INTRODUCTION

Exactly 150 years ago, August 1858, the world witnessed a historic event in the history of telecommunications: the successful transmission of telegraph messages across the Atlantic Ocean. Although the transatlantic cable carrying these messages failed after a few weeks of operation, and it wasn't until 1866 that permanent transatlantic telegraph cable transmission became possible, the 1858 transmissions were heralded worldwide as a major achievement, introducing a new Age of Information.

To commemorate this literally earth-shaking accomplishment 150 years ago, the History Column this month presents an article entitled "A History of Transatlantic Cables" by Jerry Hayes of Concordia University, Canada, a member of the ComSoc History Committee. Interestingly, it took almost another 100 years until the first transatlantic telephone cable, TAT-1, was successfully launched. Jerry covers this epoch-making event in his article as well, in addition to the various undersea telephone cables that followed in the years after. So we are actually commemorating two historic events in this column: the first successful transmission of telegraph data across the ocean, and the first successful transatlantic cable transmission of voice. We commend the article following to you.

***Special Notice:** The ComSoc History Committee is sponsoring a special History Session at the forthcoming IEEE GLOBECOM 2008 in New Orleans. This session, the first of its kind, and co-organized by History Committee members Jacob Baal-Schem of Israel and Mischa Schwartz, will take place Tuesday, December 2, from 1:30–6 p.m. It will consist of three parts: a keynote address on the history of OFDM by Steve Weinstein, a past President of ComSoc and a pioneer in the field of OFDM; four reviewed papers covering a variety of topics on the history of communications; and a panel discussion on the topic "Who Invented Radio?" The panelists, a distinguished group of authorities and historians in the field, drawn from the United States, Italy, France, and Russia, will be discussing the relative contributions of such figures as Marconi, Tesla, Popov, and Branley, among others. Ample time will be made available for audience participation as well. We hope all of you planning to come to GLOBECOM 2008 will attend this special session.*

A HISTORY OF TRANSATLANTIC CABLES

Jeremiah Hayes, Life Fellow, IEEE; Member, ComSoc History Committee

A MESSAGE FROM THE QUEEN

One hundred fifty years ago, on August 16, 1858, a congratulatory message from Queen Victoria was received by the President of the United States, James Buchanan. The President replied in kind. This first official exchange over the newly laid transatlantic telegraph cable ignited a great celebration. Figure 1 shows fireworks over New York's City Hall.[1]

The next day, there was a great parade through the streets featuring a replica of the ship that completed the final leg of the cable laying operation (Fig. 2).

The celebrations hit a sour note as the fireworks set fire to City Hall. Far worse news was to come, as the cable itself failed completely after six weeks. The cable never really worked well; the Queen's message had taken 16-1/2 hours to transmit.

One can imagine the feelings that caused this joyous outpouring. People felt themselves to be riding the great wave of technological progress that swept though the 19th century to a future full of promise. The news of the cable's failure was a cruel defeat. Predictably, some believed it was all a hoax; the cable had never worked.

ORIGINS

Progress in the 19th century had been dazzling on many fronts, but none more than the understanding and application of electricity. Within the memory of the older citizens, electromagnetic phenomena were little known and little understood even by the erudite. In 1800 Alessandro Volta introduced the voltaic pile. It was not until 1820 that the Danish scientist Hans Oersted discovered the link between magnetism and current flow. As the century progressed, wonder followed wonder. By its end, electricity lit the great cities, telephone service was common, and the telegraph network covered the earth.

Telegraph was the first application of electricity. In the United Kingdom telegraphy had been used on the railroads since 1837. Samuel F. B. Morse built the first North American telegraph system between Washington, DC and Baltimore, Maryland in 1844. The first successful cable from Great Britain to France was laid in 1851.Cables to Ireland and the Netherlands followed. In 1854 a cable was laid from Italy to Corsica and Sardinia.

The idea of an Atlantic cable had been in the air for some time. Morse experimented with telegraph cable under New York Harbor in 1842. He called the obstacles problems of "geography and lightning." On the former, there were grounds for optimism since in 1853 the U.S. Navy discovered a "telegraph ridge" on a likely cable route across the Atlantic. The depth was great enough to avoid damage by icebergs and ships' anchors, but not too deep for cable laying. The bottom showed no evidence of a scouring current that could disturb the cable.

The first proposal involving telegraph and the Atlantic was a relay scheme in which messages dropped from passing ships would be sent by telegraph from Newfoundland to the rest of North America. The scheme floundered in the attempt to construct a telegraph line across Newfoundland's rugged interior.

