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SG Undersea Cable System:

Requirements and Performance

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This paper reviews the major parameters of the SG Undersea Cable System. SG transmission goals and signal statistics were established, which led to a specific system and equalization design. As the SG design evolved, information on cable aging led to the introduction of four shore-controlled equalizers in the SG transatlantic link (TAT-6). Performance delivered by the TAT-6 link has been generally satisfactory, though some excess noise was encountered in the top third of the high band. Equalization results permit the link to handle 4200 two-way voice channels, 200 more than the objective.

I. INTRODUCTION AND BACKGROUND*

1.1 Traffic growth and forecast

Since 1956, when voice communication across the Atlantic by undersea cable began, growth in traffic has continued at a rapid rate.[1,2,4,5] The two upper curves of Fig. 1 indicate the growth of (*i*) total U.S. overseas phone messages and (*ii*) transatlantic phone messages. Data plotted here include traffic by satellite and radio, as well as by cable. Between 1960 and 1976, annual overseas phone messages have increased from 3.7 to 87.7 million. This represents an exponential growth of 22 percent per year. Transatlantic phone messages to Europe have increased from 1.0 million in 1960 to 29.7 million in 1976. Thus, Atlantic basin growth rate is 24 percent per year. Projecting 1976 traffic at growth rates experienced to date yields an expected 520 million total overseas phone messages in

* This paper broadly covers all aspects of the SG system. For greater detail on any particular facet of the system, the reader is referred to the appropriate subsequent article in this issue of the B.S.T.J.

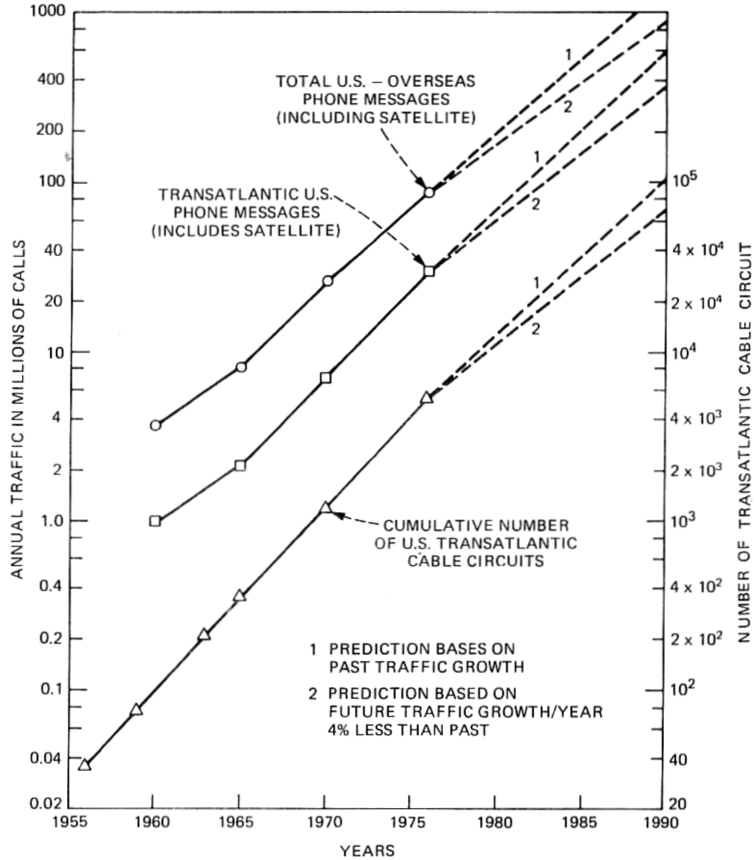


Fig. 1—U.S. overseas and transatlantic growth.

1985, of which 203 million would be transatlantic. These projections are plotted as the upper dashed curves of Fig. 1. If we assume that future growth rates will be 4 percent less than past ones, we get the lower dashed curves of Fig. 1. This more conservative forecast anticipates 385 million total overseas phone messages by 1985, of which 151 million would be transatlantic. The lower cost to the customer that can be expected to result from further economies of advanced technology, plus the convenience of direct subscriber dialing of overseas calls, will be powerful forces to continued rapid traffic growth.

1.2 Transatlantic cable circuit growth

The bottom curve of Fig. 1 shows the transatlantic undersea cable circuits installed to meet traffic needs. Beyond 1976, the circuit projection is at two rates, the past transatlantic traffic-growth rate of 24

Table I — U.S. transatlantic cable circuits

Actual Year	Cumulative Circuits*	Added Circuits	New System
1956	36	36	TAT-1
1959	72	36	TAT-2
1963	212	140	TAT-3
1965	352	140	TAT-4
1970	1172	820	TAT-5
1976	5372	4200	TAT-6

Forecast Year	24%/yr Growth	20%/yr Growth	Additional Cable Circuits Needed Beyond TAT-6	
			24%/yr	20%/yr
1980	12,700	11,140.	7330.	5770.
1985	37,200	27,720.	31,900.	22,300.
1990	109,200	68,970.	103,800.	63,600.

* Figures are for physical circuits, and do not include a limited number of TASI-derived circuits on installed systems.

percent per year, plus the more conservative rate of 20 percent per year.

Table I shows this growth in tabular form. The lower part of the table indicates the cumulative number of circuits we expect to need up through 1990. If the 24 percent growth rate is sustained, by 1980 another 7330 cable circuits will be needed beyond TAT-6, and by 1985 some 31,900 added cable circuits will be needed.* If we experience the more modest 20 percent per year growth, we will need 5770 additional cable circuits by 1980 and 22,300 new cable circuits by 1985.

With such exponential growth, it is interesting to consider the possible effect speech concentrators such as TASI (Time Assignment Speech Interpolation) could have on future demand. Moderate application of TASI could defer the forecasted circuit needs by one year. Fairly extensive application of TASI could yield a 2-year postponement. After the transient resulting from the introduction of TASI, circuit needs would be expected to grow at the same rate as before.

II. PLANNING THE SG SYSTEM

2.1 Repeater performance

Table II shows key repeater parameters of the SF and SG systems.† Although the SG repeater has five times the top frequency of the earlier SF repeater, it actually has slightly better performance. Better noise figure, linearity, and output power capability result from (*i*) use of silicon

* Future cable circuit needs shown in Table I assume that both cables and satellites will share future growth and that this sharing will continue on the basis of the present cable-satellite facility ratio.

† The appendix following this paper defines various terms and symbols which are used.

Table II — SF and SG repeater parameters

	SF	SG
Nominal top frequency	6.0 MHz	29.5 MHz
At repeater top frequency:		
Insertion gain	40.1 dB	41.0 dB
Noise figure	7.6 dB	3.5 dB
Maximum output power, rms single sine wave	20.0 dBm	23.0 dBm
Loss, amplitude output-to-cable	0.3 dB	1.2 dB
Modulation coefficients*		
M_{2E}	−65 dB	−70 dB
M_{3E}	−95 dB	−113 dB
Nominal impedance	59.4 ohms	50 ohms
Type transistor	Ge mesa	Si planar
Supervisory tone power at repeater output		
Low band	−60 dBm	−50 dBm
High band	−50 dBm	−40 dBm
DC current	136 mA	657 mA
DC potential drop	13.1 V	12 V

* Referenced at power amplifier output.

planar transistors rather than the earlier germanium mesa transistors, (*ii*) use of active rather than passive terminations at the amplifier's input and output ports, and (*iii*) more compact physical structure.

2.2 Channel capacity

The rapid growth in traffic and the state of electronic technology were major factors determining the channel capacity of the SG system. As the start of development, our target was 3500 channels; this goal was later shifted to 4000 channels. The actual U.S.-to-France SG installation satisfactorily equalizes 4200 channels.

2.3 Cable diameter

A separate article describes in detail the SG cable design.[6] Early in the development, studies considered the economics of various possible systems as a function of cable diameter. A larger diameter cable, while more expensive and more demanding of ship capacity, has less loss and therefore saves repeaters and equalizers. Thus, as systems increase in capacity and therefore top frequency, larger cables become more desirable. Our studies showed that cable of 1.7-in. dielectric diameter would yield near-minimum system cost. This size cable also offered the possibility of lower dc resistance, which would reduce terminal voltage.

2.4 Repeater configuration

Figure 2 shows the two repeater configurations considered for SG. Separate high-band and low-band amplifiers avoid the nonlinear sing problem[3] and make design somewhat easier. This configuration also prevents second-order distortion from falling in the high band. On the other hand, the single-amplifier configuration improves reliability by

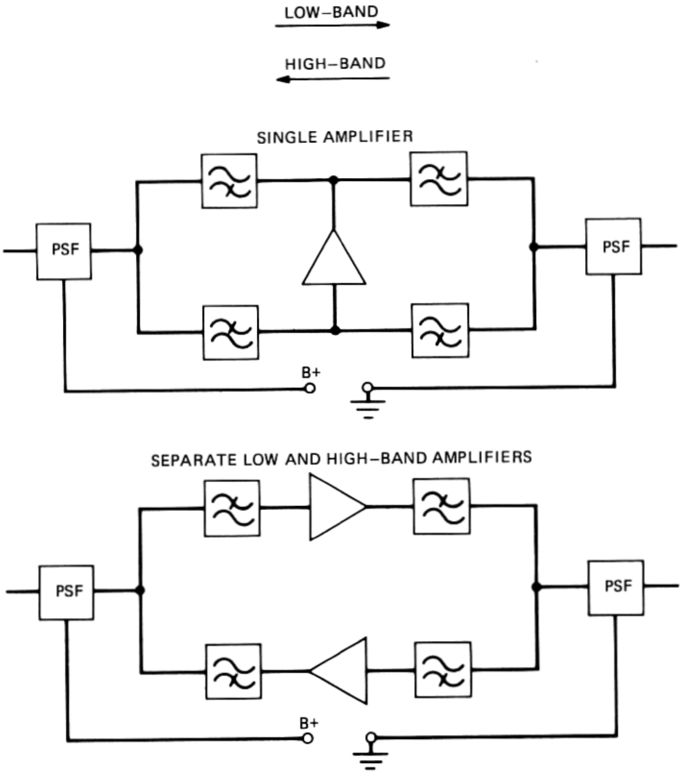


Fig. 2—Possible SG repeater configurations.

reducing the total number of components and devices. Exploratory studies indicated that the noise sing and the other design problems could be solved. These studies led to the choice of the single amplifier repeater configuration.

A side benefit of the single amplifier configuration is the use of intermodulation products from the repeaters to perform fault location and supervision, including detection of a badly modulating repeater. This supervision is done by a frequency-sweeping repeater monitoring set. In addition to the repeater monitoring set, the SG system includes a supervisory oscillator in each repeater, similar to the SF system arrangement.[7] Successive repeaters alternately have low-band and high-band quartz crystal supervisory oscillators by which each repeater may be identified. Since these supervisory oscillators inject known amounts of power, the individual supervisory powers received in the terminal also indicate transmission levels within the system.

III. GENERAL DESCRIPTION

SG is an equivalent four-wire coaxial cable system, with a nominal capacity of 4000 two-way, 3-kHz-spaced channels, and a maximum length capability of 4000 nautical miles (nmi). The TAT-6 physical layout is shown in Fig. 3.

