is worth noting that at the per channel loads assumed for land systems, the SF System has no difficulty in meeting these land objectives. The higher noise associated with the design load is justified on the basis of the high cost of improving the performance and in light of the fact that this noise level will only be reached when these higher loads are actually present. Even when the system has been lined up to carry the design load, the noise will be about 2 dB lower at any time when the high level channels are carrying a few decibels less than the design load. This is expected to be the case during most of the operating life of the system since TASI will not be applied immediately and probably never to all the channels.

2.2.2 *Impulse Noise*

High-voltage direct current is used to power the system. With such an arrangement, insulation defects can result in corona impulses or "pops". Here we deal with the requirement on this type of noise.

It is data transmission requirements that set the controlling limits on permissible impulse noise. Because of the expected long life of the system, it was difficult to anticipate all of the possible data services that may be encountered. For this reason, a very conservative impulse noise objective was adopted. The approach was to require that noise impulses occur no more frequently than momentary peaks due to the statistical distribution of the gaussian noise generated by the thermal noise and intermodulation in the repeaters.

Quantitatively, it was assumed that we should hold the undersea system contribution to error probability in a group (48 kHz) data channel to less than 10^{-7}. Gaussian noise will exceed a level 14 dB above rms with about this probability. Thus, a data system which is to achieve a 10^{-7} error rate must be immune to noise peaks 14 dB above rms. Therefore, it could also withstand impulse noise of this magnitude occurring at the 10^{-7} rate.

It had been empirically observed that the corona pop rate changes much more slowly with a given change in threshold than does gaussian noise. For example, a tenfold increase in the probability of exceeding a threshold by corona noise would require dropping the threshold by about 15 dB. For gaussian noise, the threshold would have to be dropped only $\frac{1}{2}$ dB to increase the probability of exceeding it from 10^{-7} to 10^{-6}. Therefore, if corona noise contributed as many errors as gaussian noise at a probability of 10^{-7}, it would contribute negligibly to the error at any larger probability. It also is true that if a 48 kHz channel met the above requirement, any narrower channel would have greater margin.

The above considerations lead to an objective that the undersea system group impulse noise exceed −21 dBm0 less than once every 3½ minutes. This objective was used to obtain a requirement on all components subjected to high voltage which could contribute to impulse noise (for example, repeater power separation filters, seals, epoxy belly band capacitor, and so on) by adjusting for the transmission level at the location of the component, and by allocating the pop rate among all the possible contributors.

It was practicable to impose a sufficiently tight requirement on all contributors other than the power separation filter, so that practically the whole of the acceptable pop rate could be assigned to the latter. Thus, the permissible pop rate for a power separation filter was obtained by allocating the permissible rate for the system equally to a number of power separation filters corresponding to the 25 percent nearest the shores. It is only this number of power separation filters that are subjected to a sufficiently high voltage to make corona likely.

2.2.3 *Tone Interference*

The objective for single frequency interference from linear or nonlinear crosstalk within the system was set at −65 dBm0. This objective is the same as that used for land systems.

2.3 *Repeater Performance Estimate*

Before the fundamental system parameters—cable diameter, bandwidth, and repeater spacing—could be optimized, it was necessary to estimate the obtainable repeater performance as a function of the highest transmitted frequency. The repeater performance in turn was determined by the following.

(*i*) Amplifier configuration—Early studies assumed three common-emitter stages using germanium transistors, shunt interstages, and a shunt feedback network. These could provide sufficient gain-bandwidth for a 5-6 MHz system. Simple resistive terminations were used in the coupling networks with insertion gain shaping in the feedback network. We assumed an output stage biased at one watt.

(*ii*) Repeater noise figure—7 to 8 dB.

(*iii*) Feedback—The top-frequency feedback could be limited by either the available gain or by stability in approximately the following relation:

$$\mu\beta \simeq 81 - 3\mathrm{F} - \mathrm{G_A}\ \mathrm{dB}\ \text{(gain limited)}$$

or

$$\mu\beta \simeq 46 - 33.3\log_{10}\mathrm{F}\ \mathrm{dB}\ \text{(stability limited)}$$

where F = top frequency in megahertz and $\mathrm{G_A}$ = amplifier insertion gain in decibels. For any particular case, the expression resulting in the smaller $\mu\beta$ is the controlling one.

(*iv*) Transistor intermodulation—With a bias of 1 watt, the assumed device intermodulation coefficients were

$$2f/f \simeq -50\ \mathrm{dB}$$

$$3f/f \simeq -80\ \mathrm{dB}$$

for a 0 dBm, 1 MHz fundamental output into a 120-ohm load (60-ohm termination plus 60-ohm output circuit).

(*v*) Power output capability—At the top frequency it was assumed that the repeater would be capable of delivering +20 dBm of sine wave power into the cable before reaching the gain cracking point. Although it was realized that the system would be modulation noise-limited and that the system load would not normally approach this level, the resulting 7 to 10 dB overload margin is desirable because, as discussed below, it permits equalizing misalignment in a way that minimizes the associated noise penalty.

2.4 *Selection of Top Frequency and Repeater Spacing*

The layouts of SB and SD Submarine Cable Systems were made on the basis of thermal noise performance alone, which is the so-called overload limited case. In that case, the system signal-to-noise ratio is optimized by adjusting the repeater transmission levels for maximum average signal power, subject only to the constraint that no repeater is overloaded. For the SF System, unlike earlier submarine cable systems, the resulting transmission levels would cause the repeater modulation noise to exceed the thermal noise. In such a situation, the system is termed modulation limited and the total noise can be reduced by operating the repeater at a level lower than that dictated by overload considerations alone. Optimum noise performance results when the pre-emphasis or signal shaping is adjusted to make the total noise minimum and equal in all channels.

The fact that the SF System proved to be modulation limited also had an impact on the required allowance for misalignment noise penalty. In an ideal system the repeater gain would exactly correspond to the associated cable loss—in any real system this will not be the case. The resulting net gain or loss is called misalignment.

In an overload-limited system, only the highest level repeater can be operated at a transmission level corresponding to the level at which all repeaters would operate in an ideal unmisaligned system. All other repeaters must operate at a transmission level below this ideal level and as a result the thermal noise is increased by an amount (in decibels) corresponding to about $\frac{2}{3}$ the net gain or loss.

In a modulation-limited system, since the level for the ideal case is below that required by overload considerations, it is possible to adjust levels for the misaligned case so that the average repeater level is about the same as the ideal level. In this situation low level repeaters contribute more thermal noise and less modulation noise than a nominal repeater. On the other hand, high level repeaters contribute less thermal noise and more modulation noise. The final result is an increase in system total noise, but a much smaller increase than the corresponding noise penalty for a given magnitude of misalignment in the overload-limited case.

The fact that the SF System was modulation limited, led to the conclusion that a relatively small allowance for misalignment penalty would be adequate. A 2-dB margin was assumed. As an example of what magnitude of misalignment this permits, a 10-dB gain (uniformly distributed along the length of the system and flat with frequency) would result in a 2-dB penalty.