An appeal for help by the engineer in charge of the project brought on the scene someone who was to be indispensable to the enterprise, Cyrus Field. In the course of his work on the Atlantic cable, Field would make over 30 trips across the Atlantic. It was Field's drive and enthusiasm that won through despite the deep setbacks that would be encountered.

Field seized on the concept of transatlantic telegraph transmission immediately. In contrast to land systems in which pulses could be regenerated by a relay,[2] transoceanic systems would be required to bridge great distances with cable alone. He received assurances of feasibility of long distance transmis-

[1] This as well as other wonderful illustrations are reproduced in [1]. A wealth of subcable lore is also available on the Web, notably at [2].

[2] A telegraph cable to the Russian Far East, 13,000 km long, began operation in 1872. It had been considered as an alternative to a transatlantic cable.

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Figure 1. *Fireworks at City Hall in New York [1].*

sion from both Samuel Morse and Michael Faraday. William Thompson, later Lord Kelvin, provided a theoretical basis when, in 1855, he published the distance squared law for cable transmission. The rise time of a pulse traveling through a cable without inductive loading is governed by the *R-C* time constant of the cable, which, for a cable of length L, is given by rcL^2, where r and c are the resistance and capacitance per unit length, respectively.

Thomson also contributed to the technology of submarine cable. He perfected the mirror galvanometer, in which the minutest deflections of a mirror driven by current are amplified by projection on a screen. Later, he invented the siphon recorder, which made a permanent record by depositing ink on paper.

Submarine cable technology was advanced by the introduction of gutta-percha into England in 1843. Gutta-percha, the gum of a tree native to the Malay Peninsula, was an ideal insulator for submarine cables since it is thermoplastic, softening at elevated temperatures and returning to its solid form as it cools, thus facilitating its extrusion over conductors.[3] Under the pressure and temperature conditions of the ocean bed its insulating properties improved. Gutta-percha remained the prime material for submarine cable insulation until the discovery of polyethylene in 1933.

Field spearheaded two successive projects, the first a failure and the second a success. For both, the cables consisted of a single conductor of seven strands surrounded by gutta-percha and varying degrees of steel armor wire with shallow water sections being more heavily protected. Tarred hemp provided protection against corrosion (Fig. 3). The 1858 cable weighed 2000 lbs/nautical mile. The 1866 cable was heavier, 3575 lbs/nautical mile, but with increased bulk it weighed less in water. The respective tensile strengths were 6500 and 16,500 lbs.

All of the cables had a single conductor with sea return. A sea return had lower resistance than wire return, but was subject to stray currents. Powering was by voltaic cells. For example., the 1858 cable had 70 cells at 1.1 V each. These voltage levels, together with mishandling and careless storage, contributed to the failure of the 1858 cable. The use of the mirror galvanometer allowed for far lower voltages in later systems. Since the resistance was approximately 3 Ω/nautical mile over a distance of 2000 nautical miles, currents of the order of milliamps, enough for the mirror galvanometer, could easily be generated.

In the 1860s the bipolar telegraph code was introduced. The dots and dashes of Morse code were replaced by pulses of opposite polarity. In time, more elaborate schemes involving pulse polarity were developed to curb the tails of pulses.

THE 1857 AND 1858 CABLE LAYING EXPEDITIONS

For the first cable project, 350, 000 GBP[4] was raised by stock offerings. The American and British governments guaranteed the return on investment. The first attempt was made in 1857. To hold the great mass of cable, two steamships, HMS Agamemnon and USS Niagara, were required. There were two schools of thought as to how to proceed. The engineers wanted the ships to meet in mid-Atlantic, splice the cables on each ship together when sea conditions were opportune, and then lay cable in opposite directions. The procedure favored by the electricians was for one ship to start laying from the shore station and, when its load was exhausted, to splice to the cable on the other ship. The advantage was that continuous electrical contact could be kept with the shore.

The electricians won the first round and, on August 5, 1857, the Niagara started from Valentia Bay on the southwest coast of Ireland. Agamemnon followed. They were accompanied by escort vessels, which were needed to deal with other ships in the path of the lay and to plot the course. The mass of armoring wire would bias compass readings on the cable ships. William Thompson was the electrician. The effort was terminated when the cable laying equipment failed 200 miles out as the cable was lost in 2000 fathoms. The ships returned with lessons learned for future attempts.