SG frequency allocations are specified in Fig. 4. The nominal low and high bands shown correspond to adequate bandwidth for the 4000 channels and allow for supervisory tone bands, 8-kHz guard bands between supergroups, and three order-wire channels. In the development, transmission was extended as far beyond all band edges as possible without added complexity in the repeaters and without impairing transmission within the nominal band. Practically, this meant that attention had to be paid to transmission in the extended bands of 0.5 to 13.9 MHz and 16.1 to 29.5 MHz. The bandwidths actually achieved on TAT-6 (corresponding to about 4200 two-way channels) are also indicated on Fig. 4.

A noise objective of 1 picowatt per kilometer* applied to the average noise in the 4000 channels that form the basic system, with none of these channels to exceed 2 pW/km.

The ocean-block equalizers (OBEs) equalize the gain deviations present at the time of installation due to the difference between actual repeater gain and cable section loss. The equalizers obtain the gain needed for equalization by shortening to one mile the total cable length between the two repeaters adjoining an equalizer. This makes 80 percent of the gain of a repeater available for equalization. Additional equalization gain is provided in the low band by designing excess gain relative to cable loss into each repeater (low-band gain boost).

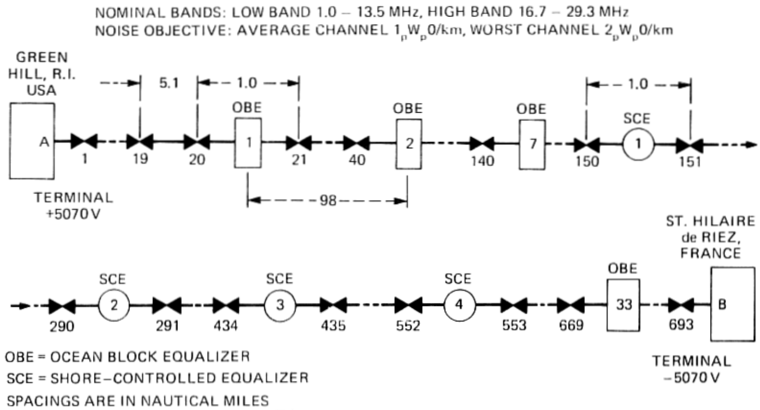


Fig. 3—TAT-6 SG link.

* The 1 pW0p/km channel noise objective corresponds to 38.5 dBrnc0 for TAT-6. Our "ideal" performance target was 36.5 dBrnc0. Thus, 2 dB of noise performance was allowed for the effects of misalignment, etc.

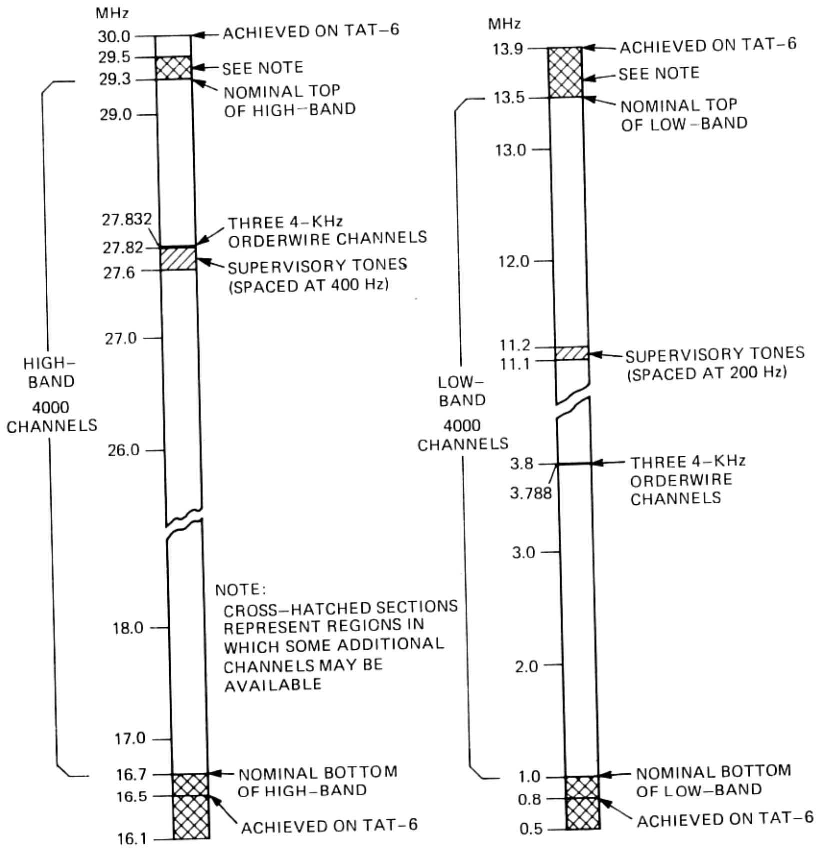


Fig. 4—SG frequency allocation.

Fairly late in the development, problems encountered during the manufacture of cable led to the discovery of phenomena that could cause the attenuation of installed cable to change with time (cable aging). Since the magnitude, frequency characteristic, and even the direction of such cable aging was uncertain, some means of adjusting the equalization along the length of the system subsequent to installation appeared to be required. On a crash basis a shore-controlled equalizer (SCE) was developed. Four such units were included in the TAT-6 link, dividing the system into five approximately equal-length "sectors." The SCEs obtain gain for equalization in the same way as the OBEs, as described above.

3.1 Transmission objectives and computed performance

The average power per channel, P_c, assumed in the SG system design is −13 dBm0. This is a conservative value for present signals and mixtures of voice and data. The −13 dBm0 figure would allow use of speech concentrators on about one-half the channels used to carry voice.

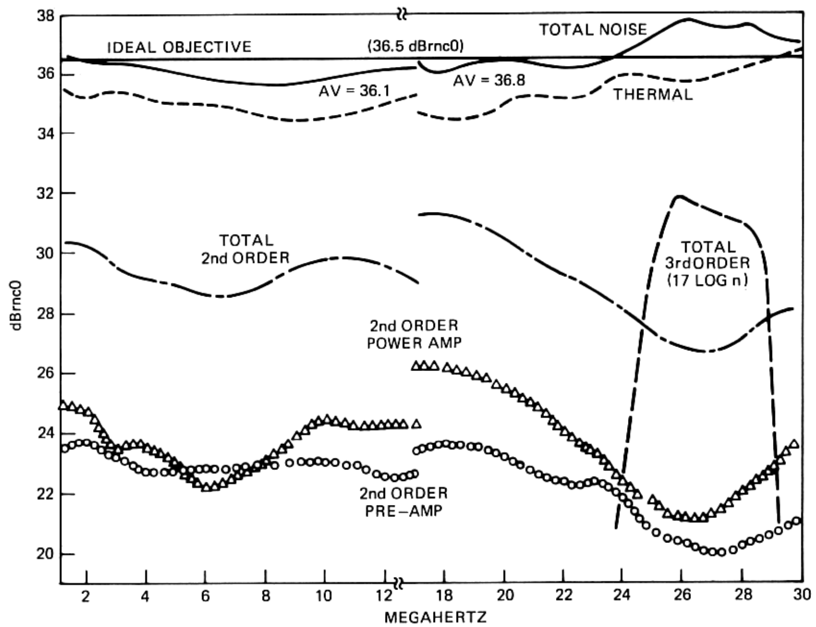


Fig. 5—SG system calculated noise performance (no misalignment, 3500 nmi, 700 repeaters, dBm0/channel = −13, overload margin = 6.2 dB).

Actually, initial convervatism and a continuing decrease in average talker and data volumes will make the −13 dBm0 average channel power adequate in the future even if there should be an increase in power on all voice channels due to the general use of speech concentrators.

A broadband load of 4000 two-way channels carrying the −13 dBm0 load per one-way channel has an average power, P_{av} of 26 dBm0 and a peak value of 39 dBm0.*

The anticipated repeater performance is discussed further in a subsequent section. From this performance, the assumed load, and the number of repeaters necessary to span the Atlantic (about 700), it is possible to compute the expected system noise performance for any assumed transmission levels across the two transmission bands. The goal is to arrive at optimum signal level vs. frequency shaping that corresponds to the minimum flat noise for a particular link. Final shaping is determined by experimentally shaping signals and evaluating the results by system noise power ratio tests.

Figure 5 is the computed noise performance of an ideal system (with only the intentional gain boost appearing as misalignment), corresponding to the transmission levels shown in Fig. 6. The objective for

* Average load = $-13 + 10 \log_{10} (2 \times 4000) = +26$ dBm0. The signal has peaks extending 13 dB higher than this 0.001 percent of the time. This peak-to-average ratio is the multichannel peak factor, k_m.

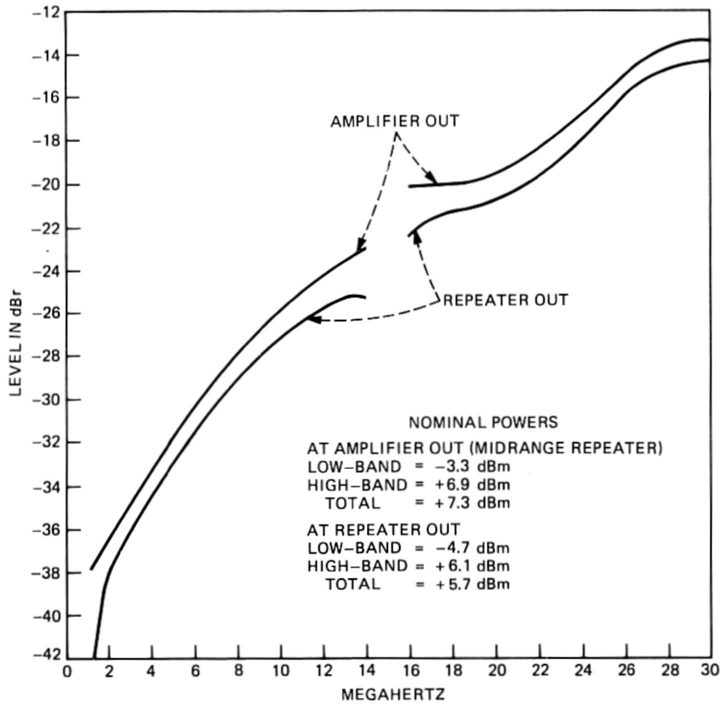


Fig. 6—Nominal transmission levels.

a 3400-nmi transatlantic length on this basis is 36.5 dBrnc0, to allow the 2-dB performance margin mentioned earlier. The results of Fig. 5 show that the estimated noise performance is approximately the desired 36.5 dBrnc0.

As stated in Fig. 5, the overload margin to take care of the highest level repeater is about 6 dB.* A *total* flat misalignment of 12 dB would use up about 1.3 dB of the performance margin. This misalignment is the maximum that can be equalized *equally* at the transmitting and receiving terminals. To avoid overloading any repeaters, additional misalignment would have to be equalized entirely in the transmitting terminal if the misalignment is gain, or entirely in the receiving terminal if the misalignment is loss.† Such nonsymmetric equalization results in considerably greater misalignment penalty than does symmetric equalization.

