

Design and Deployment of Optically Amplified Undersea Systems

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Applying optical amplifier technology to undersea cable systems using repeaters has occurred in a remarkably short time. Exploratory development of this technology at AT&T-Submarine Systems, Inc. (AT&T-SSI) began in 1989, and the first two commercial systems were installed in the Caribbean Sea early in 1994. Among the steps taken to support this aggressive development and deployment schedule were construction and performance evaluation of optical system "testbeds." Each testbed consists of an optical transmitter and receiver connected by thousands of kilometers of glass fiber and optical amplifiers configured as they would be in an installed system. This paper reports on the results of testbed measurements, and how they affected network system design. It also describes performance measures made during installation and commissioning of the first Caribbean system, to confirm design expectations, and what was learned, from special "first-system" testing, about the limits of this technology.

Introduction

In 1989 AT&T-SSI undertook exploratory development of SL2000, the first digital undersea lightwave cable system using optical amplification, rather than regenerators, in the repeaters. To support an aggressive development schedule, a *testbed* was constructed as a design tool. The testbed was a laboratory configuration that included an optical transmitter and receiver connected by hundreds of *spans*, each containing a multi-kilometer length of glass fiber and an optical amplifier. This tool was a close approximation of the optical transmission path of an installed system. Why the need for this expensive testbed? Unlike first- and second-generation lightwave systems, where the signal is electronically detected and regenerated in every undersea repeater, third-generation optical amplifier systems only process the signal electronically in the terminal stations. As a result, the optical distortion and noise that arise in each cable/repeater section are cumulative. Effects that are barely detectable in a single amplifier and fiber span build up to become significant factors in measuring the overall

system transmission performance. Although the same was true for earlier coaxial cable systems, which contained electronic amplifiers, analytic modeling techniques used at that time could reliably predict system performance. The corresponding tools now available for optical amplifier systems do not provide the needed accuracy. This problem was solved by constructing a testbed that can closely approximate an installed system and characterize its performance, even as efforts to improve analytic techniques continue.

This paper describes the laboratory testbed, the principal measurement techniques used to characterize system performance, the problems uncovered, and how the system design was changed to mitigate them. Also described are the evaluation of terminal network protection equipment and the performance achieved with the first optical-amplifier system installation.

Laboratory Testbed

The four objectives to be achieved using the testbed were to:



Figure 1. Lineup of testbed cabinets. Each cabinet contains eight optical amplifiers and their associated fiber spans.

- Verify that the amplifier and fiber designs support the required transmission performance in an installed network.¹
- Measure both the individual amplifier spans and the complete assembly, and use those measurements to improve analytical modeling tools.
- Provide a realistic environment in which to evaluate performance of the terminal transmission and line switching and monitoring equipment.
- Enable AT&T-SSI and other suppliers of integrated (multi-supplier) systems to verify that their products work together in a particular network. This includes functional testing of the terminal network protection equipment while it is operating with optical fiber paths.

The basic testbed module consists of two amplifiers and their associated multi-kilometer fiber spans. The spans are spools of optical fiber, which take only a modest amount of space. Four modules and the associated power supply fit into one six-foot cabinet, so that, for example, 17 cabinets can house a 4,500-kilometer (km) testbed with 33-km amplifier spacing. (See Figure 1.)

The architecture of the testbed amplifiers closely follows that of the product repeater.² There are, however, some accommodations for measurement flexibility:

- The amplifier pairs can be configured, using front-panel jacks, in tandem for one-way transmission, or in

line pairs for two-way transmission. For example, a one-way, 9,000-km testbed can be reconfigured as a two-way, 4,500-km link. This latter arrangement is required to test the line monitoring system, which uses high-loss optical loopback paths between outgoing and incoming amplifier pairs in a repeater.²

- Access via an optical tap to the line signal is available at each amplifier, so that the signal and the accumulation of impairments along the length of the transmission line can be observed.
- Each testbed amplifier has its own pump laser, unlike production amplifiers, in which redundant pumps are combined to supply an amplifier pair.²
- Further flexibility is provided by having access to each fiber span in order to test different chromatic dispersion compensation maps,² introduce fiber breaks to evaluate fault location,³ and add extra loss to simulate transmission degradation and the effect of added cable from undersea repairs.¹

