The Next Generation in Underwater Acoustic Detection

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Since the 1950s, AT&T has provided underwater detection equipment to the U. S. Navy to satisfy the navy's two-tier mission of studying the ocean and developing and testing sonar systems. The latest generation of hardware is a fiber-optic system that has the transmission capacity of all the previous systems combined. Its design and development has provided a challenge both from the technical aspect of meeting stringent performance requirements and from the engineering aspect of managing a large defense program having a budget greater than $500 million. Following a brief summary of AT&T's history in the development and manufacture of underwater acoustic detection hardware, this paper provides a technical description of the fiber-optic system and a project history describing the processes used in bringing the equipment into production. During the period of program execution (1989 to the present), systems engineering management philosophy has evolved from strict flow-down of requirements via military standards to concurrent engineering and product-realization teams. The Fixed Distributed System (FDS) project has followed the same route, partly by design and partly by necessity. It provided some valuable lessons that have been learned and incorporated into the present AT&T Advanced Technology Systems (ATS) engineering process, which has been the basis for AT&T Best Current Practices in systems engineering.

Introduction

AT&T has a long history of building and fielding high-reliability undersea acoustic detection equipment for the U. S. government. The equipment has been supplied as part of the sound surveillance system (SOSUS)—a fixed, undersea surveillance system having readout facilities in shore locations, which are known as *U. S. naval facilities*. These facilities support command and tactical antisubmarine forces by detecting, classifying, tracking, and reporting on submarines. They also gather long-term oceanographic and undersea geological information.

The cooperative effort with the U. S. government began in the 1950s and has continued for more than four decades. During those years—which witnessed rapid political, economic, and technological change—AT&T developed and deployed several generations of acoustic detection systems as shown in Figure 1. Each succeeding generation incorporated the latest technology advances necessary to satisfy expanded mission requirements, as well as the need for new and improved system features and capabilities. This evolution of technology led steadily to the development and production of new designs having increasingly higher transmission bandwidths, greater channel capacity, longer cable lengths, and smaller size.

The "History of AT&T Ocean Systems" section provides a brief overview of AT&T underwater detection systems. "The Technical Challenge of the FDS" section pre-