3.2 Equalization plan

The first level of equalization in the SG Undersea Cable System is to

* That is, the zero-misalignment repeater operates at an average signal power output which is 6 dB below the repeater's capability.

† Ripples across the transmission load that average out (i.e., leave the broadband load unchanged) can always be symmetrically equalized.

match the gain of the repeater to the computed loss of 5.1-nmi of cable under the nominal condition of 2.5°C and 2.5 kilofathoms (kF).

The next level of equalization is provided only in shallow-water repeaters that are subject to seasonal temperature variations. These repeaters have a temperature-sensitive gain characteristic that will compensate for loss changes in the cable resulting from ambient temperature variations.

After a route for a particular installation has been selected, cable sections are ordered from the factories by 29-MHz attenuation, not by length. The idea is to obtain a top-frequency cable section attenuation at sea bottom which corresponds to the mean top-frequency repeater gain. The ordered loss which a particular section is to measure in the factory (at 10°C, 0 fathoms) is computed so that the attenuation of this section will match repeater gain at the depth and temperature corresponding to its position in the system. This procedure thus tends to correct for manufacturing deviations and differences between actual sea-bottom conditions and the nominal conditions (2.5°C, 2.5 kF) assumed in the repeater gain objective.* The accuracy with which this correction can be done depends, of course, on factory measurement accuracy and the accuracy with which temperature coefficients, pressure coefficients, handling or laying effects, and actual seabottom temperatures and depths are known. The coefficients used to predict the sea-bottom loss are refined, and the accuracy with which the loss is matched to repeater gain can be expected to improve as experience is gained from actual SG installations.

3.2.1 Ocean-block equalizer

In the SG system, a group of 30 repeaters is followed by an ocean-block equalizer (OBE).† Each OBE is adjusted just before being laid and is designed to compensate most of the transmission deviations that have accumulated up to this point in the installation. The OBE contains directional filters that permit the independent equalization of the two transmission bands. The equalization is effected by fixed (mop-up) networks and switchable networks. In addition, each band has a build-out network. The build-out networks are designed so that the total OBE loss is at its nominal value when the switchable shapes are at mid-range.

* Superposed on the procedure described is a small cyclical length perturbation to reduce the systematic addition of interaction ripple due to finite repeater return losses.

† Because of uncertainties associated with first-time installation, the TAT-6 link has an OBE following every 20 repeaters.

This arrangement allows an OBE to provide either system gain or loss around a nominal setting.*

3.2.1.1 Mop-up networks. The mop-up networks are bridged-T designs whose purpose is to equalize deviations known at the time the equalizer is manufactured.† The mop-ups are built from a stockpile of pre-aged components on standardized circuit boards, with maximum utilization of special-purpose computer programs. The aim is to minimize the time required to incorporate new knowledge about cable or repeaters into the OBE characteristics.

It is possible, for example, to incorporate knowledge acquired in the first lay (shipload) of a system in the equalizers being manufactured for the third lay. In fact, if there is sufficient reason, an equalizer can, on an expedited basis, have special mop-ups inserted and be ready for use in the next lay. It should be made clear that different equalizers can contain different mop-up networks. Up to seven mop-up networks may be used in each band. The excess gain available for mop-up networks is 9.5 dB in the low band and 12.5 dB in the high band.

3.2.1.2 Switchable networks. The shapes available in the switched networks are shown in Fig. 7; they are relatively smooth and are related to attenuation versus frequency characteristics associated with the undersea cable. (Figure 7 shows the equalization shapes. The actual bump and $\sqrt{f} - f$ networks have some added $\sqrt{f}$ for physical realizability.) The functional forms are listed in a companion article.[8] Each of seven switchable networks in each band can be independently switched either in or out of the transmission path through the equalizer ($2^7 = 128$ combinations are available in each band). The best combination in a particular equalizer is selected on shipboard just prior to overboarding that equalizer. The choice is based on minimizing the misalignment indicated by transmission measurements made during laying. The measured transmission path extends from the shore terminal through the equalizer whose setting is to be determined.

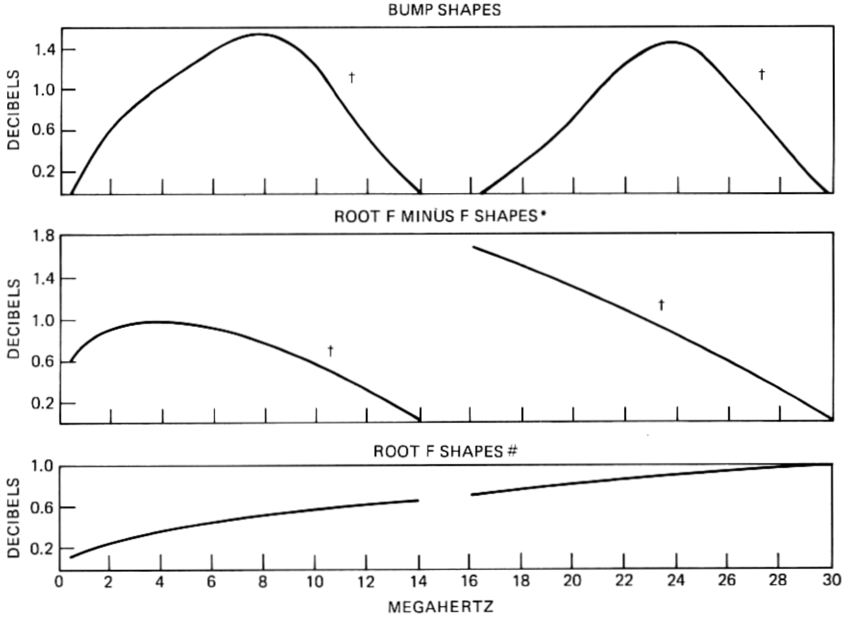
The available amount of shape having a square-root-of-frequency characteristic ($\pm 7.5 \sqrt{f/30}$) is somewhat larger than the misalignment allowed in the misalignment allocation discussed later. However, the large noise penalty which results if equalization range is exceeded dictates a comfortable margin.

3.2.2 Shore-controlled equalizer

As mentioned previously, four shore-controlled equalizers (SCE), di-

* The source of any gain, of course, is an adjoining repeater. In effect, the switchable networks may be set so that the total OBE loss is less than the loss of the 4.1 nmi of cable which are omitted from the section containing an OBE.

† Known deviations whose shape is well matched by the broad switchable network shapes can be equalized by switchable network settings during laying. In using the switchable networks to aid in the mop-up function, one must leave enough range to handle deviations between predicted and actual sea-bottom cable transmission.



*ADDITIONAL NETWORKS ARE PROVIDED, WITH 2 TIMES THE LOSSES INDICATED

ADDITIONAL NETWORKS ARE PROVIDED, WITH 2 TIMES, 4 TIMES, AND 8 TIMES THE LOSSES INDICATED

† THE CURVES SHOWN ARE THE DESIRED FUNCTIONAL SHAPES. ACTUAL SHAPES PROVIDED HAVE SMALL AMOUNTS OF $\sqrt{f/30}$ ADDED TO MAKE THEM PHYSICALLY REALIZABLE.

Fig. 7—OBE switchable shapes.

viding the system into five sectors, were included in the TAT-6 link to compensate cable aging. These equalizers contain directional filters, build-out networks, and switchable networks, but do not incorporate the mop-up function. The switchable shapes are the same as those used in the OBE but with about twice the decibel range. The larger range is possible because no gain is allocated to the mop-ups.

The ranges provided by the SCEs in TAT-6 are adequate to handle up to about 75 dB of top-frequency aging in either direction (i.e., gain or loss) and are consistent with the nonlinear sing margins discussed later in this paper. This amount of aging exceeds our forecasts based on modeling of aging to date. System aging is discussed further in Section IX.

The adjustment of SCEs is controlled from the low-band transmit terminal by a pair of control frequencies unique to each equalizer. A first control frequency is used to select the network to be switched in or out, and the second activates the switching. Second harmonics of the transmitted tones are returned to the terminal. By tuning the frequencies of the control tones to maximize the amplitudes of the returned second harmonics, it is possible to center the control frequencies in the passbands of the SCE's crystal filters. Also, level changes of the returned second harmonic are produced by padding switched in by contacts on a deck of the network-select switch. These level changes indicate which SCE network is being addressed.

By the time deep-sea laying commenced on TAT-6, indications were fairly clear that, at least initially, aging would be in the direction of increasing loss. Thus, the OBEs were adjusted to be a little deficient in loss initially, and each SCE was adjusted to compensate this intentional misalignment, which amounted to 2 dB excess gain per sector at the top frequency.

3.2.3 Terminal equalization and protection

The final level of equalization is provided in the shore terminals. A combination of smooth adjustable shapes, custom-designed residual equalizers, and regulation in the receiving multiplex holds transmission levels within acceptable limits.

At the output of the transmitting wideband line, a special circuit switches in extra loss if an excessive broadband signal is sensed. This is done to provide adequate protection against an accidental gross overload which might be capable of inducing gain changes in the undersea repeaters.

3.2.4 Misalignment allocation

In the design of a system, it is necessary to set misalignment objectives consistent with performance objectives and equalization ranges. These misalignment allocations then determine the permissible tolerances for the various contributors to misalignments. Table III shows the SG misalignment objectives, and Table IV shows the unit accuracies required to meet these misalignment objectives.

The initial uniform misalignment is in the form of sharp ripples, whose shapes preclude their equalization by the simple mop-up networks of the OBE. Sharp ripples have little effect on multichannel load and therefore can be equalized equally at the two shore terminals without cutting into the overload margin. Those ripples which are so sharp that they cannot be equalized in the broadband portion of the shore terminals may be eliminated by supergroup equalizers in the receive terminal. In the latter case, positively misaligned channels would be quieter than most, while negatively misaligned channels would be noisier than most.

3.2.5 Noise penalties due to misalignment

In estimating a noise penalty associated with the allocations of Table III, it is assumed that repeaters are fairly uniformly spread across the 5-dB level range of item I. A few repeaters that fall outside this limit on

Table III — Top-frequency* misalignment objectives for 4000-nmi link

I. Initial within-block misalignment (not including effect of OBE)	
A. Maximum difference between highest- and lowest-level repeater in block	5 dB
B. Maximum difference between extreme-level repeaters of this block and extreme-level repeaters in rest of system	5 dB
C. Allocation of above	
1. Repeaters—total in any block	±1 dB/block
a. Systematic (within each block)	±0.02 dB/repeater
b. Random (within each block)	±0.07 dB/repeater
2. Cable	
a. Same in every block (e.g., error in coefficient)	+2.5 dB/block or −2.5 dB/block
b. Different in every block (error in sea-bottom temperature or pressure and manufacturing variations)	±1.5 dB
II. Uniform misalignment along length of system	
A. Initial† (±0.2 dB/block for a maximum-length system with 30-repeater blocks)	±5 dB/system
B. Aging	±5 dB/sector‡

* Allowance at lower frequencies obtained by multiplying top-frequency values by the smaller of 1.5 or $\sqrt{30/f}$ and does not include intentional low-band boost.
† Assumed to be ripply and thus to have negligible effect on overload margin.
‡ The stated range is consistent with the system noise objective. A total equalization range consistent with up to 75 dB of system aging is provided in the SCEs.