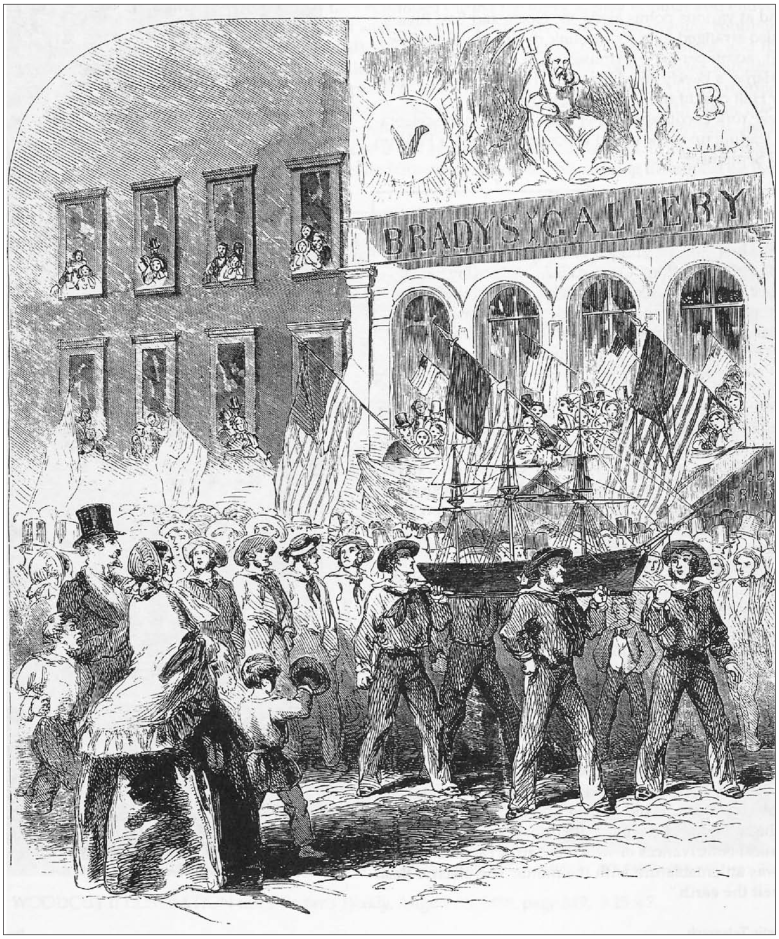
New cable laying machinery was designed by William Everett, the chief engineer aboard the Niagara in 1857. A notable improvement was a self-releasing brake, which operated when the strain on the cable reached a certain threshold.

In retrospect it was an error, but the same cable was used in 1858. This time the two ships were to meet in mid-ocean and begin laying. After a violent storm, which nearly swamped Agamemnon, the ships assembled and began laying cable on June 25 with Niagara laying to the West and Agamemnon to the East. There were two runs, both aborted by cable breaks. It was early in the season, so the ships returned to Ireland for more cable.

On July 17 the fleet set out once again for the mid-ocean rendezvous. After minor glitches, the operation went through successfully. Traveling at a steady rate of five to six knots, Niagara entered Trinity Bay, Newfoundland, on August 4. The cable was landed at Heart's Content. On the same day, Agamemnon arrived at Valentia Bay. The success led to the call from Queen Victoria recounted above.

[3] *In 1843, a process for extruding gutta-percha on copper wire was invented by Werner von Siemens, cofounder of the electronics firm.*

[4] *The best estimate of the rate of exchange prevailing at the time is $5 = 1 GBP [3]. Some idea of the value of the British pound can be gained from the fact that the weekly wage of a skilled workman was $10.*



■ **Figure 2.** *Parade with model of cable ship [1].*

THE 1865 AND 1866 EXPEDITIONS

In the next phase of the story, the British government provided vital support. The British Empire was at its apogee; one could understand the key role that near-instantaneous secure communications would play in tying it together. Even the 1858 cable, in its short life, showed the value of the transatlantic cable as a troop movement was canceled with a saving of between 50,000 and 60,000 GBP, about one seventh the cost of the whole project.

The British government was alarmed by a succession of costly failures in cable laying operations. A cable to India via the Red Sea had also failed. However, a few examples of success provided grounds for hope. The government struck a blue ribbon committee, among whose members were Charles Wheatstone and Charles Tilson Bright, the chief engineer of the expeditions. In its report of 1863, the committee made a number of recommendations concerning manufacture, handling, and design of the cable. For example, the weight of the copper conductor was increased from 107 lbs/mi to 300. To fund the new effort, Field raised 650, 000 GBP by a stock sale in a reformed company. Since the cable was heavier and bulkier, the demands on the cable ships were correspondingly greater. By a stroke of good fortune, just the right vessel was available: the Great Eastern. When completed in 1857, it was five or six times the size of anything else afloat.[5] The Great Eastern had three methods of propulsion, two of which are visible in Fig. 4. The side wheel allowed greater maneuverability. The sails were never used. The unseen screw propeller provided efficient propulsion.