The above objectives, performance estimates, and transmission level considerations were the input to an extensive system study. Various cable diameters were assumed and the impact of moderate changes in the more uncertain performance parameters was studied. A typical output from the study is shown in Fig. 1 which gives required numbers of repeaters as a function of top frequency, assuming $1\frac{1}{2}$ inch cable and nominal repeater performance parameters. The results of the system computations were studied and the largest bandwidth consistent with stable, reliable performance without excessive sensitivity to moderate changes in uncertain performance parameters was selected. The final choice was a 6-MHz top frequency, $1\frac{1}{2}$ inch cable, and 10-nm repeater spacing. This is the case indicated by the dashed lines of Fig. 1.

2.5 *Predicted Noise Performance*

The computed noise for a nonmisaligned 3500-nm SF System is shown in Fig. 2. The computations are based upon prototype repeater data

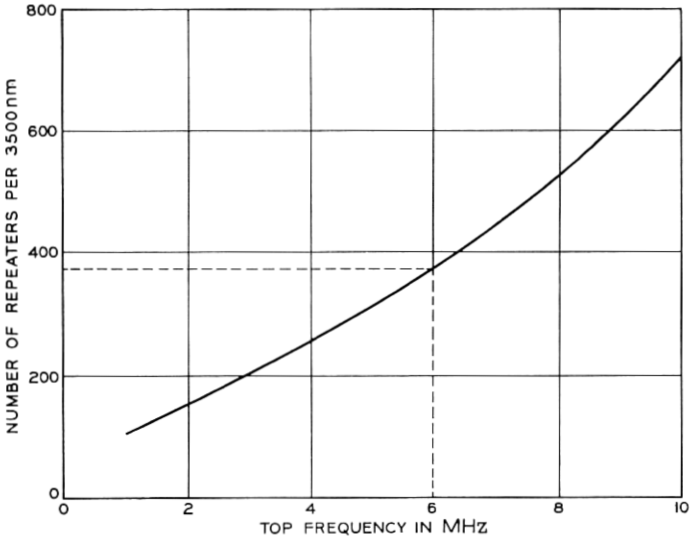

Fig. 1—Top frequency layout of SF System.

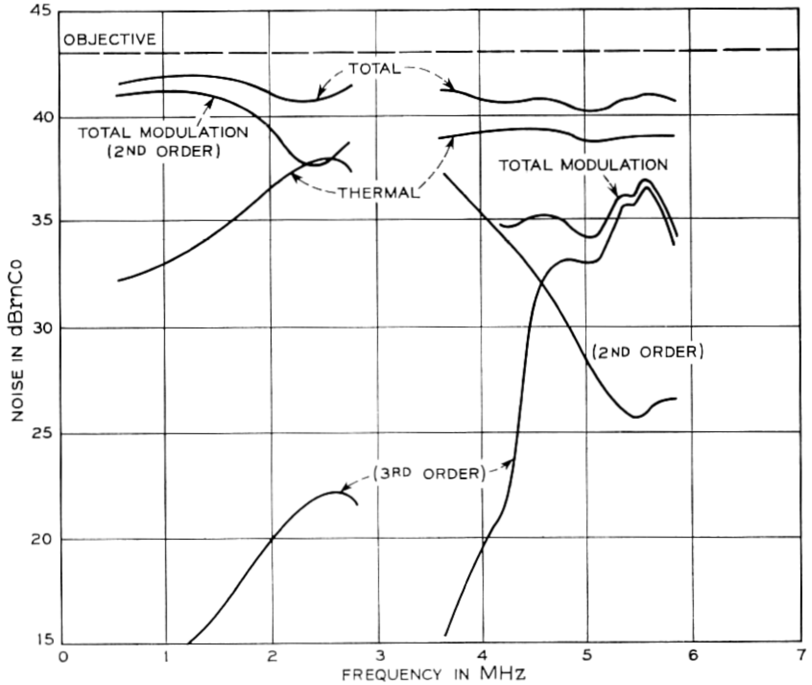

Fig. 2—SF System computed noise performance.

and include the load assumptions of Section 2.1, signal shaping, and the effect of delay distortion on the additive properties of intermodulation noise from repeater to repeater. The performance near the top of the high band indicates clearly that the system is limited by third-order modulation noise rather than overload. The repeater output levels which were obtained in the process of computing the noise are shown in Fig. 3.

Table II lists the nominal load statistics at the output of a repeater corresponding to the assumed loads and signal shaping. The results shown there correspond to a 10-dB margin against overload for an unmisaligned system whose levels have been adjusted to minimize total noise. It is also clear from Table II that the low band contributes negligibly to the total load.

2.6 *Repeater Reliability Objectives*

The SF repeater contains three transistors, four diodes and 120 passive electrical components in the main transmission path. The reliability to be achieved in these components was to be such that a repeater failure in one of the 365 repeaters making up a 3500 nm system would rarely occur. Failure rate objectives were set at:

5 in 10^9 Transistor Hours,

1 in 10^9 Diode Hours,

1 in 10^{10} Passive Component Hours.

Achievement of these objectives would result in a mean repeater failure rate of less than 0.1 failure per year over the useful life of the system. It is impractical to prove in such high component reliability levels by testing prior to installation; hence, the final evaluation of whether the objectives have been achieved or surpassed must await experience with the actual installed systems.

2.7 *System Development*

Once the main system parameters were selected, the final development of the system could proceed. Repeater circuits were refined to optimize performance, reliability, and manufacturability. Repeater gain was trimmed to match the loss of the associated cable as closely as possible. Protection circuits had to be developed to protect the active devices from the tremendous surges that occur in the power path in the event of a cable fault. Crystal-controlled oscillators were developed and incorporated in the repeater. Great care had to be exercised to insure that this additional circuitry would not jeopardize the basic

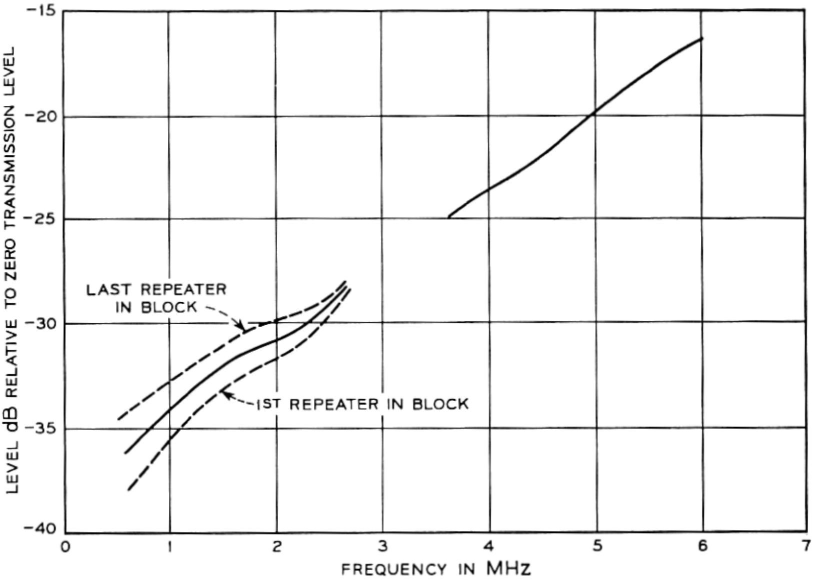

Fig. 3—SF System nominal repeater output levels.

performance of the amplifier. This required, for example, studying and setting limits on intermodulation in the output surge protection diodes. Similarly, very tight harmonic requirements were imposed on the low band supervisory oscillator. Furthermore, these "accessory" circuits had to be incorporated in such a manner that it would be unlikely for a failure in these circuits to cause a failure in the basic repeater.