Table IV — Accuracy objectives to meet misalignment objectives for a 4000-nmi SG link with 30-repeater ocean blocks

	dB per unit	Percent
I. Repeater		
A. Average deviation from objective within a block (known and equalizable in OBE)*	±0.02/repeater	±0.05
B. Random (within each block) deviation†	±0.07/repeater	±0.15
C. Unequalizable (from Table III, item II A, ±5/800 repeaters = ±0.006 dB/repeater) (Cause: error in knowledge of gain characteristic, especially any component too sharp to be equalized by the OBE's mop-up networks)	±0.006/repeater	±0.015
II. Cable loss deviations		
A. Average sea-bottom loss deviations (causes are errors in the average: temperature coefficient, pressure coefficient, and laying effect) Limits on total error*	±0.08/section	±0.2
B. Random variations (block to block) (causes are: manufacturing variations, errors in seabottom temperature and pressure, and measuring error) Limits on total error*	±0.05/section	±0.1

* Increased by a factor of 1.5 if block length = 20 repeaters.
† Increased by a factor of 1.2 if block length = 20 repeaters.

the low-level side do not have much effect on system noise performance. On the other hand, a few high-level repeaters, appreciably higher than most repeaters, cut into overload margin, and may cost almost decibel for decibel in performance. This must be kept in mind in equalizing the system as it is laid. In other words, if a high-level repeater occurs early in the installation, subsequent equalization should bring repeaters as close as possible to this level. As the installation approaches completion and a level range has been established by the repeaters already laid, special care should be taken in equalization so that the levels of subsequently laid repeaters do not exceed the maximum of the established range. With these qualifications, a broadband misalignment of 10 dB would increase the ideal noise of Fig. 5 by only 1.25 dB. The ripply uniform misalignment, insofar as it is equalizable in the terminal, could bring the penalty up to 2 dB. The unequalizable portion might degrade a few channels by about 3 dB, improving others by about the same amount.

3.2.6 Nonlinear sing margin

In addition to its effect on noise performance, misalignment is of interest in connection with nonlinear sing margin.

Nonlinear sing is a phenomenon which is possible in equivalent-four-wire systems using a single amplifier for both directions of transmission. Under conditions of gross overload (usually in the presence of large misalignments), these systems can lock themselves up in a so-called noise sing.[3] Under this situation, the nonlinearities result in so much cumulative energy shift from the low to the high band that the energy shifted to the high band can overload that band. The overloaded high band can, in turn, via the common amplifier, produce enough energy shift back to the low band to sustain the whole process.

Detailed computer studies were made using empirical data on repeater behavior under overload for a variety of conditions. It was found that the system would remain stable for superposed misalignments up to 15 to 20 dB.

IV. CABLE

The bulk of any SG system is made up of 1.7-in. core diameter armorless deep-sea cable. The portions on continental shelves are largely composed of single armored cable. The portion from the terminal to the shore as well as the first mile or so out from the shore is shielded and uses a smaller diameter dielectric. The shielding is protection against radio interference in the portions of the system that are exposed to radio fields.

Out to depths of 640 m (350 fathoms), in addition to using armored cable, the cable and repeaters of TAT-6 are buried approximately 0.6 m (24 in.) beneath the ocean floor. These measures should provide excellent protection against cable breaks due to trawlers and dredges.

The attenuation of the 1.7-in. cable at seabottom conditions (2.5 kilofathoms and 2.5°C) is given approximately by ($\alpha = 1.383\sqrt{f} + 0.0178f$ dB/nmi), where f is in MHz. The square-root term is due to resistive losses in the copper, whereas the linear term is caused by dissipation in the polyethylene. At the top frequency of 30 MHz, total loss is about 8.1 dB/nmi. Of this loss, 0.53 dB, or 6.6 percent, is due to dissipation in the polyethylene.

V. REPEATER CHARACTERISTICS

5.1 Supervisory arrangements and insertion gain

The SG repeater consists of a two-stage preamplifier, a three-stage power amplifier, an output band-limiting filter and shaping network, directional filters, power-separation filters, and a supervisory oscillator. Each supervisory oscillator has its unique frequency, which may be used to identify its associated repeater, and to pinpoint undersea system problems. Normally, repeaters with low-band oscillators alternate with repeaters having high-band oscillators.

The gain objective for the SG repeater is the sum of the loss of 5.1 nmi of cable at 2.5 kilofathoms and 2.5°C and the low-band gain boost. The gain shape is shown in Fig. 8.

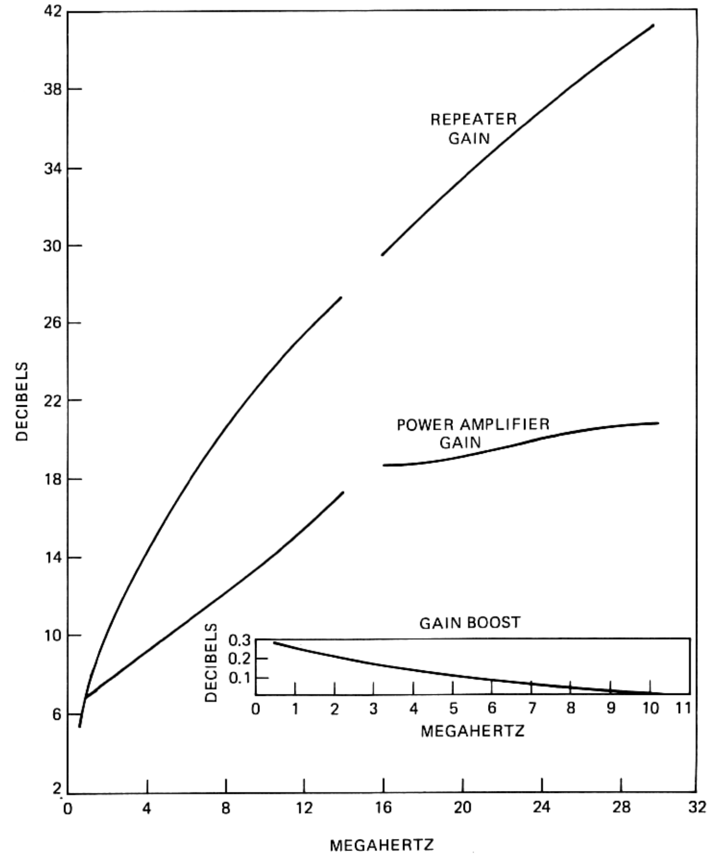


Fig. 8—Repeater and power amplifier gain.

5.2 Noise and modulation performance

Figures 9 through 15 show the values of the various parameters* which, along with repeater gain, determine the noise performance of the system. As was indicated in Fig. 5, the pre-amplifier and power amplifier contribute about equally to the second-order intermodulation noise. The total for the repeater is the voltage sum of the noise produced by the pre-amplifier and power amplifier. The power amplifier is the dominant contributor of third-order noise. The computed contribution of the pre-amplifier raises the total amplifier noise by less than ½ dB, even when the two sources are added on a voltage basis.

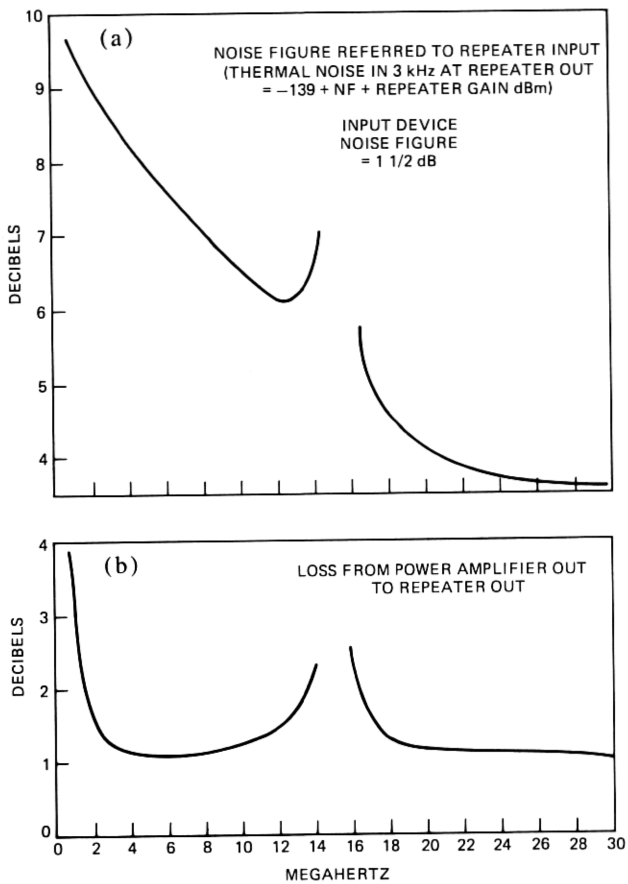


Fig. 9—(a) Repeater noise figure. (b) Output loss.

* These data are the ones determined prior to the installation of TAT-6 and used for the noise computation results of Fig. 5. As discussed later in this paper, the M_{3E} values shown were better than actual repeater performance over the upper portion of the high band.

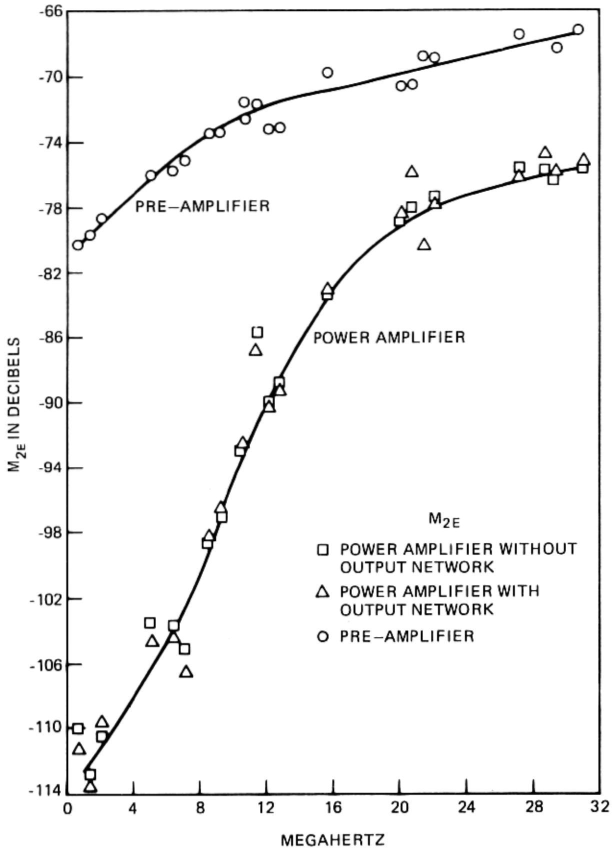


Fig. 10—M_{2E} repeater modulation coefficients (referred to POWER AMP OUT and to PRE-AMP OUT, respectively).

5.3 Load-carrying capacity

Figure 13 shows the behavior of M_{2E} and M_{3E} coefficients as a function of peak repeater output power. Four frequencies are used in the test to give a reasonable peak factor, even though only two or three of the four sine waves are involved in the measured product.