At a rate of 20 nautical miles a day, 2300 nautical miles of cable weighing 5000 tons were loaded in three tanks aboard the Great Eastern. The tanks were filled with water in order to protect the insulation.

Armed with experience and new equipment, the 1865 lay went well until there was a break 600 miles from Newfoundland. There were several attempts to retrieve the cable, which failed simply because there was not enough rope of sufficient strength aboard the Great Eastern to pull up the cable end. The position was carefully noted for future reference.

As flaws were identified and corrected, confidence in ultimate success grew. Money was raised for yet another cable in 1866, which was successful. The cable was brought ashore at Heart's Content, and a message was sent from Vancouver to London on July 31, 1866. There was a double triumph as the Great Eastern grappled for,[6] and found, the end of the 1865 cable. Thus, in a stroke, there were two fully operational cables! There has been continuous operation ever since. Celebratory messages were passed between Queen Victoria and President Andrew Johnson.

The faith of the investors was rewarded. For example, between July 28 and October 31, 1867, 2772 commercial messages were transmitted at a cost of $10 per word with a 10-word minimum. The rate of transmission was 6–8 words per minute. In Table 1 the progression of submarine capacity from this point on is summarized.

SUBSEQUENT TELEGRAPH SYSTEMS

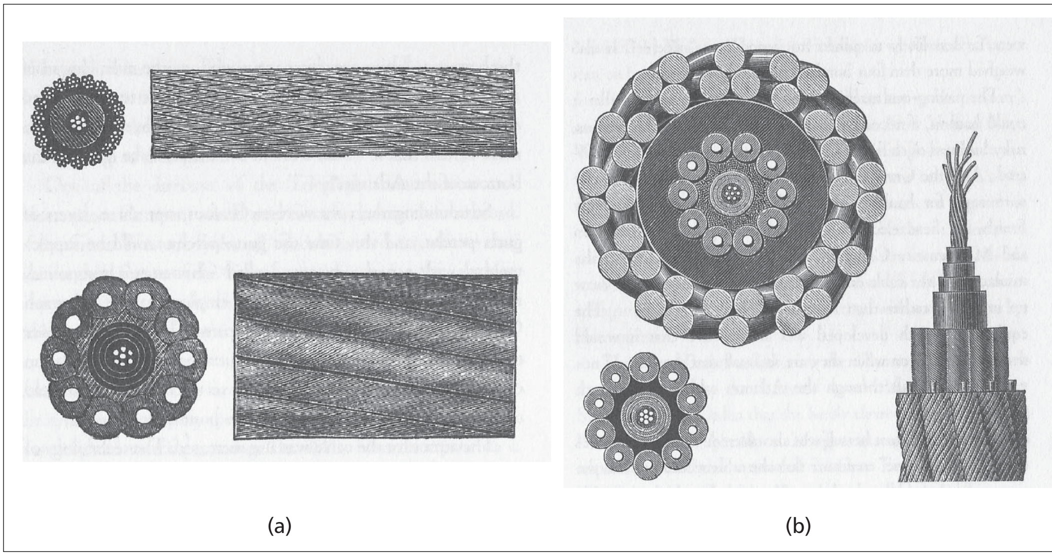
With the Atlantic bridged, other routes followed in succession. An all-sea route to India was completed in 1870 with participation of the Great Eastern. In the following year the network was extended to other parts of the Empire in the Far East, Madras-Penang-Singapore-Hong Kong. From Singapore, via Batavia (now Jakarta), the network was extended to Darwin in northern Australia and on to Adelaide. In 1904 a globe circling path connecting the British Empire was completed, the All Red Route.

Progress was also extensive in the western hemisphere. For example, Florida and Cuba were connected in 1866. Portugal was connected to Brazil via the Cape Verde Islands by a 5386 km long link in 1874.

A major technical advance was the application of the theoretical work of Oliver Heaviside on the benefit of inductive loading. With improved loading using Permalloy [5], improved insulation, and automatic transmitting and receiving equipment, a speed of 400 words per minute was attained in 1928.

[5] *It was not until the Oceanic was built in 1899 that its length was equaled. Its bulk was exceeded by the Mauritania in 1907. For a good description of the Great Eastern, see [4, pp. 155–62].*

[6] *The operation was "seat of the pants" as someone sat on the taut cable to feel when the grapple had caught.*



■ **Figure 3.** *Cable comparisons [4]: a) comparison of 1858 and 1865 cables; b) shallow and deep water versions of 1865 cable.*

TELEPHONE SERVICE: TAT-1

With the advances in cable technology, it was inevitable that attention would turn toward transmitting speech across the Atlantic. After Marconi's first transatlantic transmission in 1901, radio transmission was continuously developed, culminating in shortwave service in 1928.[7] Submarine cable still had a role to play since radio bands were subject to the vagaries of sunspot activity and to seasonal and daily variations. In spite of this clear need for cable, it was not until 1956, nearly 100 years after the first telegraph message, that a transatlantic telephone cable began service. There were formidable technical problems to overcome and worldwide calamities to be endured.