At this point in the development, an unusual situation during the installation of an SD System led to the discovery of a new phenomenon. It was found that equivalent-four-wire-systems using a common amplifier for both directions of transmission were subject to a so-called "overload sing." Under certain conditions, a momentary overload could

TABLE II—MULTICHANNEL LOAD AT REPEATER OUTPUT

Band	Instantaneous Peak Load (dBm)	rms Load (dBm)
Both	13.8	− 0.7
High	13.5	− 1.1
Low	2.8	− 11.8

Repeater maximum permissible output power = 20 dBm rms sine wave.

produce a situation in which intermodulation shifts energy from high band to low band and low band to high band in such a way that the overload becomes self-sustaining even in the absence of any signal power. Analysis of the SF System indicated that it had inadequate margins against this type of instability. A method for obtaining adequate margins had to be discovered.

The problem was ultimately solved by including a diode limiter in the low band transmission path in the ocean block equalizer. This limiter prevented the power in the low band from ever reaching a level at which significant energy transfer from low band to high band could occur. It was possible to find a limiting point sufficiently low to achieve this and yet high enough so that normal signals are not significantly affected. The values of Table II which show a 20-dB margin between low band peak power and repeater load carrying capacity, make clear why this is practicable. The directional filters in the ocean-block equalizer prevented the harmonics generated by the limiting itself from entering the high band transmission path and contributing to the instability. The phenomenon, the method of analysis, and the effect of the limiter in increasing margins have been described in detail in a previous article.[1]

Many of the proven SD System features were retained in the SF design.[2] The basic mechanical structure of the high pressure housing, the cordwood type assembly of electrical components, and many of the component types were carried over from the SD design. The directional filters followed the SD design scaled to the new frequencies. The deep sea coaxial cable for SF is $1\frac{1}{2}$ inches in diameter (as compared to the 1 inch diameter of SD Cable) and uses a lower conductance loss polyethylene, but has the same armorless structure that was used in the SD System. The composite center conductor of the SF Cable, composed of strength member and conductor, is identical to that used in the SD Cable.

Subsequent to the development of SD, burial of cable was developed as a technique for protecting cable on the continental shelves from trawlers. Armored cable extending hundreds of miles from the terminals would therefore no longer be necessary. For those limited exposures where burial would not be possible, an armored cable using a 1-inch coaxial was developed. This cable has $1\frac{1}{2}$ times the loss per nautical mile of the deep sea cable, but is much easier to handle than the unwieldly cable that would result from armoring the $1\frac{1}{2}$ inch cable.

III. SYSTEM DESCRIPTION

3.1 *Physical Layout*

The general layout and physical properties of the SF System can be summarized as follows:

(*i*) Signals are transmitted in both directions over a single lightweight $1\frac{1}{2}$ inch armorless cable. The cable has a 6 MHz loss of about 4 dB/nm at sea bottom and a characteristic impedance of 59.4 ohms.

(*ii*) At every repeater, the transmission signals are separated by directional filters into a low band originating at the A shore terminal, and a high band originating from the B shore terminal. (Equivalent-four-wire operation.)

(*iii*) The repeaters, which are spaced at nominal 10 nm intervals, are housed in rigid containers similar to those of the SD System. A brief summary of the achieved repeater performance at 6 MHz is given in Table III. In addition to the usual features of power separation and signal amplification, each repeater includes an oscillator for generating a unique supervisory frequency. These supervisory frequencies are transmitted from adjacent repeaters alternately in the high and low bands. They appear in the system spectrum above the high band channels and below the low band. Figure 4 shows a block diagram of the repeater.

(*iv*) Ocean-block equalizers are placed after every twentieth repeater (counting in the direction of lay). Thus, the length of an ocean block is about 200 miles (192 nm, to be precise) as it was for SD, but the reduced repeater spacing doubles the number of repeaters in a block. The repeaters adjacent to an equalizer are separated by only 2 nm of cable instead of the 10 nm for which the repeater gain is intended to compensate. The missing 8 nm, plus some excess gain incorporated in the repeater at low frequencies, provide the gain needed to permit the equalizer to perform its function of reducing the accumulating misalignment. Directional filters in the equalizer provide separate paths for the two transmission bands, permitting independent equalization of the two bands. This is a departure from the SD design in which equalizer networks were common to both bands.

(*v*) The shore terminals at each end of the undersea system contain

Table III—SF System Average Repeater Performance at 6 MHz

Repeater insertion gain	40.146 dB
Repeater noise figure	7.6 dB
Repeater output power	20.0 dBm
Feedback	22.5 dB
Loss from output collector to cable	3.1 dB
Repeater modulation coefficients*	
M_{2R}	−65 dB
M_{3R}	−95 dB
Nominal repeater impedance	59.4 ohms

* Referred to the output collector at a fundamental tone power of 1 milliwatt.

multiplexing equipment, power plants for the undersea repeaters, and means to equalize the undersea system for flat end-to-end transmission and optimum noise performance. Automatic gain control has also been provided to compensate for the variations in the repeater compression observed when the system load varies around the design value.

The physical layout of the SF System is shown in simplified block diagram form in Fig. 5. Figure 6 shows the frequency allocation for the system. Table IV summarizes the dc power requirements for the undersea system.

IV. EQUALIZATION PLAN

4.1 *General Objectives*

In a 3500-nm SF System the total cable attenuation at the top frequency is about 15,000 dB. Basic equalization of the cable loss is accomplished by shaping the repeater gain to match the loss of its associated cable section. Any difference between repeater gain and cable loss at a particular frequency will cause a transmission deviation. These deviations can accumulate in the overall system, producing misalignments with an associated signal-to-noise penalty. To reduce the misalignment to tolerable limits equalizers are inserted after every 20 repeaters. Residual transmission deviations are equalized in the two terminals.