If the repeater behaved according to the classical Taylor series model, the curves displayed on Fig. 13 would be horizontal lines, i.e., intermodulation coefficients would be constant. Actually, the coefficients deviate from this ideal picture as the load is increased, eventually going off in the unfavorable (upward) direction. One can define the load capability in terms of a departure of the coefficients by a few decibels from their low-level values. One can conclude from Fig. 13 that the peak power capability of the SG repeater is approximately 26 dBm.

To obtain the results shown in Fig. 14, the circuit is loaded with frequency-shaped thermal noise except for a slot at 27 MHz. In this slot,

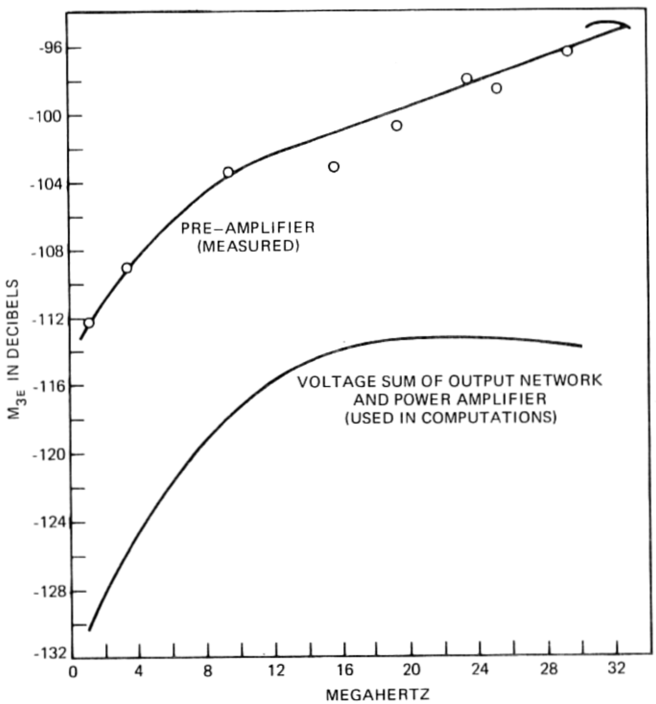


Fig. 11—M_{3E} repeater modulation coefficients (referred to POWER AMP OUT and to PRE-AMP OUT, respectively).

the intermodulation noise of a single repeater is fed into a 1.74-kHz bandwidth detector and then into a multi-channel amplitude analyzer.

The resulting amplitude distributions are plotted for a number of repeater output powers in Fig. 14. As the curve shows, at +14 dBm, very slight departures from a Gaussian distribution are noted. By the time the test signal has been raised to +15 and +16 dBm, gross departure from a Gaussian distribution is observed. Although the results are not plotted in Fig. 14, for test signals of +13 dBm and lower, the amplitude distribution of intermodulation noise is indistinguishable from a Gaussian distribution.

The test results shown on Fig. 14 prove to be a very sensitive means of determining the repeater's load capacity. Note that a random noise test signal of +13 dBm corresponds to a peak power of +26 dBm or an rms sine wave power of +23 dBm. Thus, the load capability determined from Fig. 14 agrees with that determined from Fig. 13 and the value used in the system layout shown in Table II.

Finally, Fig. 15 presents the limits on gross overload; exceeding these would risk inducing repeater gain change. These last limiting powers, which exceed considerably the load capacities defined by Figs. 13 and

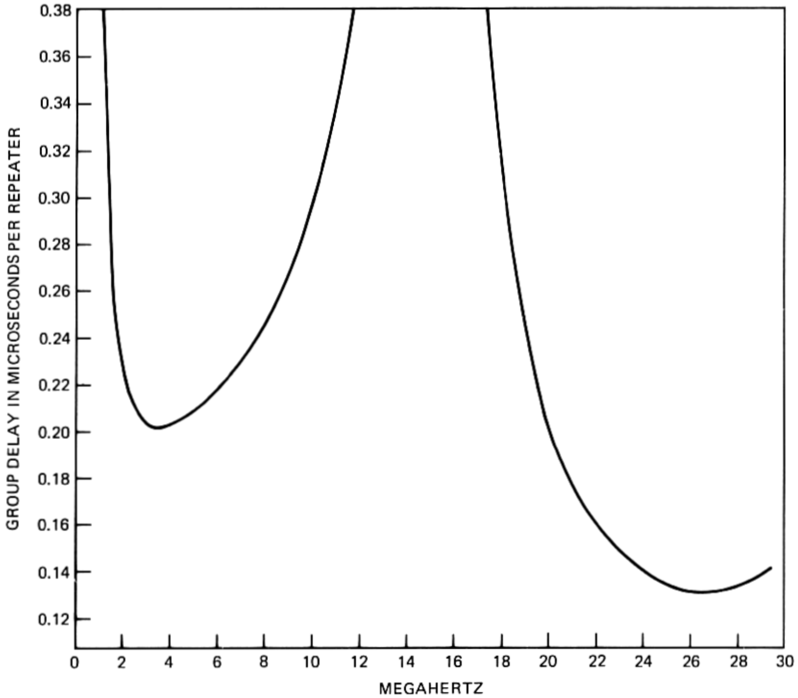


Fig. 12—Repeater group delay.

14, form the basis for adjusting the SG terminal's undersea system protection circuit, which was referred to in Section 3.2.3 and is covered in greater detail in Section VII.

VI. RELIABILITY OBJECTIVES

Newer generations of undersea cable systems pose ever more challenging problems. Between one generation and the next, the number of repeaters for a given length approximately doubles. At the same time, the complexity of each repeater increases. Despite these trends, the newer generation goal is to achieve approximately the same system reliability as that of earlier systems.

In the SG development, reliability was enhanced by a number of measures. Throughout development, mechanical design proceeded hand-in-hand with electrical design. (This was necessary for both performance and reliability reasons.) Highest quality raw materials were used. Inspection extended all the way from raw materials to the finished product. The 30-MHz top frequency required components and devices which were close to the state of the art. Each such new item was accompanied by its own carefully thought-out reliability testing and inspection program tailored to the new art.

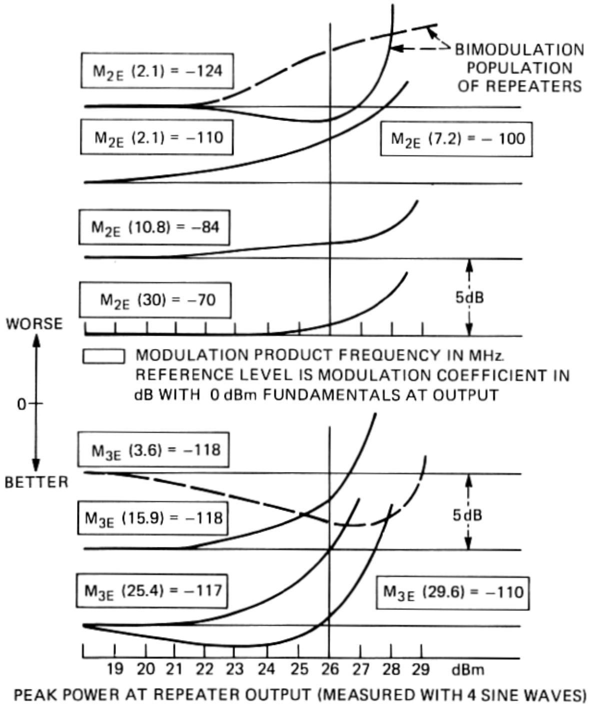


Fig. 13—Repeater excess modulation vs load power.

Early in the project, studies allocated reliability targets to various devices and components. Table V compares the device and component objectives of the SG system with reliability achieved in earlier generations of undersea cable systems. Note that the design objectives of the SG system correspond approximately to those which have been achieved in field experience on the earlier systems.

Achievement of the SG reliability targets would result in a repeater electronics reliability of 21 FITS. On the basis of experience, one might expect an approximately equal number of failures associated with other portions of the undersea link. If this proved to be the case for SG, the TAT-6 link would experience a mean system rate of 0.26 failures per year.

At the time of writing, TAT-6 has functioned reliably with no interruption since it went into service in July 1976.

VII. SHORE TERMINALS

Functionally, the shore terminal consists of: (*i*) terminal transmission

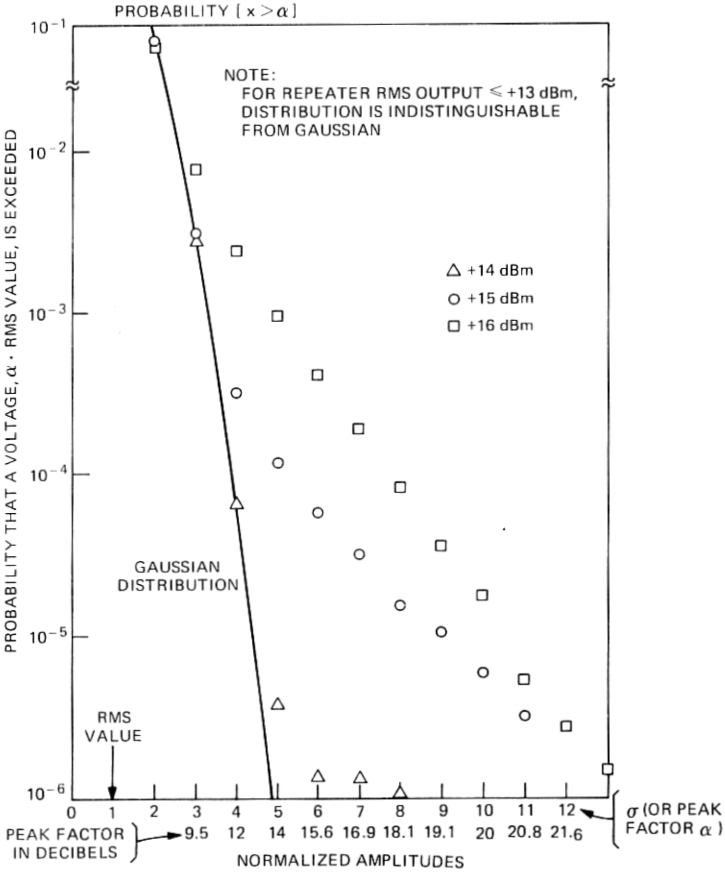


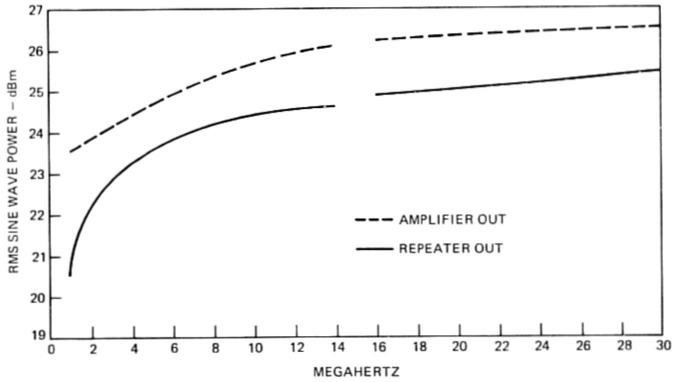
Fig. 14—Normalized amplitude distribution of 27-MHz intermodulation noise of a single repeater as a load-capacity defining phenomenon.

equipment made up of the multiplex, wideband line, and pilot monitoring equipment, (*ii*) power feed equipment for the undersea repeaters, and (*iii*) fault location measuring equipment.