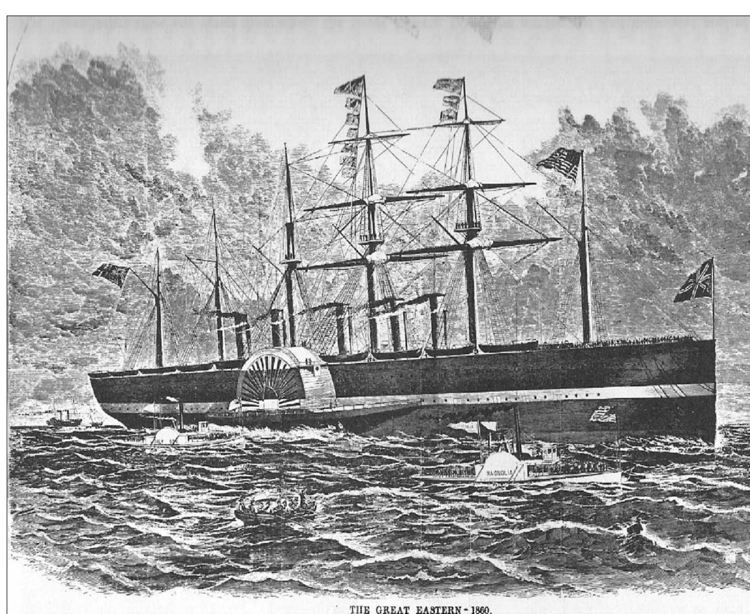
In 1919, a study of transoceanic submarine telephone was initiated by American Telephone and Telegraph Company (AT&T). In 1921 deep-water telephone cables were laid between Key West and Havana. In 1928 there was a proposal for a repeaterless cable bearing a single voice channel across the Atlantic. The cost of $15,000,000 in the midst of the Great Depression (1929–1939), as well as improvements in radio technology, aborted the project.

By the early 1930s electronic technology had advanced to the point where a submarine cable system with repeaters became feasible. The design of repeaters presented an unprecedented challenge, since they were required to lie on the ocean bottom for 20 years. The electrical components, particularly the vacuum tubes, were subject to stringent reliability requirements. Beginning in 1932, extremely reliable vacuum tubes were life-tested for a period of 18 years. Those finally used were significantly below the existing state of the art, but they were the most reliable design extant. Furthermore, they were manufactured under conditions presaging modern semiconductor manufacturing.

[7] *Oliver Heaviside contributed to this aspect of transoceanic transmission as well; he suggested the existence of an atmospheric channel for radio waves, the Heaviside layer.*

The system design also contributed to reliability. In order to increase tube life, the signal levels were carefully controlled. In parallel to the three stages of the amplifier was a gas tube which would fire and bypass the stages in the event of a tube failure. In each repeater, there was a crystal tuned to a frequency unique to the repeater, thus allowing a malfunctioning repeater to be identified. The value of this careful engineering can be judged by the results; TAT-1 operated for 22 years without a single tube failure.

Laying repeaters in the open sea to depths of up to two and a half statute miles was another challenge. If the ship stopped to drop a repeater, coaxial cable with spiraled external armoring could develop kinks. The solution was a flexible repeater which, with some modification, could be laid with equipment designed for telegraph systems. The repeater used



■ **Figure 4.** *The Great Eastern [3].*

Cable	Year	Speed or capacity
Atlantic, Ireland–Newfoundland	1858	A few words per hour
Atlantic, Ireland–Newfoundland	1866	6–8 words per minute
Long cables with automatic transmitting equipment	1898	40 words per minute
Newfoundland–Azores	1928	2500 characters per minute (~400 words per minute)
TAT-1	1956	36 telephone channels
CANTAT	1961	80 telephone channels
TAT-3	1963	138 telephone channels
TAT-5	1970	845 telephone channels
TAT-6	1976	4000 telephone channels
TAT-8	1988	Two fibers/cable, 280 Mb/s/fiber
TAT-9	1992	Two fibers/cable, 560 Mb/s/fiber
TAT-12/13	1996	Two fibers/cable, 5 Gb/s/fiber
TAT-14	2001	Four fibers/cable, 16 wavelengths/fiber, 10 Gb/s/wavelength
Apollo	2002	Four fibers/cable, 16 wavelengths/fiber, 10 Gb/s/wavelength

Table 1. *Milestones in capacity [2, 10].*

in TAT-1, shown in Fig. 5, was designed to flex enough to be wound over the cable drum. The physical limitations of the flexible repeater limited its bandwidth; consequently, amplification could only be in one direction, resulting in a physical four-wire system.