Environmental Control. Temperature fluctuations, which can change such fiber characteristics as length, can also affect testing. Though these changes may be small, the cumulative effect over thousands of kilometers of fiber is significant. To lessen this effect, environmental control equipment was installed to confine testbed ambient temperature variations to a 1° Fahrenheit range. Polarization effects, discussed later in this paper, are sensitive to temperature variations, which tend to be small and slowly varying in installed undersea systems. To enhance the ability to conduct accelerated testing of polarization effects, time-operated heating elements were placed in the cabinets. The on/off cycling of these heaters ensured that relatively short-term tests would include the effects of various states of polarization.

Multiple Test-Bed Constructions. Eventually, three separate testbeds were constructed for SL2000 system development. The first was a prototype for AT&T's initial commercial installation, Americas-1 North. Located between Florida and St. Thomas in the U.S. Virgin Islands, it consisted of 28 spans measuring 70 km each, for a total length of about 2,000 km. Performance, measured at bit rates from 2.5 to 10.0 gigabits per second (Gbits/s),⁴ was largely what we expected, and gave us confidence to pursue the design of longer optical amplifier systems.

The second testbed is a prototype for the AT&T portion of Segment J of the TPC-5 system (U.S. mainland

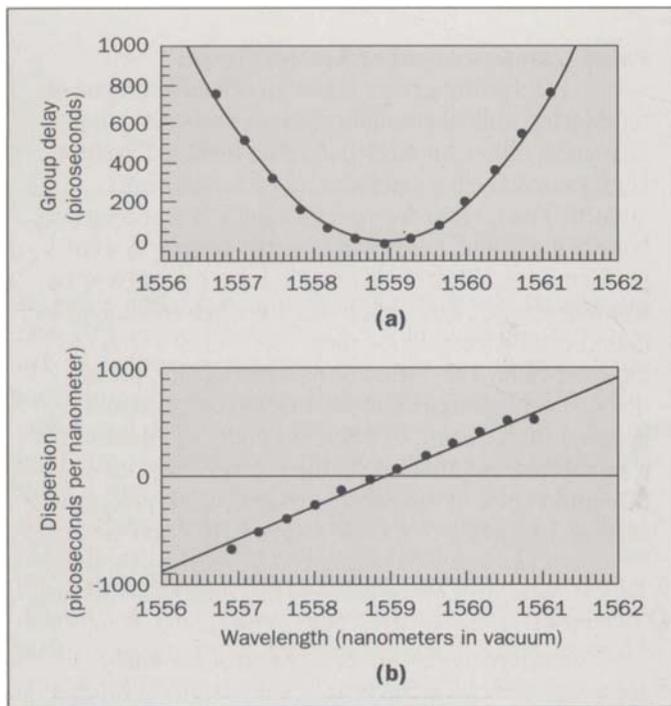


Figure 2. (a) Group delay versus wavelength measured for a 4200-km-long testbed fiber path, including 92 optical amplifiers. (b) The derivative with respect to wavelength of (a), which identifies the zero-dispersion wavelength as 1558.97 nanometers, and shows the net cumulative dispersion at other wavelengths.

to Japan). (See Panel 1 for definitions of abbreviations, acronyms, and terms.) TPC-5, the fifth trans-Pacific cable system, will contain two fiber pairs, each operating at about 5 Gbits/s. For enhanced reliability, TPC-5 will contain six separate segments, forming a ring configuration between the U.S. mainland and Japan. There are two distinct Pacific crossings: one direct (Segment J), and the other through Hawaii and Guam. The AT&T Segment J testbed contains 4,500 km of fiber, with amplifiers every 33 km. At times, this facility is tested in tandem with another 4,500-km-long testbed supplied by Kokusai Denshin Denwa Co., Ltd. (KDD), AT&T's Japanese partner in developing and supplying the TPC-5 system. This testbed was developed to test the most challenging of the TPC-5 links, the 9,000-km-long Segment J.^{5,6} This combined testbed, set up in AT&T-SSI's integration facility, allows the developers to investigate phenomena that only become pronounced on very long optically amplified fiber systems. These will be discussed later in this paper.