The repeater gain is shaped to match the loss of 10.07 nm of armorless cable at a nominal sea bottom temperature of 3°C. and depths of 2000 fathoms. In addition, the SF repeater has a specified excess gain in the low band for the purpose of providing additional equalization range at

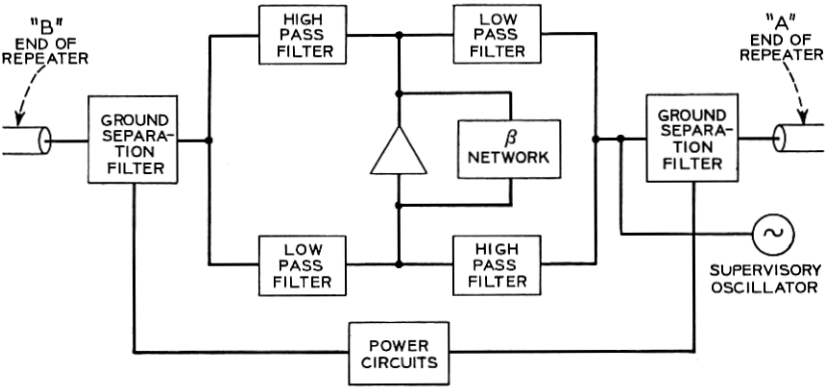

Fig. 4—SF repeater block diagram.

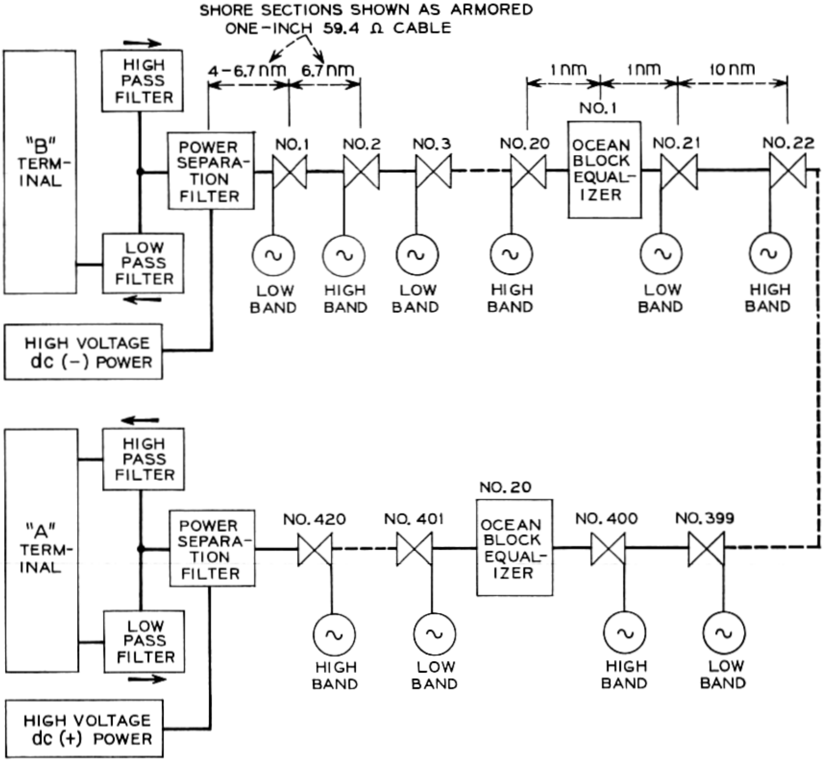

Fig. 5—Physical layout of SF Submarine Cable System.

ocean-block equalizers. The physical lengths of individual cable sections are trimmed at the time of manufacture to give a measured factory loss at 6 MHz that, when adjusted to the sea bottom conditions at the assigned location, will be equal to the repeater gain at that frequency. In this manner, misalignments produced by cable manufacturing variations and other-than-nominal sea bottom conditions can be reduced considerably. The maximum allowable repeater insertion gain deviation from design objectives is $\pm 0.05\ (6/f)^{\frac{1}{2}}$ dB*, resulting in an allowable 6-MHz misalignment of 1 dB in a 20-repeater ocean block.

The cable length adjustments mentioned above will correct manufacturing deviations in cable at all frequencies only if these deviations have the same frequency characteristic as the cable loss itself (that is, the deviations are a constant percentage of the attenuation across the

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* In this and the following expressions, *f* is in MHz.

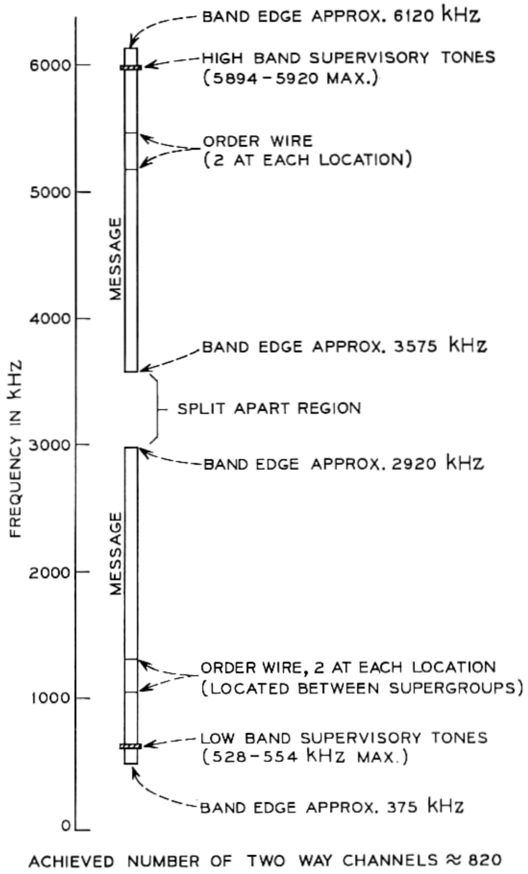

Fig. 6—SF System frequency allocation.

transmission band). To allow for this, as well as for small errors in the adjustment process, a tolerance of $\pm 1(6/f)^{\frac{1}{2}}$ dB of misalignment per block was allocated to the cable at the point where it leaves the factory.

Finally, there can be considerable error in predicting the change in attenuation experienced by cable from the time it is measured in the factory to the point where it is in place at sea bottom. This error is attributed to the effects of handling and possible small errors in the assumed sea bottom temperature and pressure. Errors as large as 2 dB per block at the top of the band are not uncommon—especially if there are several different factories doing the manufacturing. Adding up the various causes of misalignment itemized above gives the result that misalignments as large as 4 dB per 200-mile block could occur. If these were allowed to accumulate across a 4000-nm system, they could accumulate up to 80 dB of net gain or loss at some frequencies. This is clearly unacceptable. Hence, the need for ocean block equalizers.

4.2 *Ocean-Block Equalizer*

The ocean-block equalizer contains directional filters to separate the two transmission bands. This, in addition to simplifying the design of many networks, increases the effectiveness of the equalizer, since each transmission band can be considered independently.

Most of the gain available to the ocean-block equalizer for equalization corresponds to the loss of the 8 nm of cable that the equalizer replaces. Since this is not sufficient at low frequencies where the cable attenuation per nautical mile is much less than at high frequencies, excess gain was built into the repeaters at low frequencies to provide additional gain for equalization. This excess gain is 0.2 dB per repeater at the bottom of the low band and tapers off to zero at the top of the low band approximately linearly with frequency.