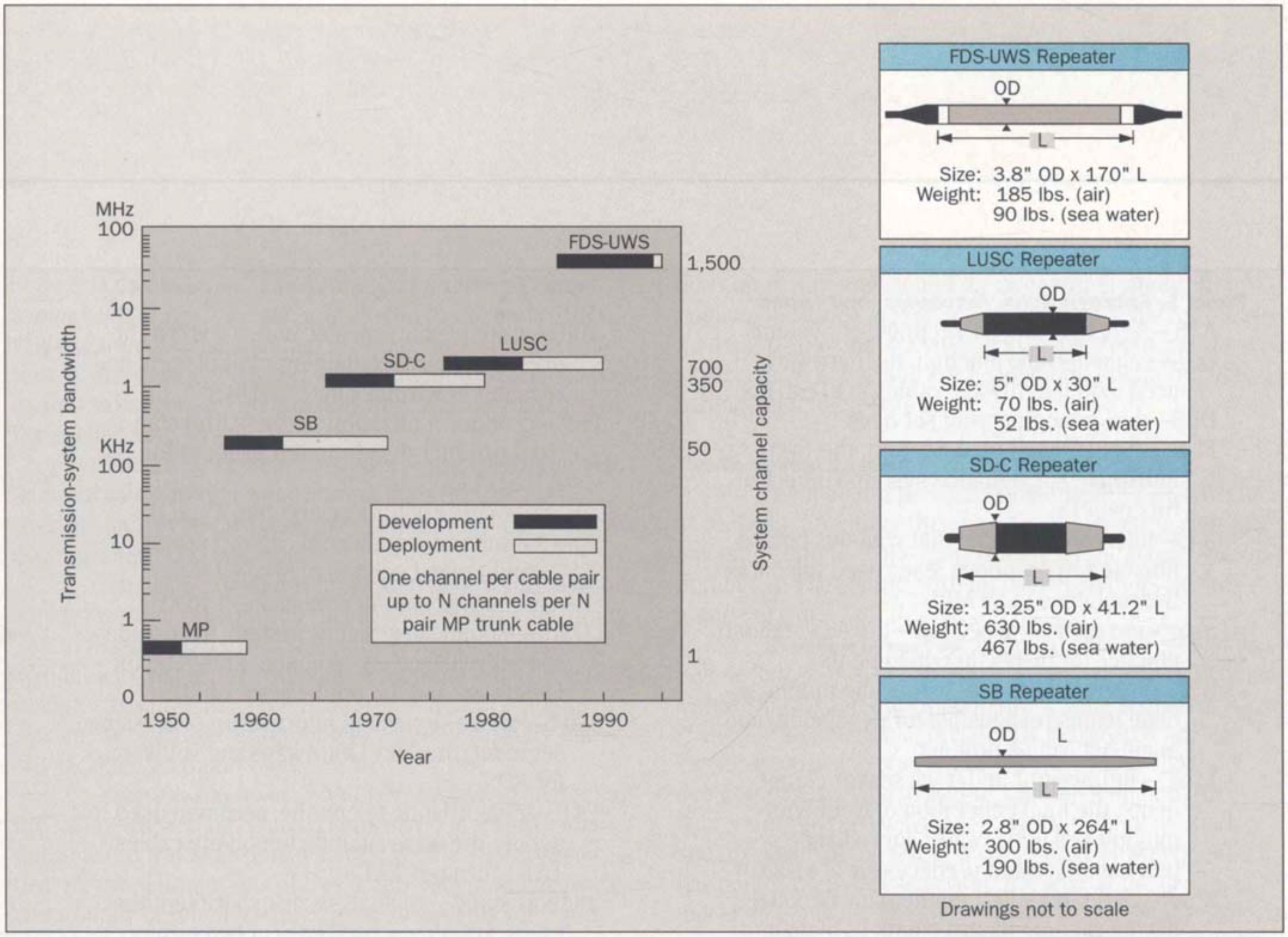

Figure 1. The AT&T effort to develop underwater acoustic detection equipment for the U. S. government began in the 1950s and continues today. During those years, AT&T developed and deployed several generations of acoustic detection systems as shown in the illustration. Each succeeding generation incorporated the latest technology advances necessary to satisfy expanded mission requirements, as well as the need for new and improved system features and capabilities.

sents a detailed description of the Fixed Distributed System – Underwater Segment (FDS-UWS). "The Development Process" and "Development Process Successes" sections discuss FDS development and illustrate some of the program's challenges and achievements. The "Lessons Learned" section concludes the paper and describes the ATS product realization process, which was developed, in part, through disciplined system engineering.

History of AT&T Ocean Systems

AT&T's first entry into the undersea acoustic detection arena occurred in 1950. Since then, five generations of systems have been produced. A summary of each of the five system types follows.

Multipair Systems. Cable transmission systems employing multiple pairs of wire to send acoustic information as electrical signals were the first to be developed by AT&T. Each *multipair system* employed a hydrophone that drove its own dedicated, balanced cable pair to bring electrical signals to a user. These systems used hydrophones of the moving-coil (electrodynamic) transducer type, which provided enough output signal power to drive the entire two-pair cable without underwater amplification.

The cylindrical hydrophones were massive, however, weighing approximately 53 pounds and measuring about five inches in diameter and 24 inches in length. The underwater cable was also physically large in proportion to the number of system channels. These early systems suffered from limited channel capacity, channel bandwidth, and cable-length range.

SB Systems. The successors to the multipair systems were the *SB coaxial cable systems*, which were introduced in the early 1960s.[1] The design of these second-generation systems was based on an adaptation of the SB repeater and coaxial ocean cables that were developed for the first AT&T trans-Atlantic telephone cable systems—TAT-1 and TAT-2.

Panel 1. Abbreviations, Acronyms, and Terms

ATS—AT&T Advanced Technology Systems
CCJ—cable-to-cable junction, the hardware used to join lightwave cables in FDS-UWS
DES—design engineering services
FDS—Fixed Distributed System, the first lightwave surveillance system subject of this paper
ICC—interconnect cable that contains optical fiber and hydrophone leads used to connect hydrophones to an MRU
in-process quality inspection—the ATS standard practice for inspecting documents
IPT—integrated product teams, the multidiscipline teams responsible for developing and manufacturing a product
LUSC—lightweight undersea sensor components, the final generation of frequency-multiplexed underwater surveillance system hardware and predecessor of FDS-UWS
Monte Carlo model—a mathematical model having random features built in that simulate uncontrollable statistical variations in the modeled process or product
MP—multipair underwater cable having sets of twisted-pair copper wire to transmit signals
MRU—multiplexer repeater unit, a watertight pressure vessel containing multiplexing and repeater electronics for FDS-UWS
PRP—product realization process, the standard product development process for AT&T-ATS
SB—submarine commercial cable, Type B
SD—submarine commercial cable, Type D
SD-C—militarized version of SD cable
SF—submarine commercial cable, Type F
SOSUS—sound surveillance system, fixed undersea surveillance equipment operated by the U. S. Navy and the predecessor of FDS
SSIPS—shore signal and information processing segment, the "dry" hardware and software for FDS
TAT—trans-Atlantic telephone, acronym used to denote the trans-Atlantic telephone cables TAT-1 through TAT-8
tradeoff study—an analysis or experiment that weighs relative advantages of two or more designs or approaches to reach a decision on which choice to implement
UWS—underwater segment, the "wet" hardware for FDS

SB systems were considerably more sophisticated than the multipair systems. They incorporated frequency-division-multiplexed signal transmission to provide the capacity for greater system bandwidth, cable length, and much smaller diameter cable. Specially developed and qualified high reliability semiconductors, vacuum tubes, and discrete circuit components were used in the underwater multiplexer and repeater designs to enhance system performance and ensure meeting the 20-year system service life requirement.