Finally, a 4,200-km-long testbed was built, with 45-km amplifier spacing, which operates at 5 Gbits/s. A prototype for the AT&T portions of TAT12/13, another planned undersea cable ring configuration with two trans-Atlantic cable crossings, is also used in tandem with simi-

Panel 1. Abbreviations, Acronyms, and Terms

ASE — amplified spontaneous emission
 STM-1 — synchronous transfer mode optical signal at 155 Mbits/s
 STM-16 — synchronous transfer mode optical signal at 2.5 Gbits/s
 TAT-12/13 — the twelfth and thirteenth trans-Atlantic cable systems
 TPC-5 — the fifth trans-Pacific cable system

lar testbeds provided and operated by other undersea system suppliers of portions of TAT12/13. Such cooperative testing is essential to validate proper operation of an integrated (multi-supplier) network.

Development of Measurement Techniques

Because optical amplifier technology is just emerging, it was necessary to develop new measurement techniques to characterize system performance.

Amplifier Noise Figure. An amplifier's *noise figure* is a measure of the noise added by the amplification process. The amplified spontaneous emission (ASE) noise added by optical amplifiers is a major source of system impairment. Accurate measurement of individual amplifier noise figure is essential for predicting end-to-end transmission performance of a system.¹ The method developed by AT&T-SSI for this measurement takes advantage of the different polarization characteristics of the signal and ASE noise. A tandem combination of a polarization controller and polarizer is placed after the amplifier to "cancel" the signal while measuring the noise in the signal wavelength band. This technique proved accurate even for high-input signal powers (amplifier in saturation), the normal operating condition of amplifiers in a system.⁷

System Chromatic Dispersion Measurements.

Chromatic dispersion in the optical fiber is another important factor that affects undersea system performance, as explained in a companion article.² Dispersion is usually measured by observing the group delay (picoseconds per nanometer [ps/nm]) over a wavelength range around the expected zero-dispersion wavelength. From this, the actual zero-dispersion wavelength (nm) and the dispersion slope (ps/nm²) can be calculated. Because of the accumulated ASE noise and the reduced

wavelength range (a few nanometers), test equipment available for measuring chromatic dispersion of fiber spans² cannot measure the dispersion of a long fiber path containing many optical amplifiers. Moreover, in the presence of several thousand kilometers of fiber, the absolute end-to-end delay variations caused by even small environmental changes can be many times larger than the changes in group delay versus wavelength that need to be measured. To overcome this, measured group delay versus wavelength is compared to a reference wavelength, also transmitted over the system. A reference measurement is made between each variable wavelength measurement, and the resulting data is processed to eliminate the effect of absolute delay changes. This test can determine the zero-dispersion wavelength of a multi-thousand-kilometer optically amplified fiber path to within 0.1 nm. Figure 2 shows the results of a typical system dispersion measurement.

Impairments and Design Solutions

Testbed measurements proved not only valuable, but essential to the successful design of the SL2000 system. The data collected allowed designers to characterize the cumulative effect on system signal-to-noise ratio from various sources of impairment, principally:

- Fiber nonlinearity as a function of light intensity,
- Component aging,
- Chromatic dispersion, and
- Light polarization phenomenon.

As a result, they were able to set realistic requirements on components, determine optimum operating signal-power levels, design for appropriate beginning-of-life performance that is consistent with end-of-life performance requirements, develop a dispersion management strategy, and optimize the design of terminal transmitters and receivers. What proved particularly enlightening was what they learned about the cumulative effects of polarization phenomenon on transmission.

Polarization Effects. Three separate manifestations of polarization in glass fibers can degrade transmission in long, optically amplified lightwave systems: polarization-mode dispersion, polarization-dependent loss, and polarization hole burning, which is sometimes referred to as polarization-dependent gain.⁹ Polarization-mode dispersion is primarily associated with glass fibers, polarization-dependent loss with passive optical components in the