Various categories of networks appear in the equalizer. The build-out network in each band has a shape such that an ideal block with no misalignment would require half of the total loss of all the switchable networks plus flat loss to be equalized perfectly. The flat loss is available for mop-up and factory option networks. In other words, the build-out network takes out the *shape* associated with 8 miles of cable, the low band gain bias, and one half of the total switched network loss.

TABLE IV—SUMMARY OF POWER REQUIREMENTS FOR UNDERSEA SYSTEM

Total repeater current	136	mA
Voltage drop across repeater	13.1	volts
Resistance of deep sea cable at 3°C	1.7	ohms/nm
Volt drop (0.136×1.7)	0.231	volts/nm

Voltage drop for 4000-nm system with 417 repeaters:
$4000 \times 0.231 \approx$ 900 volts cable drop
$417 \times 13.1 \approx$ 5500 volts
Total 6400
Earth potential allowance = 2000 volts
Total 8400 volts
Maximal volts per terminal $= \frac{1}{2} \times 8400 = 4200$ volts

In order to achieve the high reliability required of submarine cable systems, extended periods of aging and testing of electrical components are required. This results in a long interval between ordering of components and completion of the first repeaters. This means that some components for equalizer networks had to be ordered before a single repeater was completed by the factory. However, we knew that one of the largest sources of misalignment attributable to the repeater would be the difference between the insertion gain of laboratory prototypes and the average of the manufactured product.

In order to be able to compensate for this difference, a stockpile of submarine cable resistors, capacitors, and inductors was ordered in time to permit adequate aging and testing. Universal mounting plates were also manufactured in advance. Then, when a reasonable number of repeaters had been manufactured to permit estimation of the average, mop-up networks were designed to compensate for the difference between average repeater gain and cable loss.

These networks are restricted to simple series resonance, parallel resonance, low-pass, and high-pass bridged-T configurations. However, there is room for up to seven networks in each band per equalizer and different equalizers may contain different mop-up networks so that there is considerable flexibility available. The amount of flat loss available per equalizer is 8 dB in the low band and 13 dB in the high band, so flat loss transformations can be used to avoid impractical element values.

Provision is made to permit series or parallel connection of resistors and capacitors, allowing ten resistor codes and nine capacitor codes to achieve acceptable granularity. Adjustable inductors with 41 different nominal values complete the stockpile. This approach, coupled with massive use of machine computation, permits a three month interval between design and the completion of a finished unit containing that design. This compares to a period of one to two years for the other networks in the undersea system.

Certain sources of manufacturing deviation in the insertion gain of the repeaters had frequency shapes which could be anticipated. These were the deviations due to variations in the Q of directional filter coils and mu-beta effect. Networks to compensate for these shapes were designed and built in advance to be used, if necessary, in one of the mop-up slots. Similarly, networks to compensate for variations in the dissipation factor of the polyethylene were designed and built. The same shape can be used to compensate for the difference between $1\frac{1}{2}$ inch deep sea cable and 1-inch armored cable (whose length has been shortened to make the top frequency loss correct). These cable networks, when used, are the only ones which are common to both transmission bands.

The last category of networks in the equalizer are the switchable networks. There are seven in each band, each one of which may be switched in or out of the transmission path just prior to the laying of an equalizer. This means there are 128 possible combinations in each band. This ship-board adjustment is the last opportunity to equalize the undersea system.

Most of the sources of misalignment between the time the mop-up networks are designed and the time of laying are associated with the cable. These misalignments are due to the inability to predict the sea bottom loss of the cable in a 200-mile ocean block to better than a couple decibels. Therefore, shapes associated with cable were selected for the switchable networks.

The most basic of these are networks whose loss in decibels is proportional to the square root of frequency. These correspond to a deviation in cable loss that is a percentage change in attenuation constant with frequency. It would be disastrous to run out of range in this shape so a very generous range of $\pm 7.5(f/6)^{\frac{1}{2}}$ dB in one-decibel steps is provided. Two other shapes are provided, both associated with the dissipation of the polyethylene in the cable. These shapes are combined with the $(f)^{\frac{1}{2}}$ to provide one network shape that has its maximum loss near the bottom and the minimum near the top of each band. The other network shape has a maximum near the center and minimum near the edges of each band.

These switchable shapes are shown in Fig. 7. It can be seen that though they are obtained from cause-associated functional forms, they also make a reasonable family for general purpose equalization. Switching circuits permit selection of the desired networks at the time of laying. A specially designed selector on board ship is attached to the switching pigtail brought out of the equalizer housing through a high pressure seal. The selector connects the networks in or out as desired by means of a series of dc pulses. The pigtails are then detached and insulated from the sea water prior to laying the equalizer.

In addition to the equalizing networks, the ocean-block equalizer also contains the previously described diode limiter for suppressing the overload sing.

The equalizing objective for the ocean-block equalizer is to hold the residual cumulative misalignment to an average value of less than ±0.2 dB. This leads to a uniform misalignment of less than ±4 dB in a 3500-

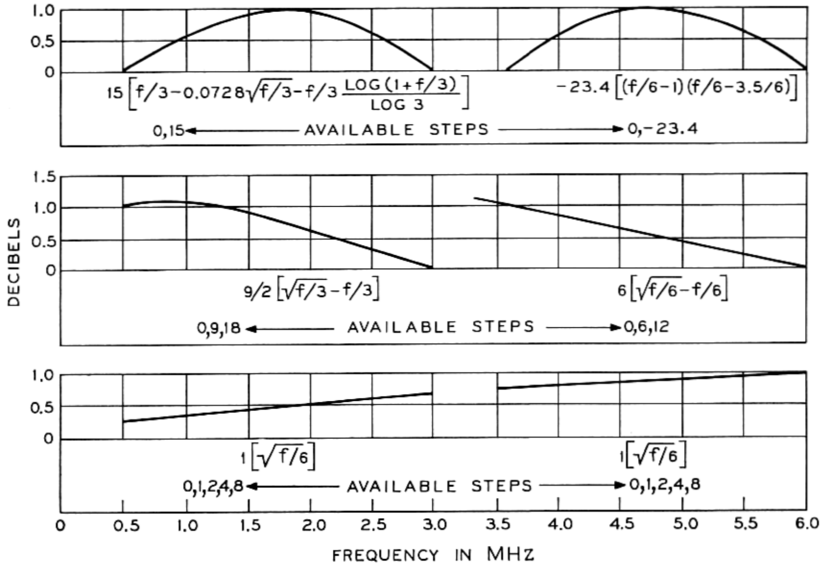

Fig. 7—Ocean block equalizer switchable shapes.

nm system and requires that the equalizer reduce the misalignment accumulated in 200 miles by a factor of 20. When the ±4 dB uniform misalignment is superimposed on the within block misalignment of less than 4 dB, the resulting noise penalty will be below the allocated 2 dB.