The British Post Office (BPO) pioneered an alternative approach to submarine telephone cable, deploying rigid repeaters with a far larger diameter and greater bandwidth. With suitable filtering, the same repeater could be used for both directions of transmission.

The project was resumed after a hiatus during the Second World War (1939–1945). In 1950 the flexible repeater technology in deep water was tested by a system linking Key West and Havana. Over the summers of 1955 and 1956, the flexible repeater cable was laid between Oban, Scotland and Clarenville, Newfoundland on a route well to the north of existing telegraph cables. (The geography of TAT-1 is shown in Fig. 6.) Each link was approximately 1950 nautical miles long with 51 repeaters spaced at 37.5 nautical mile intervals. The maximum feasible number of repeaters was determined by the maximum terminal voltage that could be applied to power the systems without affecting the reliability of the high voltage components. The powering was +2000 V at one end and –2000 V on the other. The bandwidth of the system was, in turn, dictated by the number of repeaters. In addition to the repeaters, there were eight undersea equalizers in the East-West link and six in the West-East link. The equalizers served to correct accumulated misalignment in the frequency band. Although the gross difference in cable loss across the transmission band of 144 kHz was 2100 dB, the correction of the equalizers and repeater circuits led to a difference of less than 1 dB across the band.

In the first 24 hours of service, beginning on September 25, 1956, there were 588 London-United States calls and 119 from London to Canada. Perhaps this is a reflection of the fact that TAT-1 immediately tripled the circuit capacity across the Atlantic. The frequency band of the Atlantic link was between 20 and 164 kHz, allowing 36 voice channels (4 kHz), which were split with six between London and Montreal and