Panel 2. Measurement of System Margin

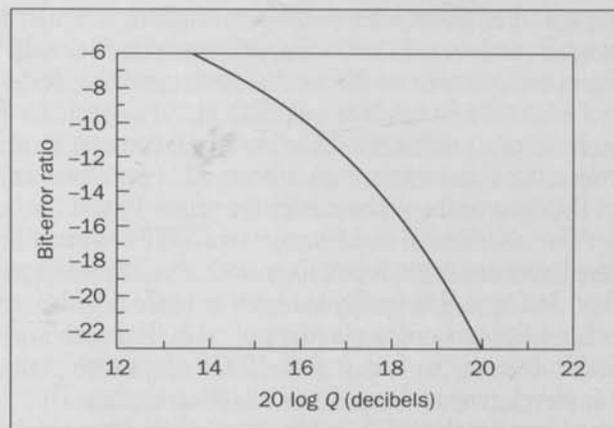
Detecting errors is not an effective means of monitoring optical amplifier system transmission performance, either for a testbed or an installed system. Under normal circumstances, errors occur infrequently. Thus, error-free performance is a necessary, but not sufficient, condition to verify proper system performance. What is also needed is a measure of *system margin*, i.e., how much of a signal-to-noise degradation can be tolerated without exceeding a specified bit-error ratio. The measure of transmission performance developed to allow for margin determination is called the *Q-factor*, or often simply *Q*. Equivalent to a signal-to-noise measure at the electrical decision threshold point in the receiving terminal, it is a measure of the quality of the *eye diagram*, defined as:

$$Q = \frac{|u_1 - u_0|}{\sigma_1 + \sigma_0} dB$$

where $\mu_{1,0}$ is the mean value of the ones/zeros rail, and $\sigma_{1,0}$ is the standard deviation. With this definition and an optimum threshold, the corresponding bit-error ratio (*BER*) is approximated by:

$$BER = \frac{1}{Q\sqrt{2\pi}} e^{-\frac{Q^2}{2}}$$

This relationship is plotted in the accompanying figure.



To achieve practical measurement times (a few minutes), the *Q* measurement is accomplished by varying, in discrete amounts, the decision-circuit threshold between the 0 and 1 rails and measuring the corresponding bit-error rate in the range of 10^{-5} to 10^{-9} . From this information, a corresponding *Q* for the actual receiver threshold can be calculated.⁸

repeater, and polarization hole burning with the erbium-doped fiber amplifier.² Accurately quantifying these effects at the component level challenges existing optical measurement capability. The state of polarization of the signal as it travels along the system is constantly changing because of random effects, such as even slight variations with time in fiber temperature and stress. As a result, the accumulation of these effects along the length of an optical amplifier system is a statistical process, and the Q measured on the testbed varies with time. (Panel 2 describes measurement of system margin.) Long-term Q measurements reveal that the variations often approximate a Gaussian probability distribution (characterized by a mean and standard deviation).

The effects of polarization-mode dispersion were anticipated before the testbed was constructed. Tight requirements on fiber polarization-mode dispersion were in place, and testbed measurements have proven their adequacy. Not anticipated was the significance of the cumulative effects of polarization-dependent loss and polarization hole burning. The challenge with polarization-dependent loss is that the state of signal polarization randomly varies as the signal propagates down the system. There will be times, though perhaps rarely, when the polarization-dependent loss will add systematically. The result is Q fading,¹⁰ analogous to fading in microwave radio systems. From long-term testbed Q measurements it was learned that component polarization-dependent-loss requirements had to be considerably lowered, compared to the original design, to satisfy system outage and error performance requirements.

Also revealed by testbed measurements is the cumulative effect of polarization hole burning.¹¹ The issue here is that the gain of the erbium amplifier is slightly larger for the polarization state orthogonal to the large (saturating) input signal. Thus, polarization hole burning raises the level of a portion of ASE noise with this polarization state, compared to the signal, thereby degrading the effective noise figure of each amplifier in the system. Because the total (signal plus noise) power at the amplifier output tends to be held constant by the gain regulation in the system (owing to the amplifiers operating in saturation), polarization hole burning robs power from the signal and gives it to the noise. The decrease in Q can be several decibels for long systems (e.g., 6,000 to 9,000 km).

Polarization Scrambling. The effect of polarization hole burning was mitigated by adding *polarization scrambling* to the design of the terminal optical transmitter. Scrambling reduces the degree of polarization of the launched signal enough that the erbium-doped amplifier no longer "sees" a preferred signal polarization.