SD-C Systems. The third-generation AT&T product was the *SD-C system* introduced in the early 1970s. Functionally, the SD-C system was the same as the earlier SB, but this newer version had significantly more bandwidth, channel capacity, and longer maximum cable length.

The SD-C designs also relied heavily on reuse of previously developed commercial undersea technology—in this case, technology used in the SD[2] and SF[3] telephone cable installations TAT-3 through TAT-5. Specific examples were reuse of the commercial SD armorless coaxial cable design and SF repeater high-pressure housing containing newly designed transistorized regenerator electronics, which replaced the older SD commercial system's vacuum-tube repeater circuitry.

While this approach offered significant advantages in increased channel capacity and cable length, it also had the disadvantages of large physical size and excessive weight for the system multiplexer and repeater electronics. Even though SD-C represented an improvement over multipair and SB systems, even greater channel capacity ultimately was needed.

LUSC Systems. The *lightweight undersea sensor components (LUSC) system*, introduced in the early 1980s, was the fourth-generation AT&T acoustic detection system. It was developed to provide additional channel capacity and to overcome the size and weight disadvantages of the earlier SD-C system.

The LUSC system introduced new hydrophones and multiplexers that were compatible with the SD-C transmission system. Thus, they could be used in conjunction with the SD-C systems.

The LUSC design represented another significant step forward in underwater electronics with the introduction of thin-film integrated circuits, component miniaturization, and quadrature-amplitude modulation. These technologies resulted in a significant reduction in equipment size and weight and a doubling of channel capacity without sacrificing channel bandwidth.

Lightwave Systems. The LUSC system represented the last of the analog, coaxial cable, frequency-division-multiplexed transmission systems. By the 1980s, the practical physical limitations of this technology and hardware were finally reached, requiring the design and development of a new-generation system to meet the technical challenges of future mission requirements.

The fifth generation of AT&T acoustic detection systems is known as the *fixed distributed system underwater segment* (FDS-UWS). Unlike earlier systems, which were militarized versions of commercial technology, the FDS-UWS was designed and developed specifically for military purposes as a major defense system acquisition. This approach was necessary to respond to significant advances in submarine technology.

Meeting the more stringent mission requirements necessitated the incorporation of advanced digital data transmission and lightwave technology. The FDS-UWS uses time-division-multiplexed data transmission over a fiber-optic undersea cable. This results in lower per-channel costs, greater channel capacity, longer cable lengths, as well as smaller, lighter underwater components.

These characteristics increase system flexibility considerably, facilitating the practical realization of large, complex underwater configurations. The FDS-UWS is currently in production and is scheduled for deployment in the mid 1990s.

Future System Uses. In addition to oceanographic data-gathering and sonar research, future system evolutions are being envisioned for many other applications. Such applications include monitoring systems for unlawful drug trafficking activities and arms shipments, as well as Exclusive Economic Zone violations (including illegal fishing) and nuclear testing.

The Technical Challenge of the FDS

As in all the previous systems, the FDS-UWS has as its basic functions the sensing and transmission of acoustic signals. Following is a brief functional description of the FDS, along with an overview of its performance drivers.

Overview of the FDS. A typical FDS is depicted in Figure 2. It consists of an underwater segment (UWS) and a shore signal and information processing segment (SSIPS). The function of the UWS is to transmit acoustic signals from sea to shore. The SSIPS functions include detecting, classifying, tracking, and reporting on the sources of the received signals. Details of the methods and operation of the SSIPS are classified. However, AT&T has contributed to research in this area, some of which has been published in unclassified literature.[4] The SSIPS is being developed by a separate contractor for the FDS. This discussion concentrates on AT&T's contribution to the FDS, which is the development of the underwater segment of the system.

Hydrophones are located at the input of the UWS. The hydrophones convert acoustic pressure variations into electrical signals. The electrical signals are transmitted over twisted-pair leads in the interconnect cable (ICC) to the multiplexer repeater unit (MRU). The combination of an MRU and its associated hydrophones and ICC is known as a *cluster* (Figure 2).

The MRU combines two functions in a single, flexible, water-tight pressure vessel. The first of these is the *multiplexer function*, in which the hydrophone signals are amplified, digitized, and multiplexed onto the optical transmission data stream. The second is the *repeater function*, in which the optical data stream is received from a prior unit, converted to an electrical signal, reamplified, and retransmitted as an optical signal. If the MRU detects no prior signal, then it becomes the first system unit and generates the system clock and initial data stream.