4.3 *Terminal Equalization*

Once the system has been laid and misalignments are known, the signal-to-noise performance is determined by the operating signal levels on the system. It is the function of the equalizer networks in the transmitting terminal to adjust transmitted signal levels to optimize noise performance; that is, levels are adjusted to realize maximum and equal channel signal-to-noise ratios. The networks in the receiving terminal are then adjusted to deliver proper levels at the receiving multiplex. Figure 8 is a block diagram of the transmitting and receiving terminal equalizers.

4.4 *Special Equalization Considerations*

4.4.1 *Temperature Misalignment*

In the presence of temperature-associated misalignment, optimum noise performance requires that the transmitting equalizers be adjusted so that the levels of the majority of the repeaters, namely those in deep water, are unchanged. To insure that such equalization is not constrained by overload of the off-shore repeaters, those shoreward cable sections in shallow water may be installed with their loss trimmed to an extreme rather than an average temperature condition. Since the high band signals are pre-emphasized about 10 dB above those in the low band only the high band direction of transmission need be considered. If the B-end cable sections, high-band transmit, are trimmed to nominal loss at the high temperature extreme and the A-end sections trimmed to the low temperature extreme, then transmission level of the shallow water repeaters will never be greater than that of repeaters in deep water. Such a scheme results in a negligible noise penalty but provides an increased margin against overload in case of subsequent change of system loss due to aging.

4.4.2 *Compression*

It has been observed that the gain of the SF repeater is very slightly dependent upon load. At nominal signal levels this "compression" is about 0.2 dB per block at 6-MHz. To compensate for this effect the TAT-5 System was laid with excess gain. With nominal system load, the excess gain compensates for the compression. With a lighter than normal load, there is a slight excess gain in the system, thus reducing the system thermal noise. The modulation noise, because of the assumed

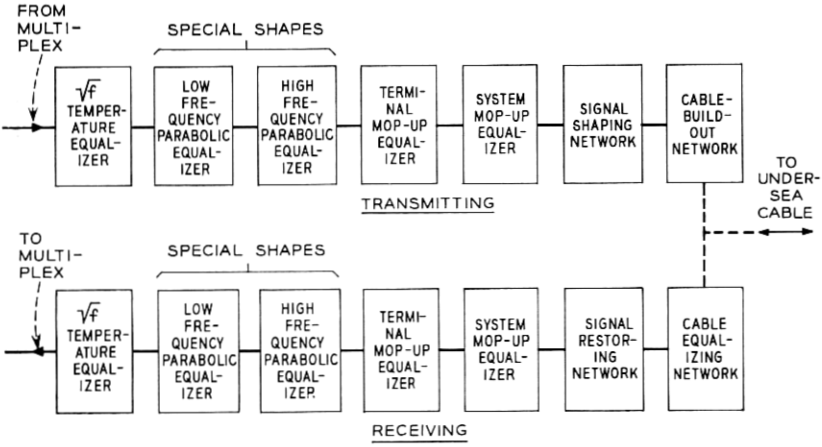

Fig. 8—Transmitting and receiving terminal equalizer.

reduced load, does not increase; consequently, the system noise should never be greater than it would be in the absence of compression.

V. INSTALLATION

Since the capacity of the C. S. LONG LINES is about 1100 nm of the $1\frac{1}{2}$ inch cable, multiple lays are necessary for the installation of trans-oceanic systems. The number of lays required is further increased by the multiplicity of cable factories on different continents, the constraints of manufacturing schedules, and the burying of cable on the continental shelves. The burial has so far been carried out by the Canadian cable ship JOHN CABOT which is ideally suited to the operation. A burial typically involves 50 to 150 nm whereas a deep sea lay usually consists of from 800 to 1200 nm.

Once the repeaters, equalizers, and cable have been manufactured in their respective factories, they meet aboard the cable ship, where they are spliced together and tested to verify that they are working properly. The ship then sails to the end of the previously layed cable. (This end has been left attached to a buoy.) The previously layed end is brought on board and spliced to the shipload. The buried portion and the whole shipload are then powered and laying commences. Testing is carried out continuously during the laying so that any trouble condition becomes evident immediately. Testing also yields data for setting the ocean-block equalizers. Each equalizer has a transmission pigtail coming out of the housing to permit measurements between shore and the next equalizer to be layed. Just prior to laying, the equalizer is stepped to a set of networks selected on the basis of the measurements.

Next, the stepping and transmission pigtails are overmolded to insulate them from the sea. Measurements are then made through to the subsequent equalizer. The data collected during laying is useful in the administration of the systems after installation and makes possible improvements in performance on subsequent systems.

VI. ACHIEVED PERFORMANCE

At this time, two SF Systems have been installed. One system extends between Florida and St. Thomas in the Virgin Islands. The other is TAT-5 between Rhode Island and Spain, which has just been completed. In both systems about 100 additional two-way channels beyond the nominal 720 were achieved.

System performance is measured and optimized during line-up by noise loading the entire transmission band to the design load and then measuring the total noise in a number of cleared narrow slots. Thermal noise is measured conventionally on the unloaded system. Figure 9 shows the results of measurements on TAT-5 after level optimization has been completed, and Fig. 10 shows the corresponding transmission levels. In both cases, results are compared to the *a priori* computed values of Figs. 2 and 3. Discrepancies are due to the 100 extra channels, the misalignment, and the fact that, practically speaking, a unique best signal shape is hard to define. Most channels are seen to meet the 43 dBrnC0 objective with a margin of at least 1 dB.

Impulse noise measurements on a few groups while the system was unloaded, confirm that noise peaks obey the gaussian distribution typical of thermal noise. This verifies that corona impulse noise is not contributing.

Figure 11 shows an average within-block misalignment (misalignment of 20 repeaters and the associated cable, without the equalizer). The large shape across the low band is the previously mentioned excess gain which was purposely incorporated in the repeaters to provide enough low frequency gain for equalization by the ocean-block equalizer. The dashed curve is the average deviation per block after equalization by the ocean-block equalizer. An expanded scale plot of this is shown in Fig. 12. The results of Fig. 12 are average values. There is considerable variation from one block to the next. This is shown in

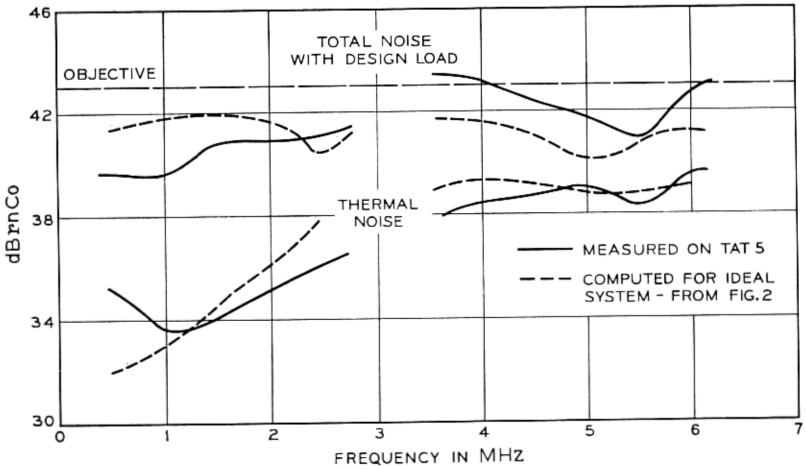

Fig. 9—Measured thermal and total noise for TAT-5.