Besides removing the signal-to-noise ratio degradation that would result from polarization hole burning, polarization scrambling interacts with polarization-dependent loss to introduce amplitude modulation onto the signal. Although it could also lower Q , this can be avoided by operating the scrambler at a higher speed than the signal bit rate, and by limiting the linear-channel pass band in the terminal regenerator to pass the data signal, but to block the amplitude-modulation frequencies. The polarization can also be scrambled at speeds that are low with respect to the low-end frequency cutoff of the receiver (i.e., ~10 kHz). AT&T-SSI has validated both types of designs on the testbeds.

Verification of the SL2000 LMS

The testbed provides the only environment, prior to system installation, in which to verify performance of the SL2000 Line Monitoring System (LMS). The LMS provides for both routine in-service transmission monitoring and out-of-service fault location (to a repeater section). What is actually measured on each line pair is *loop gain* between a terminal and each repeater. The loop is completed in the repeaters by means of a high-loss optical path between the outgoing and incoming amplifier pair.²

Configuring the testbed as a two-way system with high-loss loopbacks between amplifier pairs enabled the developers to conduct tests that verified the performance of the LMS. In service, the LMS is expected to locate line impairments greater than 3 dB. Out of service, it is expected to quickly identify a failed fiber path to within a repeater section. The time it takes to locate a transmission change in service depends on the size of the change. A large change can be located in minutes, but a small change may take several hours to pinpoint. Even intermittent faults can be located to within a repeater section by careful correlation between the regular LMS loop-gain data and the error performance data (obtained from the terminal transmission equipment).

Network Protection Equipment Testing

The testbeds, including those provided at the AT&T-SSI facility by other TPC-5 and TAT-12/13 undersea system suppliers, are also used to test the performance of network protection equipment, provided by still another supplier. The network protection equipment provides both an STM-1/STM-16 multiplex function, add/drop capability at the STM-1 level, and network protection switching capability to support the ring configuration of TPC-5 and TAT-12/13.¹²

In the event of a failure in any or all of the traffic paths over one cable segment of the network, the ring configuration with network protection equipment in the terminals provides—for the first time with undersea cable systems—automatic traffic restoration that is fast enough to avoid service interruptions. In recent laboratory testing the entire network, including four sets of network protection equipment and transoceanic lengths of optically amplified transmission lines, successfully switched traffic around the ring in less than 300 milliseconds (ms) when various fault scenarios were simulated. These results verified that transoceanic telecommunications would not be interrupted even if one of the cables in the ring is cut. The probable worst-case scenario in the cable network—a “slow” cut of one cable—was also tested. In this case, a service fiber was cut first, followed by, in less than 100 milliseconds, a cut of protection fiber(s) in the same cable. The ring nodes responded first, by trying to restore traffic on the protection fiber. Before this restoration was completed, the protection fiber was cut and recognized to be unavailable. At this point a ring switch was made to an alternative path in the network, and traffic was restored. STM-1 traffic was out of service for less than 300 ms.

First System Installation

Americas-1 North, installed in the spring of 1994, was the first SL2000 system to be deployed and the first commercial installation of an undersea cable system using optical amplifier technology. It contains two fiber pairs, each operating at 2.5 Gbits/s at a nominal wavelength of 1,558.5 nm, and has 26 repeaters spaced approximately 80 km apart. Commercial service started in September 1994. The remainder of this paper reports on performance and characterization measurements made on this system during assembly in the factory, during

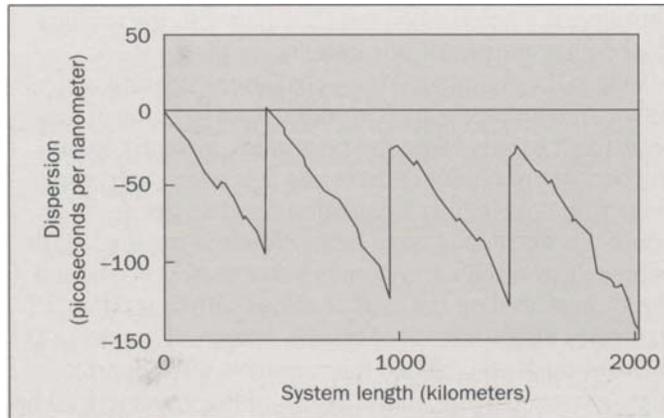


Figure 3. Dispersion map of one of the four fiber paths in Americas-1 North.

cable laying, and over the commissioning interval. To more fully characterize the performance limits of this first installation, the results of special testing are also described.