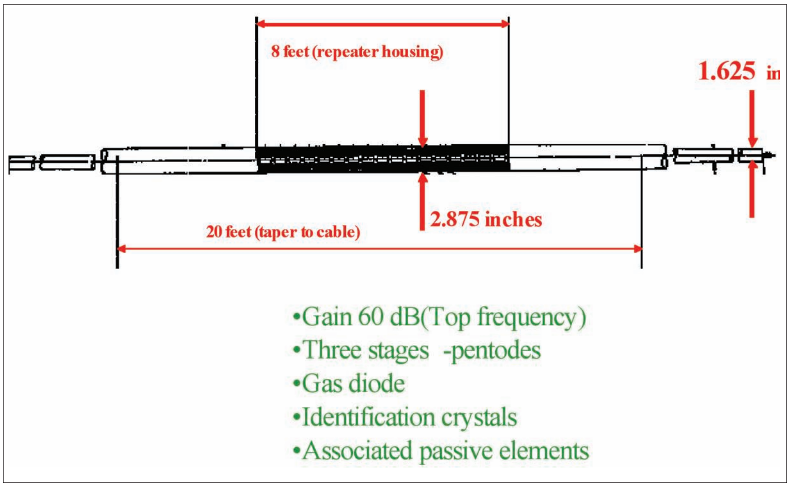


Figure 5. *Flexible repeater.*

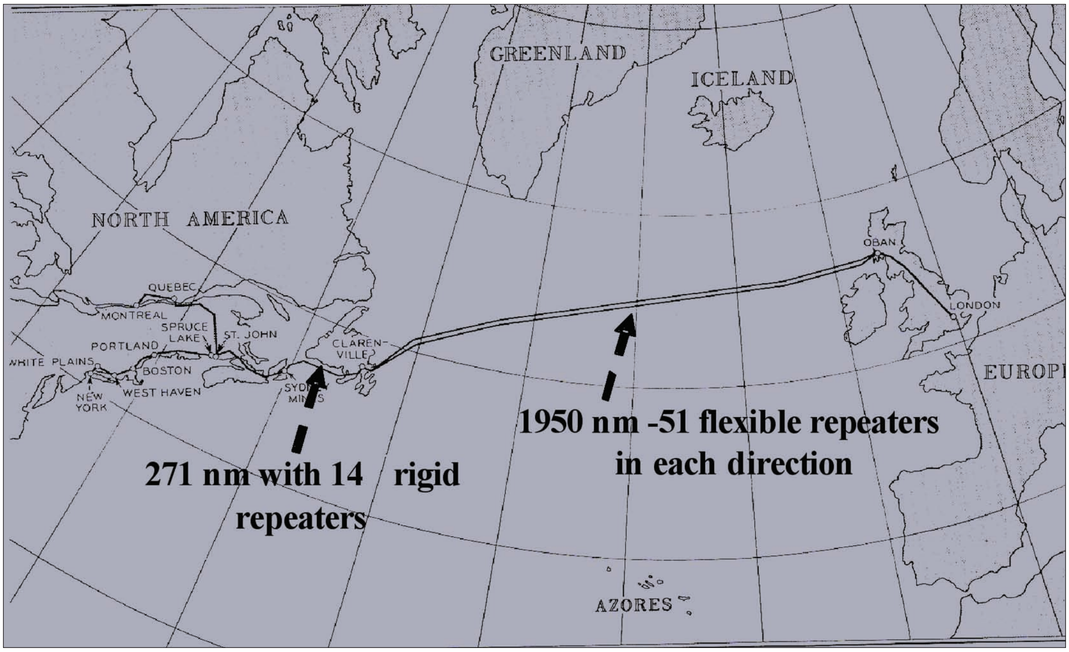


Figure 6. *TAT-1 system.*

29 between London and New York. A single channel was dedicated to narrowband uses such as telegraph and maintenance.

The system also included an overland link across Newfoundland and an underwater link to Nova Scotia. The two links consisted of a single cable 271 nautical miles long with 14 rigid repeaters designed by the BPO spaced at 20-nautical-mile intervals. The capacity was 60 voice channels, 24 of which carried traffic between Newfoundland and Nova Scotia.

The total cost of TAT-1 was $42,000,000 or 15,000,000 GBP at the then prevailing exchange rate.[8] The cost was split in proportion to usage among three partners: AT&T and its Canadian subsidiary, the Eastern Telephone and Telegraph Company, the BPO, and the Canadian Overseas Telecommunications Corporation. The cost attributed to the BPO was met by contributions of cable, repeaters, and terminal equipment, and by the services of CS Monarch, which laid all of the cable.

The cost of over $1,000,000 per voice channel spurred the development of terminal equipment that would use bandwidth more efficiently. The BPO designed the 16-channel bank, which increased the number of voice channels in the standard 48 kHz group band from 12 to 16 by fitting the voice signal into 3 kHz rather than the standard 4 kHz band. A second advance in terminal equipment was Time Assigned Speech Interpolation (TASI) developed at Bell Labs. TASI allowed a doubling of the number of voice circuits by taking advantage of gaps in speech.

The same flexible repeater systems were laid to France, Hawaii, and Alaska. With a growth of 20 percent in traffic, sub-cables after TAT-1 increased capacity by employing technology that was ever closer to the state of the art. After 1961, systems used rigid repeaters and a cable whose strength member was in the center rather than on the periphery. Germanium semiconductors were introduced in 1970. This was followed, in 1974, with silicon transistors. The last coaxial cable system was laid across the Atlantic in 1983 [8, 9].

[8] *In 1956 the starting salary of a newly minted graduate engineer was $4800.*

OPTICAL SYSTEMS [10–12]

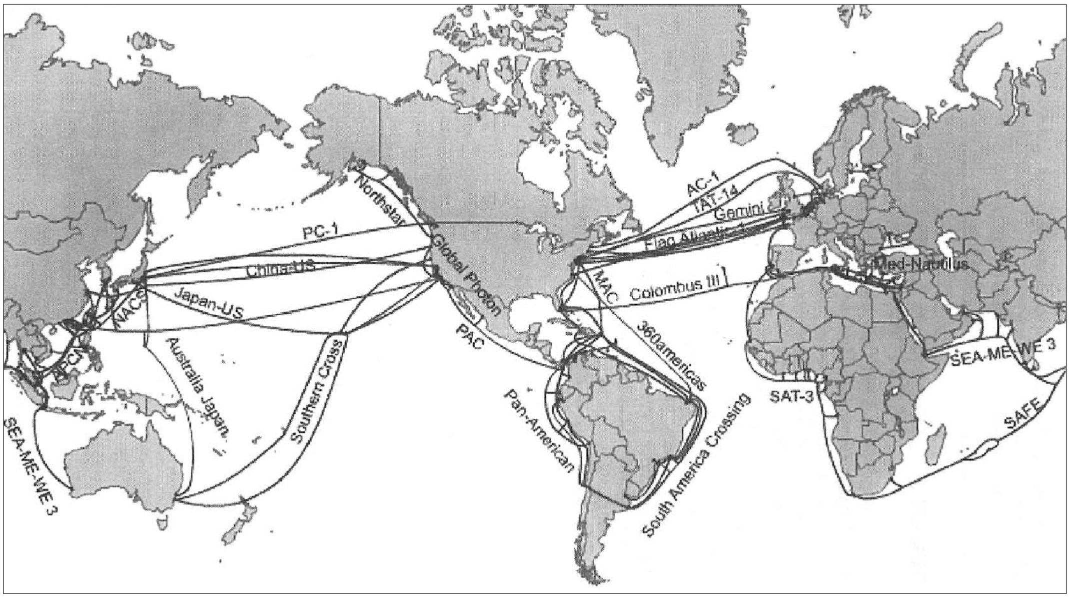
The first transoceanic optical system, TAT-8, went into service in 1988. Repeaters regenerated pulses electronically by converting signals from optical form to electrical and back again. There were two working pairs of fiber in the cable, each fiber operating at a rate of 280 Mb/s. By 1993 more than 125,000 km of TAT-8 systems were in service worldwide. This figure almost matched the total length of analog submarine coaxial installations. A second-generation regenerative system, TAT-9, went into service in 1992. The rate per fiber was increased to 580 Mb/s (Table 1.)