From a transmission point of view, the SG system is defined from transmit supergroup input to receive supergroup output. The multiplex (and its associated carrier supply) consists of supergroup and hypergroup* frequency translation. Terminal wideband lines provide equalization capability to optimize noise performance and provide end-to-end flat transmission.

Signal limiting is provided at the input of each transmitting super-

* In SG, the hypergroup consists of an assemblage of 10 supergroups. Hypergroup 1, an exception, contains 14 supergroups.



NOTES:
1. RMS BROADBAND POWER OF A MULTI–CHANNEL SIGNAL AT AMPLIFIER OUT SHOULD BE LIMITED TO + 18 dBm.
2. EXCEEDING LEVELS SHOW IN GRAPHS CAN RESULT IN REPEATER GAIN CHANGE

Fig. 15—Maximum permissible single sine-wave power.

Table V — Reliability of active and passive components

Component Type	Component Reliabilities in FITS*	
	SG Design Objectives	Field Experience†
Active device (transistor or electron tube)	1.0	0.9
Diodes	0.5	0.0
Passive components	0.05	0.06

* FITS are defined as the number of failures in 10^9 component hours.
† Basis is failures observed on the earlier generations of U.S. systems designated SB, SD, and SF.

group. In addition, a protection arrangement in the transmit wideband line introduces added loss if necessary to avoid gain change in undersea repeaters due to gross broadband or single-frequency overload. (Figure 15, referred to earlier, shows these repeater limits.) This protection is adequate, even in the presence of positive misalignment.

The power feed equipment provides a current-regulated source of 657 ± 0.3 mA to power the undersea repeaters. It is capable of providing up to 7500 volts and shuts down in the presence of voltages and currents capable of damaging the system.

Fault location equipment consists of general purpose dc and low-frequency test sets, and a repeater monitoring set. The repeater monitoring set is capable of measuring: (*i*) repeater supervisory tones and (*ii*) "echoes" produced by high-level test signals acting on repeater nonlinearities.

VIII. ACHIEVED PERFORMANCE

8.1 Transmission equalization

Initial misalignments encountered during installation of TAT-6 were generally within the allocations of the system plan. Figure 16 shows the within-block misalignment (i.e., net gain or loss from the first repeater to the last repeater in an ocean block, ignoring the intentional low-band gain boost) averaged over all the blocks. Comparison of the two curves of Fig. 16 shows the effect of OBEs in reducing misalignment. The broad component of pre-OBE misalignment was less than ±2 dB in most blocks and was about ±4 dB in the worst block. The ripply structure was somewhat larger than expected and hard to predict since it was mostly a result of reflection at the repeater termination. It is a function of the exact length of the pigtail (flexible coaxial lead) between repeater and cable termination and is different for a pigtail surrounded by water as compared to one in air. The actual pigtail length depends on the relative orientation of repeater and termination aboard ship at the time of splicing. The ripple is very small per termination (and therefore hard to measure) but becomes important when many terminations occur in series (1400 in a system).

The solid curve of Fig. 17 shows the transmission of the undersea system from first to last repeater. The dashed curve in the figure shows transmission from a flat level point in one terminal to that in the other. Comparison of the two curves shows the effect of the terminal broadband equalization. Beyond this, there is still equalization at the receive supergroup level, where required, to flatten out the transmission.

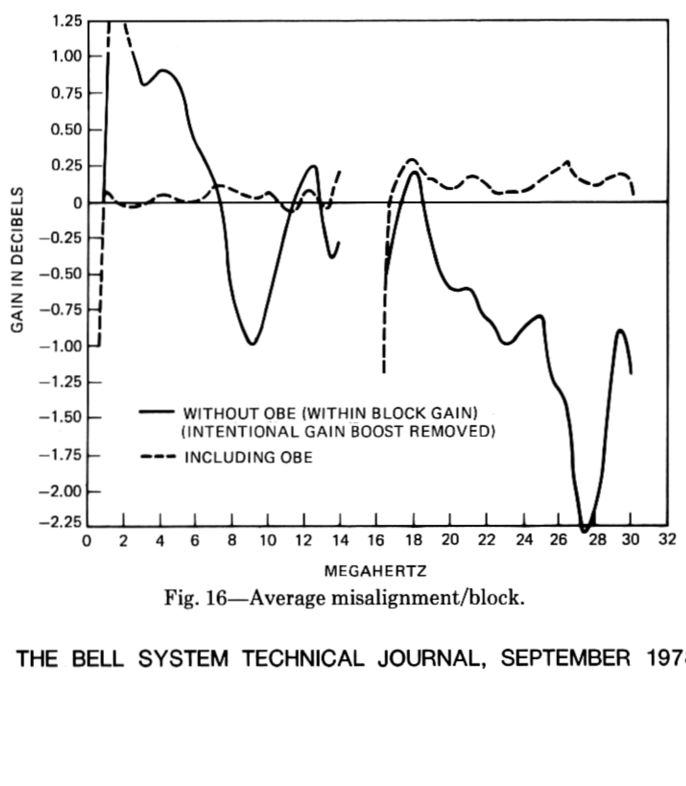


Fig. 16—Average misalignment/block.

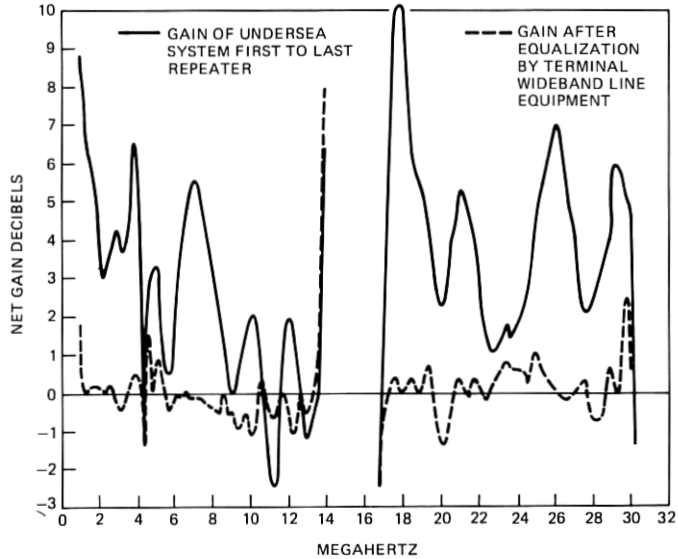


Fig. 17—Gain of TAT-6 before and after equalization by terminal wideband line equipment.

Figure 18 shows some level diagrams along the length of the system at some sample frequencies to illustrate SG equalization as a function of length. Most of the diagrams show behavior at ripple maxima and minima, with only the cases at 10.5 and 22 MHz representing behavior near zero crossings. The sawtooth pattern at 2 MHz is due to the gain boost. The data in these figures are obtained from laying measurements.

8.2 Noise performance

Noise performance of a new system is measured and optimized during commissioning[9] by means of noise loading tests. Commissioning refers to the large number of tests and adjustments required to carry a system from the time of the final splice to the time of initial commercial service. In these tests, the multichannel load is simulated by a noise "signal," and the system noise is measured in selected frequency slots, which can be cleared of signal by inserting band-stop filters in the transmitting terminal. The stop filters are sufficiently narrow to have negligible effect on the total load. A signal-to-noise ratio is determined by the ratio of the received power in the selected slot without and with the insertion of the corresponding band-stop filter (this ratio is referred to as the noise power ratio, or NPR). Transmitting levels are adjusted to give the best achievable signal-to-noise ratios.

Initial noise loading tests on TAT-6 were made with the noise power

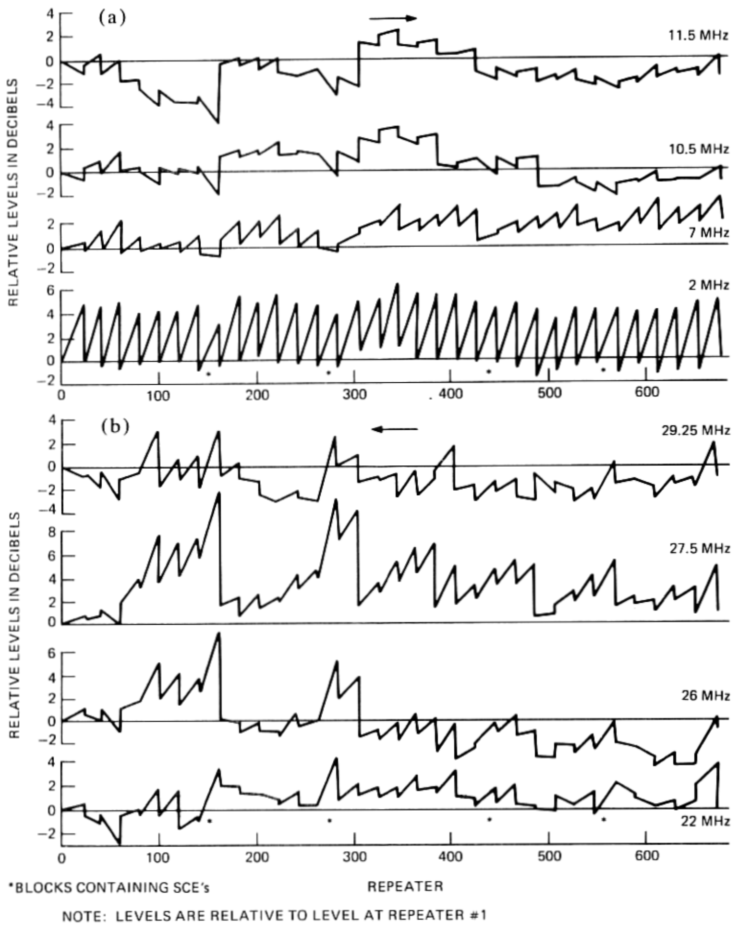


Fig. 18—Levels along length of TAT-6 at selected frequencies. (a) Low band. (b) High band.

density shaped vs frequency in such a way as to realize near-optimum noise performance if the repeater behaved in the expected manner. Actually, in these tests, the low band and the lower two-thirds of the high band came out largely as expected. However, the top one-third of the high band was noisier than anticipated. After considerable time was spent verifying that this was due neither to a measuring problem nor to a few repeaters suffering from some kind of a fault condition, it became apparent that this was an intrinsic property of the system.