System Assembly Testing. Like the earlier generation of undersea regenerative systems, SL2000 links are assembled in the cable factory, then loaded aboard the cable ship for laying. Each cable section is checked (i.e., qualified) to determine if it meets the specified performance requirements,² and each repeater is checked prior to being assembled in the cable. The end-to-end testing done at the completion of system assembly is required to qualify performance before proceeding with the installation. The primary performance parameters measured for each fiber path are:

- Net cumulative (end-to-end) chromatic dispersion,
- ASE gain, and
- *Q*-factor.

The importance of these parameters to system performance was explained earlier. Moreover, the terminal line monitoring equipment of the LMS is used to obtain reference loop-gain readings—via the high-loss loopback path in each amplifier pair—from both ends of the system for each line pair.² Such a “baseline” is needed to compare with later measurements, to help detect and locate a loss increase or fault that might occur in the assembled system during ship loading or cable laying.

Net cumulative dispersion, which is measured for each end-to-end fiber path, provides a check of the

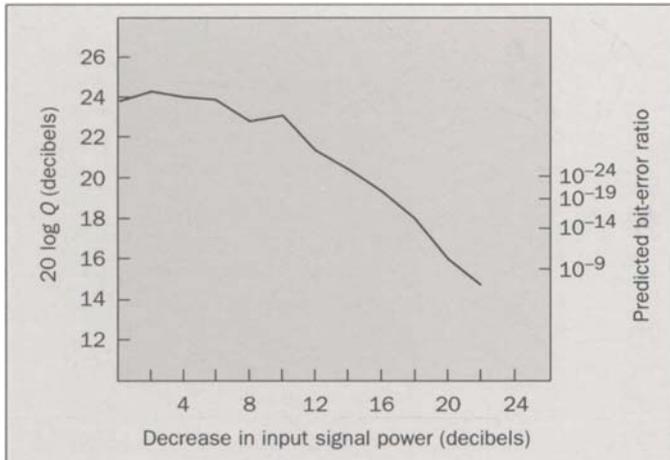


Figure 4. The change in Q resulting from the decrease in input signal power, as measured on one fiber path in the assembled Americas-1 North system at the cable factory.

dispersion management process that is in place during assembly of the cable sections² and system. It also allows computation of the length of dispersion compensation fibers that will be placed in each receiving fiber path in the terminal stations of the installed system. Such compensation brings the cumulative chromatic dispersion of each optical line to near zero at the system operating wavelength.

Figure 3 shows the dispersion map for one of the four fiber paths in Americas-1 North. The dispersion map is calculated from dispersion data for individual lengths of manufactured cable, and for the three lengths (each ~5.7 km) of dispersion compensation cable added at the quarter points of the system. The cumulative dispersion measurement results agreed to within 42 ps/nm, on average, with those determined from the Americas-1 North dispersion maps. Dividing by the measured dispersion slope (in ps/nm²) converts this to a difference in zero-dispersion wavelength of 0.28 nm.

If no signal is applied at the transmit end, the optical spectrum at the output of a system fiber path provides a good measure of system gain peak. The tandem filtering action of the many “band pass” amplifiers produces a narrow transmission band (compared with the band of an individual amplifier), which is called the “ASE gain.” This is an important performance parameter,

because the system operating wavelength will be set in the peak region of the ASE gain.

A Q measurement, described in Panel 2, allows a quick characterization of transmission performance, from which the implied bit-error performance can be deduced. From measured Q , the “system margin” can also be determined, in decibels, relative to a required background bit-error ratio. Because Americas-1 North was the first undersea optical amplifier system to be assembled, we went beyond the routine Q measurement under nominal operation. Q was characterized, for one of the four fiber paths, as a function of decreased input signal power. Figure 4 illustrates the performance robustness of optical amplifier systems, operated in deep gain compression,² in the face of transmission degradation. These may include increased losses in the undersea system resulting from either a fiber or amplifier component fault, or from the addition of extra cable during a deep-sea repair. Figure 4 shows only about a 1-dB decrease in Q with a 10-dB decrease in input signal power, yet the implied bit-error-ratio performance is still in the 10⁻¹⁰ range after a 20-dB reduction. This insensitivity to loss increase is indeed impressive.