In the late 1990s the development of Erbium doped optical amplifiers led to a quantum leap in the capacity of submarine cable systems. Optical signals in the band centered at 1.55 μm could be amplified directly, and capacity was no longer limited by the speed of electronics. The first optically amplified system laid across the Atlantic was TAT 12/13 in 1996. The transmission rate on each of two fiber pairs was 5 Gb/s.

Within the optical band covered by the amplifier, dense wavelength-division multiplexing (DWDM) can place traffic streams on different wavelengths. In 2001 the TAT-14 system carried 16 wavelengths at a rate of 10 Gb/s on each fiber of four fiber pairs for a total capacity of 640 Gb/s. DWDM also allows data streams to be added as technology advances. For example, in TAT 12/13 three wavelengths were added in 1999, thereby tripling its capacity.

As indicated above, several pairs of fiber can be housed in the same cable sheath. Not all of the available pairs need to be used immediately. This provides redundancy for cable failure and allows for growth.

Modern optical submarine cable systems carry such large volumes of traffic that redundancy is crucial. Typically, modern fiber optical systems, such as TAT-14, have two separate transatlantic cables, which are part of a ring topology. Two other links connect shore stations on each side of the Atlantic. Traffic flows concentrically around the ring in both directions. Should there be a cable break, the ring is self-healing; traffic is looped back onto spare fiber pairs in operating cables.



■ **Figure 7.** *The extent of modern cable systems [10].*

Advancing technology has not been the only change in the world of submarine cable. In 1994 the U.S. Federal Communications Commission ended AT&T's monopoly, thereby beginning a new era in telecommunications. In a few years the telephone business transformed from a decades-old regulated monopoly to an arena of fierce competition. Submarine cable was part of the trend. Previously, the TAT series of submarine cables were installed by consortia composed of traditional telecommunications companies, AT&T in the United States and Standard Telephone and Cable (STC) in the United Kingdom, for example. Beginning with TAT-1, they rolled on the scene in an orderly fashion (Table 1). Toward the turn of the millennium, there was a frenzy of activity as one new system after another was installed[9] — AC1 (1998), Gemini (1999), Columbus 3 (1999), Flag Atlantic (2000), Yellow 2(AC2) (2001), Hibernia (2001), and Tyco Atlantic (2001). All are roughly similar to the Apollo system (2002) shown in Table 1. This activity, part of the dot-com bubble, resulted in overcapacity.

The consequences of this particular rush of enthusiasm for new technology were more serious than a fire at City Hall. The bursting of the bubble caused a spate of bankruptcies, and people lost pensions and life savings. One of the major players, Global Crossing, suffered the seventh largest bankruptcy in U.S. history. In recent years there have been no significant new systems as the overcapacity has gradually been absorbed by increasing traffic.

The advances in submarine cable technology can be encapsulated by the advances in transmission capacity shown in Table 1. Figure 7 gives a picture of the worldwide deployment of modern cable systems.

[9] *The same system may assume different names in different contexts. We have followed [10]. See also [11].*

ACKNOWLEDGMENT

The author would like to thank Bill Burns and Steve Weinstein for their aid and encouragement.

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BIOGRAPHY

JEREMIAH HAYES received his B.E.E. from Manhattan College in 1956, whereupon he joined the submarine cable department of Bell Laboratories, where he spent four years. Subsequently, he received an M.S. in mathematics from New York University and a Ph.D. in electrical engineering from the University of California, Berkeley. Since retirement from Concordia University in Montreal on 01/01/01 he has pursued his life-long interest in history.