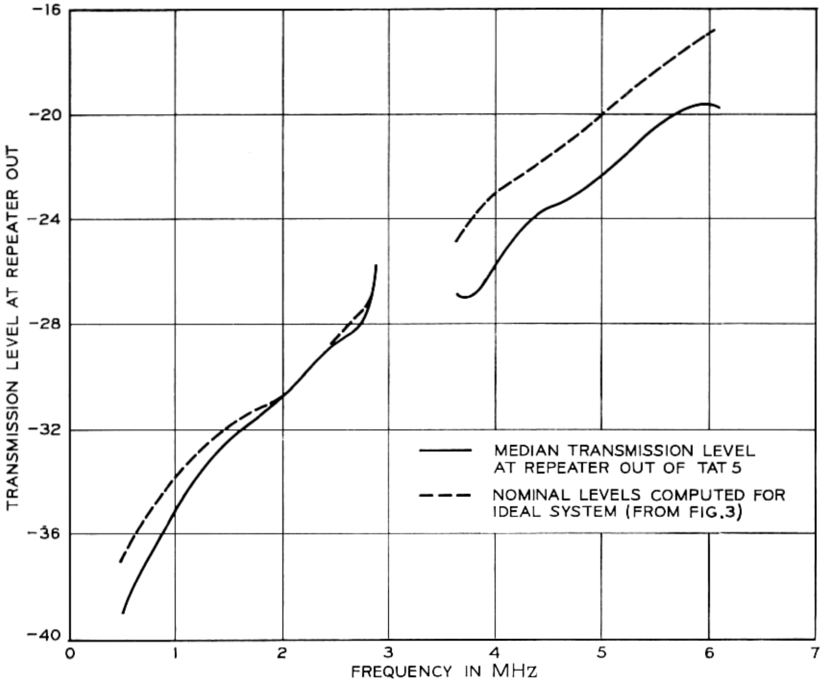

Fig. 10—Signal levels for TAT-5.

Fig. 13 which shows the relative levels of the first and last repeater in each block for a few typical frequencies.

Figure 14 shows the total misalignment of the undersea system. It is composed of the residual misalignment which accumulates from block to block plus the misalignment of the last block which has no ocean block equalizer associated with it. Figure 15 shows the residual misalignment after equalization by the high frequency lines in the terminals. In other words, this is the misalignment which remains to be mopped up by the multiplex. Examination of the equalization results discussed in this paragraph indicates that the equalization objective has been met or exceeded. Future systems can be expected to do somewhat better as the knowledge gained during the installation of TAT-5 will be applied to the design of new mop-up networks for the ocean-block equalizer.

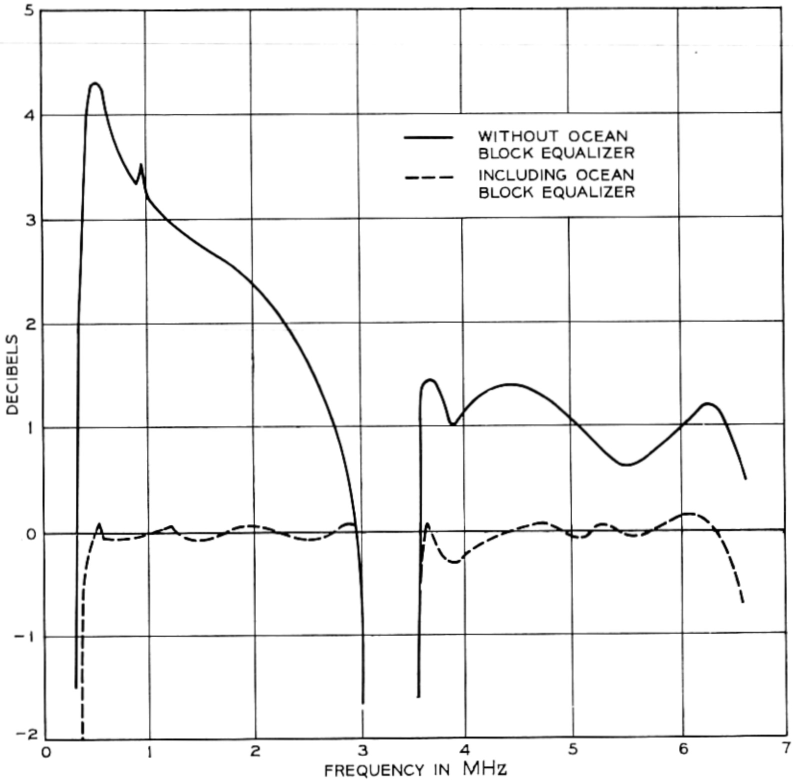

Fig. 11—Average within block misalignment.

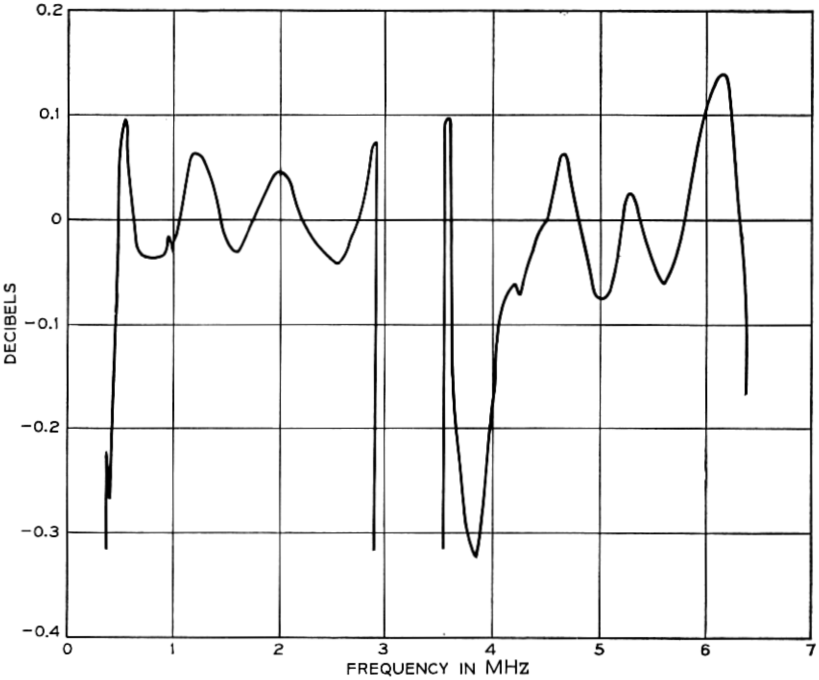

Fig. 12—Average misalignment after equalization by ocean-block equalizer.