Performance Measures During Cable Laying. Two performance criteria were of interest during the cable laying of Americas-1 North: the effects of large environmental changes that the system undergoes between shipboard and sea-bottom (e.g., temperature and pressure), and any power or transmission anomalies/faults and their locations. The routine transmission measurements were:

- Error monitoring,
- ASE gain, and
- Line monitoring (loop gain).

Error performance was monitored continuously while the system was powered and cable laying was under way, except when line monitoring and ASE gain measurements were being made. Loop gain was measured every few hours on both line pairs, from the ship and from the shore. ASE gain was typically measured twice a day. No change in ASE gain was observed during the entire cable-laying procedure. Error monitoring was particularly intense when repeaters were launched overboard. Unlike the experience during the laying of regenerative repeaters, no errors were detected when the optical repeaters were launched, despite the mechanical

shocks they underwent.

During placement of the cable, external aggression caused a shunt fault, a breakdown of insulation between the cable power conductor and the ocean. Line monitoring quickly located it to within a repeater section. Figure 5 plots the differences in loop gain before and after the fault, as seen from the ship. Cable laying continued after the faulty section was recovered and repaired.

The fault was located from the ship by observing that returns were not being received from beyond Repeater 8, and that the loop gain to/from the amplifier pairs near the ship-board side of the fault had substantially increased. This is the loop-gain pattern that is expected from a fault condition. Because of the fault, no signal power is present at the input to the amplifier facing the ship in Repeater 8. That amplifier comes out of saturation, and gain increases substantially. The same is true for the next few amplifiers toward the ship. Their gain, however, does not increase as much with distance from the fault, because their loss of input signal is being compensated for by increased ASE noise from the higher than normal upstream gains.

Commissioning Tests

After an undersea system is installed, its performance and operational features are tested to verify that they meet the requirements specified in the supply contract. This terminal-to-terminal test interval is referred to as *commissioning*. As with earlier coaxial undersea cable systems that contained electronic amplification, an important portion of commissioning an optical amplifier system is the "line up." For the SL2000, the correct power levels were set at the interface of the terminal and the undersea equipment, and the signal wavelength and net zero-dispersion wavelength were adjusted to maximize the signal-to-noise ratio, as determined by measurement of Q . For a system as short as 2,000 km, which has a relatively broad gain spectrum and essentially no nonlinear interactions, the optimum wavelength range is broad. Polarization effects do cause some variation in Q , over time, even for a length of 2,000 km. Nevertheless, all four fiber paths had a mean Q greater than 23 dB, and a standard deviation of less than 0.2 dB.

Another important feature of commissioning is the *confidence trial*, in which error performance is monitored for many days with the system "left alone." For

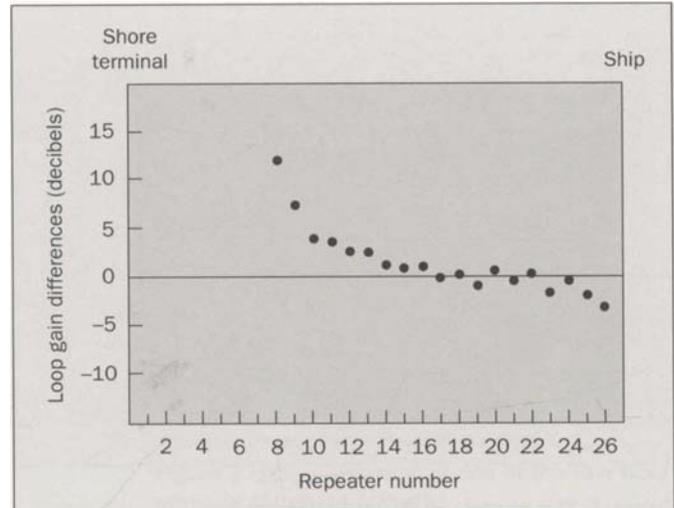


Figure 5. Differences in loop gains from the ship (R26 end) to amplifier pairs in each repeater, measured before and after a shunt cable fault occurred. This measurement helped to pinpoint the fault, located between Repeaters 7 and 8.