Figure 19 shows the noise performance achieved after level re-optimization, as compared to that originally expected. Figure 20 shows optimized levels corresponding to this result, also compared to those expected. The results of Fig. 19 were obtained by measuring thermal noise

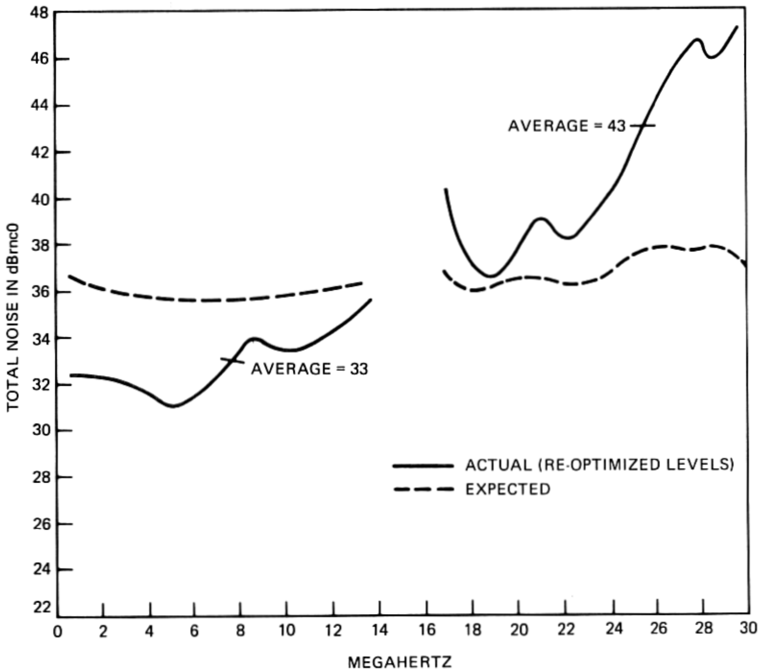


Fig. 19—System noise performance.

and calculating the increase due to modulation noise. The modulation noise for this calculation was obtained from noise loading measurements, interpolating between measured points where necessary. System noise performance shown on Fig. 19 was better than anticipated at lower frequencies. This was because optimized levels at the higher frequencies were lower than expected, thus reducing the *A-B* intermodulation products falling in the low band.

8.2.1 Nature of excess noise

The portion of the frequency spectrum in which the excess noise occurred suggested that the source of excess noise was third (or higher)-order intermodulation. This was confirmed by loading the high band only. Since this band is less than one octave wide, no second-order intermodulation can contribute to noise within it.

The NPR curves of Fig. 21 show that, whereas one would expect the curve at higher loads to have a slope of −2,* the system shows a much

* Third-order products or noise are expected to increase 3 dB for each 1-dB increase in signal. Thus, the signal-to-third-order noise ratio should decrease 2 dB per 1 dB increase in signal.

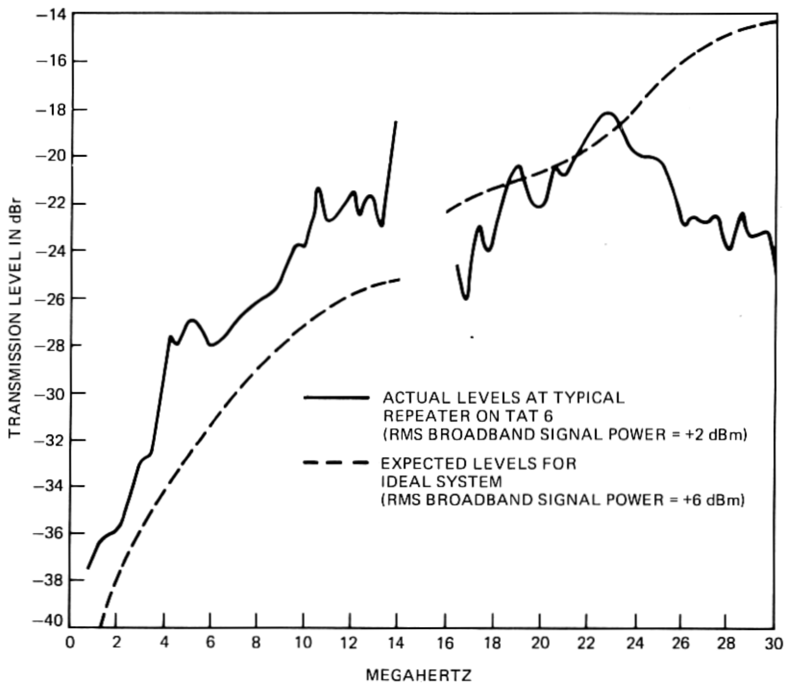


Fig. 20—Transmission levels at repeater out.

shallower slope. This is clearly indicative of anomalous behavior and provides the beginning of an explanation of why this behavior had not been clear from measurements on single repeaters or from testing an assembly of ten repeaters during SG development. The dashed curves show what was expected from the assumed constant values of M_{3E}, but using the "actual" levels of Fig. 20.

Third-order intermodulation noise is only of system significance compared to second order and thermal noise because, in the absence of delay distortion, it adds on a voltage (systematic) basis while the other two noises add on a power (rms) basis. Thus, by normal measuring techniques, the only way to see third-order intermodulation noise produced by noise loading of one or a few repeaters is to load with a power much higher than normal for a system, and extrapolate down to the operating point, assuming the classic 2-for-1 slope. The results of Fig. 21 show that a much shallower slope prevails, so that such an extrapolation would be much too optimistic.

The usual way to compute intermodulation performance is to measure intermodulation products produced by two or three discrete fundamental frequencies. Techniques then exist to estimate performance with a real load from the modulation (M) coefficients determined from the discrete tone measurements.[10] However, these techniques assume that

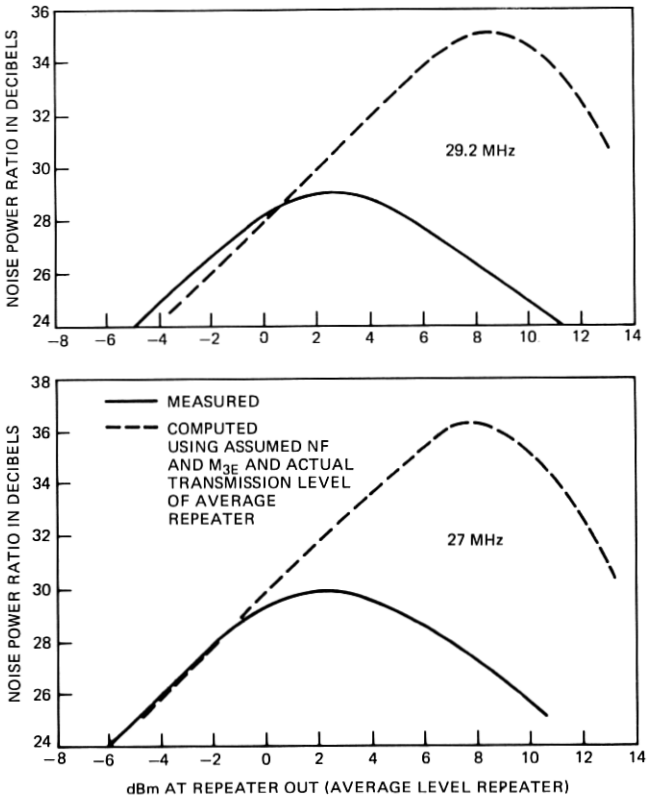


Fig. 21—NPR (signal-to-noise ratios) on system—highband only loaded.

the discrete tone intermodulation is a function only of product frequency and not of the frequencies of the fundamentals. This assumption had been substantially true in earlier systems.

In the development and manufacture of SG, a set of fundamental frequencies believed to be typical had been selected to measure intermodulation. The behavior of products generated by these fundamentals was normal, and the values obtained were those shown in Fig. 11. These results led to computed noise performance consistent with the objective, as shown in Fig. 5.

After the discovery of the third-order intermodulation problem, extensive additional measurements were made. It was found that fundamentals existed which produced products of a much higher level than those produced by the standard fundamentals used during development and manufacture. Furthermore, these products did not vary 3 dB for each decibel of change in the power of fundamental power (i.e., M coefficients were not fixed, but were a function of power). Finally, whereas third-order modulation from the standard fundamentals was slightly better at sea-bottom temperature as compared to room temperature, these new fundamentals generated much more intermodulation at the cooler sea-bottom temperature than at room temperature.

What made the problem much worse was that many of these "bad" fundamentals were in the portion of the spectrum where there was almost no delay distortion (see Fig. 12). This meant that the intermodulation products of highest amplitude were the very ones that added in-phase from repeater to repeater. Figure 22 shows some M_{3E} coefficients determined from discrete tone measurements on the system using fundamentals very close to the product frequencies. These can be compared to the "nominal" -113 dB M_{3E} and to the M_{3E} coefficients of Fig. 11. The values in Fig. 11 which were measured with "standard" fundamentals had been thought to be the correct ones.

Figure 23 shows the dependence of M_{3E} on source frequencies. These modulation coefficients were measured on a single repeater at sea-bottom temperature at a particular power level and for a particular product frequency. Instead of the usual situation in which one might expect at most a few decibel variation over the whole range of possible source frequencies (up to the overload power), these "isomods" show gross changes as a function of fundamental frequencies.

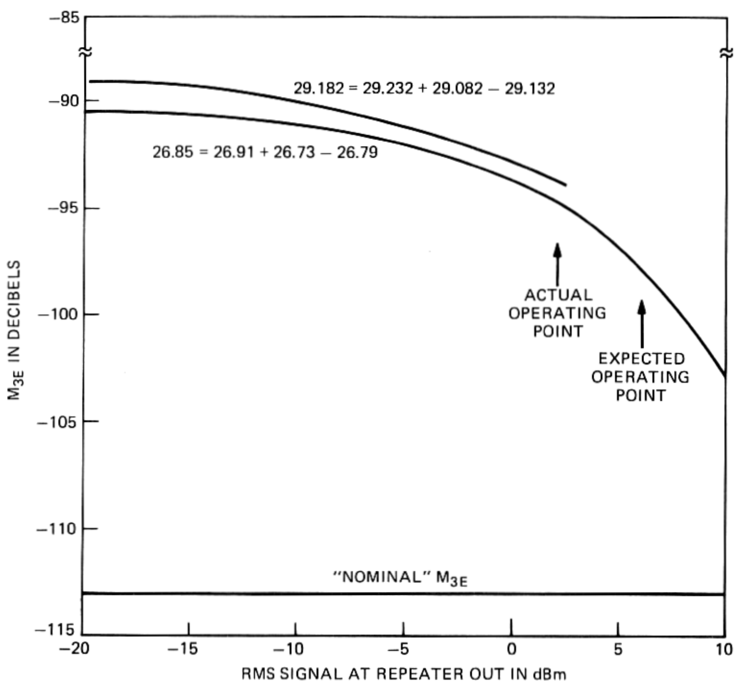


Fig. 22—M_{3E} determined from system measurements using fundamentals close to product frequencies.

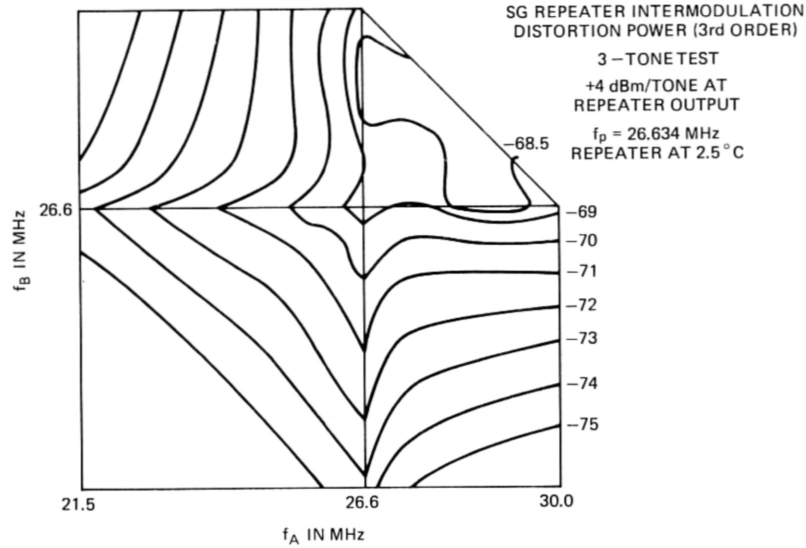


Fig. 23—Three-tone ($A + B + C$) isomod contours for SG repeater with surge protection diodes (sea-bottom temperature).