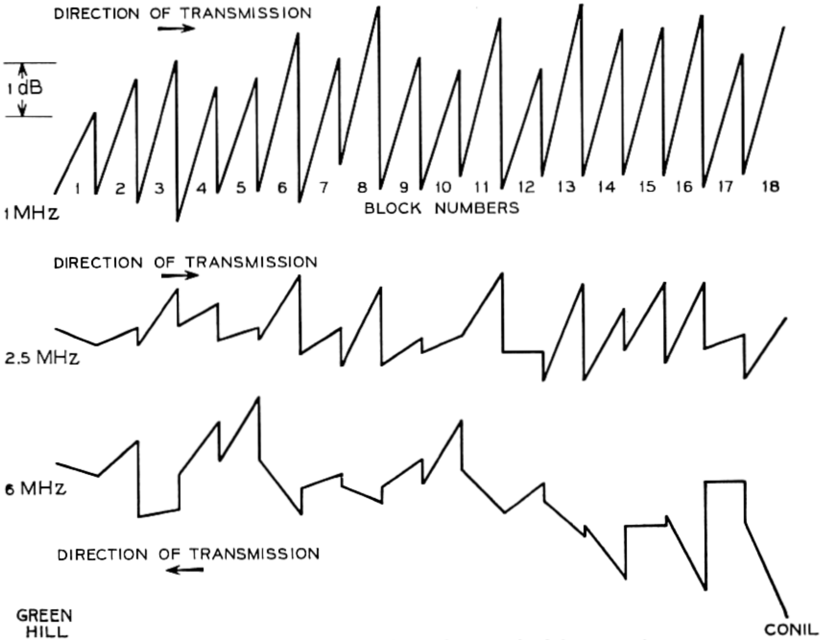

Fig. 13—Ladder diagram for a few typical frequencies.

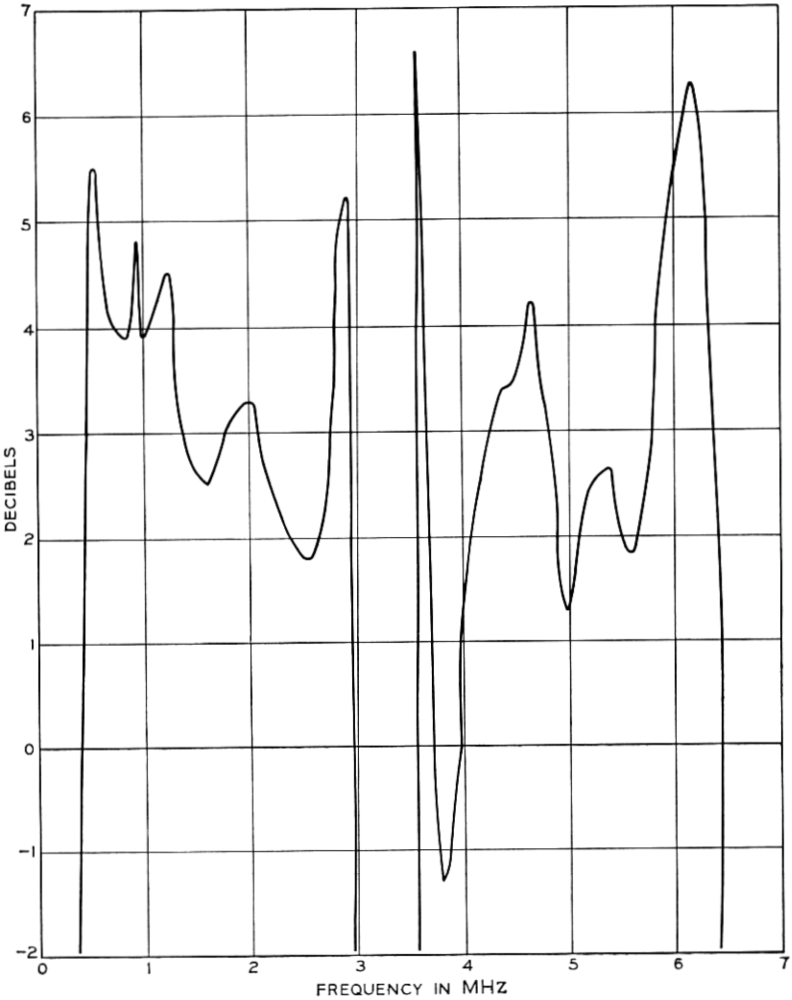

Fig. 14—Misalignment of undersea system.

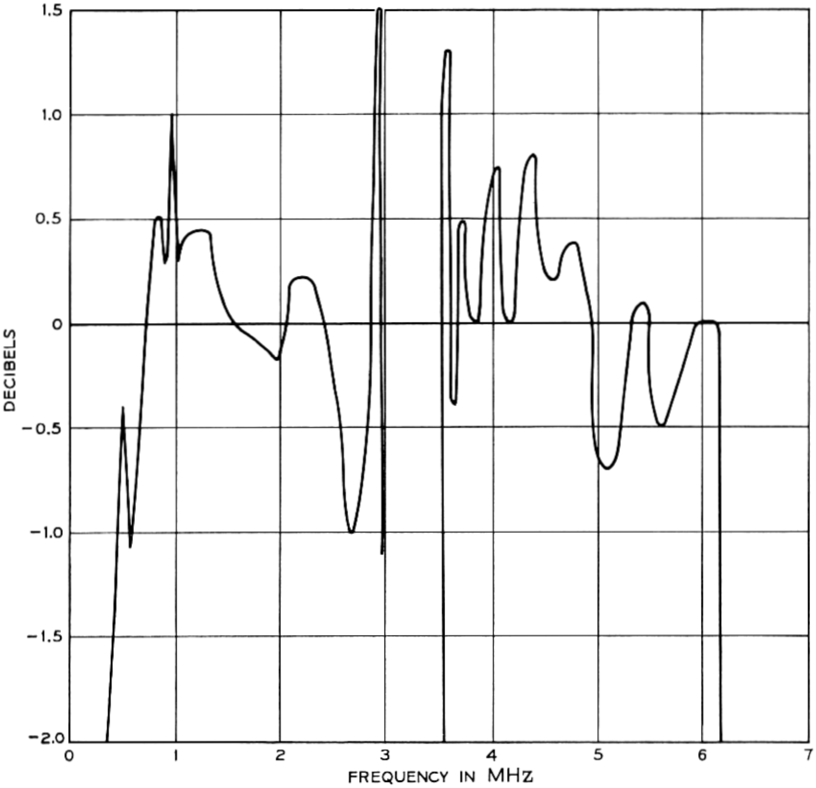

Fig. 15.—Residual deviation after terminal equalization (MX-out to MX-in).

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