Americas-1 North, this period was 15 days. Not a single error occurred on any line during this time.

Characterization of Performance Limits. Because Americas-1 North was the first installed SL2000 system, some special tests were performed during the commissioning interval. They included:

- Measuring Q performance for system lengths up to 8,000 km (by appropriate optical looping in the terminal of the four 2,000-km fiber paths), and
- Characterizing wavelength-division-multiplex performance using two signal wavelengths.

Figure 6 shows the Q versus system length results. At 8,000 km, the link was operating at a Q of 16 dB (implied bit-error rate of approximately 1.5×10^{-10}). The amount of signal spreading in the wavelength domain as a function of system length was also measured. (Signal spreading is caused by the slight nonlinear behavior of glass fiber with light intensity.) No spreading was seen after 4,000 km; after 8,000 km, the increase observed was less than 25 percent. These results are impressive considering that the design parameters of repeater spacing, amplifier gain, and average signal power on the line were chosen for a system length of 2,000 km. For optimum performance, an 8,000-km system

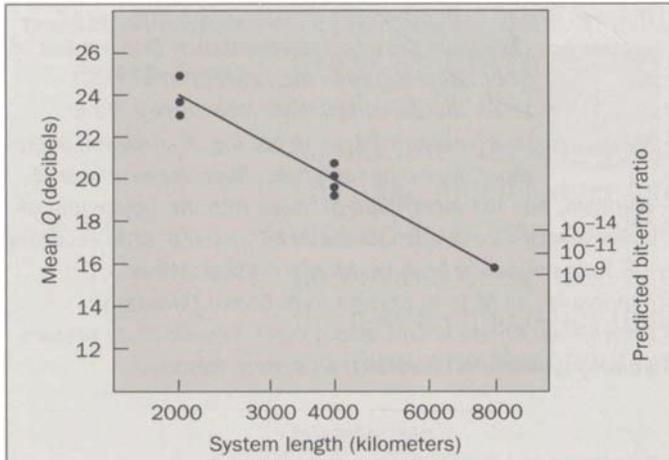


Figure 6. Q performance versus system length. Measurements were made after optically looping back combinations of the four fiber paths in Americas-1 North.

design would have had shorter repeater spacing, lower amplifier gain, and less average signal power.

Various special tests were performed during the commissioning interval for the 2,100-km Columbus-II B segment, the second SL2000 system to be installed. Various transmission formats were tested, including wavelength division multiplex. The tests established that the system can be upgraded to 10 Gbits/s without adjusting any portion of the system on the ocean floor. In the near future, wavelength-division-multiplex technology will most likely increase the transmission capacity of optical amplifier systems.

Summary

Testbeds proved to be a useful design verification tool during development of the SL2000, AT&T's first undersea cable system designed to use optical amplifier technology. The cumulative effects that degrade the performance of long optical amplifier systems—mainly, ASE noise, chromatic dispersion, fiber nonlinearity, and polarization phenomenon—were evaluated and mitigated by design. The testbeds were also used to prove-in operation of terminal network protection equipment planned for use in the TPC-5 and TAT-12/13 ring-configured undersea networks. Measurement techniques developed initially for testbed use also helped to characterize transmission performance during assembly, installation, and commissioning of

actual systems. Special tests of Americas-1 North, the first commercial optical amplifier system installation, indicate that it can operate satisfactorily at twice the nominal signal bit rate, and likely even increase that by a factor of two. In addition, special tests on Columbus-II B indicate the potential for future upgrades on installed AT&T-SSI optically amplified systems.

Acknowledgments

Dozens of AT&T-SSI engineers were involved in construction and performance evaluation of the testbeds, and in development of measurement techniques and equipment for testbed and system installation testing. The authors acknowledge them all, as well as our KDD partner in the TPC-5 development, and other TAT-12/13 and TPC-5 suppliers, who cooperated during test development and integration testing. We also thank the transmission engineers involved with assembly, installation, and commissioning testing of Americas-1 North.

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