Thus, the much-worse-than-anticipated values of M_{3E} at the anticipated operating level were the source of the problem. It was then further aggravated by the shallow slope; that is, signal-to-noise ratio improved at a much more gradual rate than 2 for 1 as levels were reduced to diminish the third-order noise. This behavior forced us to reduce levels even more, degrading the signal-to-thermal noise ratio in the process.

In the top third of the high band, the achieved noise performance is poorer than the worst-channel objective by as much as 5 dB, and the average noise in the high band exceeds the average-channel noise objective by about 4.5 dB. These levels of noise do not render circuits unusable, but do represent an undesirable service degradation.

8.2.2 TAT-6 modulation improvement

Our program of modulation improvement involves placing equipment at the Green Hill, Rhode Island terminal to cancel third-order distortion in the upper portion of the high band. Transmission and delay equalizers will duplicate the electrical conditions at the middle of each ocean block of the undersea system. Then at each such virtual ocean-block point, a distortion generator will introduce distortion to balance out third-order distortion of the corresponding ocean block of the undersea link.

Field trials at Green Hill with a single distortion generator have achieved significant noise cancellation. These were feasibility trials performed by noise-loading a single supergroup at a time in the part of the high band where delay is relatively flat. Indications are a 12- to 15-dB reduction in third-order intermodulation can be realized, which will allow the TAT-6 link to meet its original performance objectives.

The Green Hill installation will include duplicate distortion canceling chains. Normal terminal monitoring and automatic switching arrangements will assure service continuity.

8.2.3 Intermodulation improvement of future SG links

Studies of the third-order modulation concluded that the reverse-biased output protector diodes were a major source of anomalous distortion. These diodes protect the power amplifier output stage against surge damage.

Independent of the modulation problem, Bell Laboratories had examined a double-epitaxial transistor design. The deeper second epitaxial layer makes these transistors highly resistant to second-breakdown damage. Using double-epitaxial transistors in the output stage eliminates entirely the need for the reverse-biased diodes. Laboratory tests indicate that the new combination is actually more rugged than the earlier arrangement.

Studies of intermodulation further indicated that interface states at the boundary between silicon and silicon-oxide layers of the transistor were a second source of the anomalous third-order distortion. This boundary, or interface, is produced by the transistor's silicon oxide (plus silicon nitride) passivation. Experiments suggested that shifting the crystalline orientation of the transistor starting material from $\langle 111 \rangle$ to $\langle 100 \rangle$ would greatly reduce the number of interface states, and hence the amount of anomalous distortion. Future SG links will have improved performance based on such a change in the output stage of the power amplifier. The first two stages of the power amplifier will retain transistors with the $\langle 111 \rangle$ orientation, since experiments established that a *small* amount of anomalous distortion will cancel some of the normal distortion, leading to an amplifier which is more linear than one using $\langle 100 \rangle$ transistors in every stage.

IX. SYSTEM AGING

In its two years of service (since commissioning), the system has aged in the direction of increased loss by about 25 dB at 30 MHz with a shape that is approximately linear with frequency. The incorporation of shore-controlled equalizers is thus seen to have been well worth while. Work is currently going on to identify the physical mechanisms responsible for the transmission change. Until a particular physical mechanism or mechanisms are proven to be the cause, predictions of aging over the life of the system must be made with caution. On a pure curve-fitting basis, log or exponential functions of time appear to fit the observed data. These functions would predict end-of-life top frequency aging as large as 50 dB or as low as 30 dB.

Suppose end-of-life total aging proves to be 35 dB. This is 7 dB per

SCE sector. Since the TAT-6 link was pre-equalized by 2 dB per sector, as described in Section 3.2.2, we would be left with a net loss per sector of 5 dB, which is within the system misalignment allocations.

X. EQUALIZATION AND PERFORMANCE

The initial equalization results achieved on TAT-6 are satisfactory and in keeping with misalignment allocations. Equalization knowledge gained in laying TAT-6 will allow the use of 30-repeater ocean blocks in future systems, still keeping misalignments within the desired range.

Regarding reliability, definitive statements require further operational experience. However, the TAT-6 link has been operating continuously since commissioning in July 1976. We fully expect that the superior job of burying the shore ends with Sea Plow IV, plus the great care in each step of design and of manufacture, will result in meeting our reliability targets.

Although less than six months elapsed between the start of design and initial shipment of shore-controlled equalizers, the four SCEs in the TAT-6 link are performing satisfactorily. These have been reset once since commissioning, to compensate cable aging.

It now appears that there will be enough range in the SCEs to compensate aging throughout TAT-6's lifetime. By keeping misalignment within bounds, and thus minimizing the noise penalty associated with cable aging, the SCEs are contributing importantly to the performance of TAT-6.

APPENDIX

Glossary

A.1 Terms for system description

REPEATER SECTION A length of cable with its associated repeater. Nominal deep-sea repeater sections for SG are 5.1 nmi long.

OCEAN-BLOCK EQUALIZER (OBE) Passive unit designed to reduce the residual gain or loss at the time the system is laid, which results from discrepancies between the gain of repeaters and the loss of the associated cable sections.

OCEAN BLOCK A number of repeater sections and their associated OBE. For TAT-6, ocean blocks were 20 repeater sections (98 nmi) long. Future SG links will have 30-repeater (149-nmi) ocean blocks.

SHORE-CONTROLLED EQUALIZER (SCE) Undersea unit placed following a number of ocean blocks. The basic purpose of the SCE is to compensate long-term changes in transmission occurring after installation, such as those due to cable aging.

SECTOR, OR SCE SECTOR An SCE and its associated ocean blocks. In TAT-6 there are seven ocean blocks per SCE; hence, sectors are about 680 nmi long.

A.2 Terms for signal description

ZERO LEVEL POINT (0 dBr) Used to provide a reference for expressing transmission level.

TRANSMISSION LEVEL The net gain or loss in decibels from a reference point (the zero level point) to the point in question. For net gains, the transmission level is positive; for net losses, it is negative. Transmission level may be expressed as $\pm X$ dBr.

CHANNEL LOAD, P_c The average signal power in a one-way voice channel. This power is expressed in dBm0, decibels relative to one milliwatt at the zero-level point. The SG average channel load was taken as -13 dBm0.

BROADBAND LOAD, P_{av} The total average power in a wide-band signal. Where this signal is composed of N two-way voice channels combined with equal weighting, $P_{\text{av}} = P_c + 10 \log_{10} 2N$ dBm0.

MULTI-CHANNEL PEAK FACTOR, k_m The ratio, expressed in dB, between the 0.001 percent peak power and the average power of the multi-channel signal. When the number of channels is very large, the signal's k_m approaches that of Gaussian noise. Thus, for SG the multichannel peak factor = 13 dB.

PEAK FACTOR, α The *ratio* of peak voltage to rms voltage. A peak factor of 5 would indicate voltage five times larger than the rms voltage. To express the peak factor as a power ratio in decibels, we take 20 log α.

A.3 Channel noise terms

CHANNEL NOISE The background interfering power in the bandwidth of a single channel.

WEIGHTING The function vs frequency which allows for the fact that different frequencies interfere with voice communication to different degrees.

PSOPHOMETRIC WEIGHTING, (p) A noise weighting curve adopted as international standard by the CCITT.

C-MESSAGE WEIGHTING, (c) Noise weighting currently in use in the Bell System domestic plant.

REFERENCE NOISE, *rn* One picowatt, or -90 dBm before applying any weighting.

A.4 Equalization terms

EQUALIZATION The process of adjusting system elements (typically equalizers) so that transmission is kept within prescribed limits at all frequencies and points in the system.

MISALIGNMENT (dB) The extent to which equalization departs from the ideal. Positive misalignment represents gain, while negative represents loss. Misalignment can be absolute (departure from a nominal level), or relative (departure of level from levels at other units along the system). In laying an undersea system, one is concerned with relative misalignment, since all undersea levels may be shifted up or down by terminal adjustments after the system is laid.

UNIFORM MISALIGNMENT Misalignment which increases at a constant rate going along the system.

A.5 Cable terms

NAUTICAL MILE (nmi) When used for cable, refers to a cable nautical mile, 1855.3 meters, or 6087 feet.

DISSIPATION FACTOR, $\tan \delta$ The tangent of the polyethylene dielectric loss angle. For high quality dielectrics, $\tan \delta \doteq \delta$, and the dissipation factor is given in microradians at a particular frequency.

TEMPERATURE COEFFICIENT, $\Delta\alpha_t$ The change in loss of cable with change in temperature. Usually given in percent per degree Celsius at specified frequency and reference temperature and pressure.

PRESSURE COEFFICIENT, $\Delta\alpha_p$ The change in loss of cable with change in pressure. Usually given in percent change per kilofathom at specified frequency and reference temperature and pressure.

A.6 Repeater terms

NOISE FIGURE, NF* The number of decibels by which the output thermal noise power of a repeater, when referred to the input by the repeater's available power gain, exceeds the ideal value given by kTB (k = Boltzman's's constant = 1.3806×10^{-23} joules/degree Kelvin, T = temperature in degrees Kelvin, and B = bandwidth in hertz). At room temperature of 17°C, or 290°K, this limiting or ideal value of noise is given by P = (−174 + 10 log B) dBm.

MODULATION COEFFICIENT, M_{2E} An equivalent second harmonic coefficient which, acting in a repeater whose nonlinearity can be modeled by a Taylor series, would give the observed *A-B* products. If $M_{\alpha-\beta}$ is the *A-B* coefficient, $M_{2E} = M_{\alpha-\beta} - 6$ dB. For an M_{2E} of −70 dB, application of α and β frequencies, each with a power of 0 dBm at the point at which the modulation coefficient is defined, would result in a power at frequency $(\alpha - \beta)$ given by: $P_{\alpha-\beta} = -70 + 6 = -64$ dBm.

MODULATION COEFFICIENT, M_{3E} An equivalent third-harmonic coefficient which, acting in a repeater whose nonlinearity can be modeled by a Taylor series, would give the observed $A + B - C$ product. If $M_{\alpha+\beta-\gamma}$ is the $A + B - C$ coefficient, $M_{3E} = M_{\alpha+\beta-\gamma} - 15.6$ dB. For an M_{3E} of −113 dB, application of α, β, and γ frequencies, each with power of 0 dBm at the point at which the modulation coefficient is defined, would result in an $\alpha + \beta - \gamma$ power given by $P_{\alpha+\beta-\gamma} = -113 + 15.6 = -97.4$ dBm.

* Reference 10 discusses noise figures in detail.

MAXIMUM SINE WAVE OUTPUT POWER, P_R The maximum power the repeater can handle before some specified impairment or distortion occurs.

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