Located after the sensing portion of the system, known as the *field*, is a trunk portion whose function is

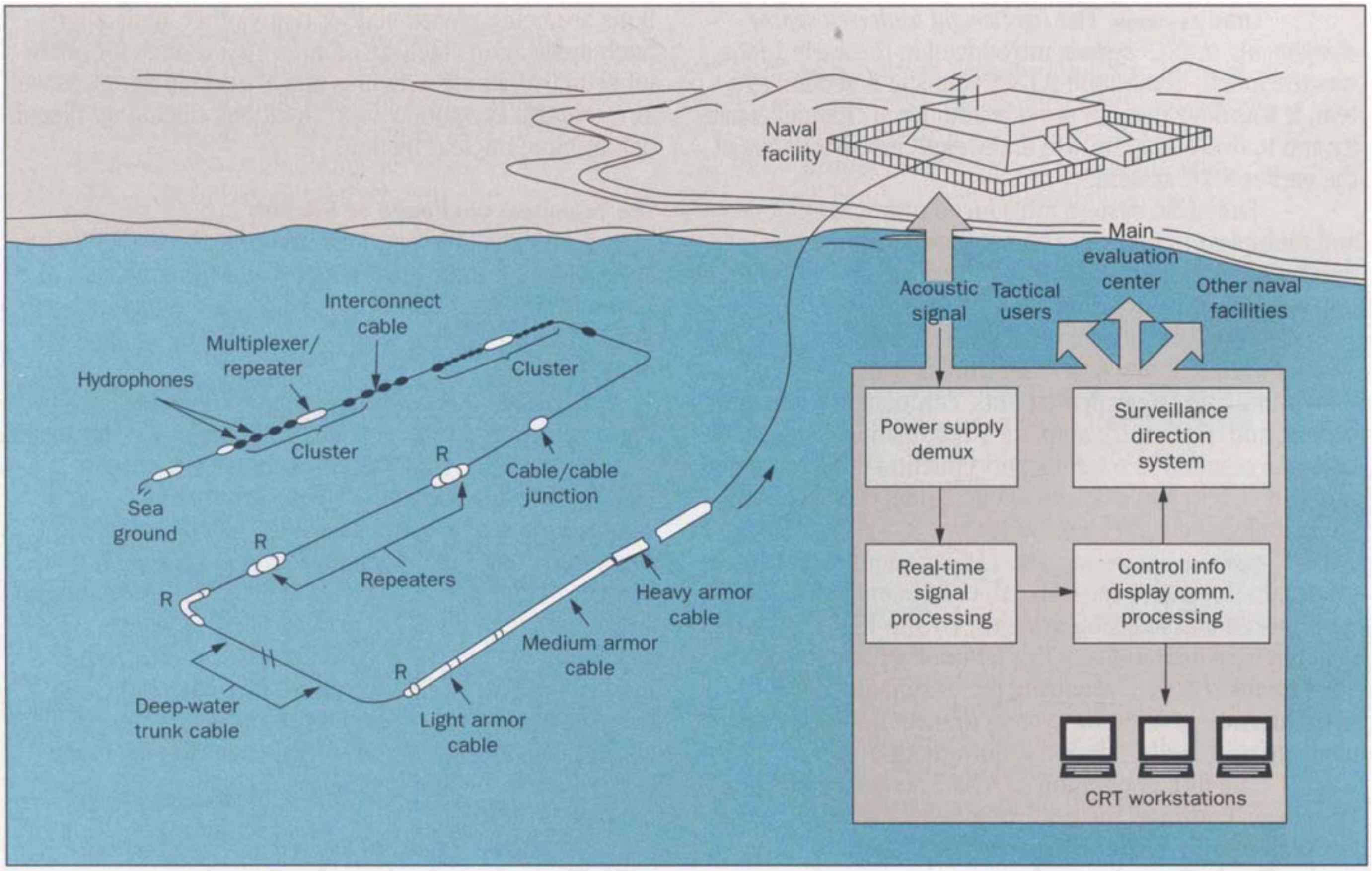

Figure 2. This drawing depicts a typical fixed distributed system. It consists of an underwater segment (UWS) and a shore signal and information processing segment. Hydrophones are located at the input of the UWS. The hydrophones convert acoustic pressure variations into electrical signals. The electrical signals are transmitted over twisted-pair leads in the interconnect cable (ICC) to the multiplexer repeater unit (MRU). The combination of an MRU and its associated hydrophones and ICC is known as a *cluster*.

simply to transmit the signals to shore for processing. The trunk consists of repeaters and trunk cable. The repeaters are contained in a pressure vessel and use the same electro-optics as the repeater portion of an MRU.

To configure a system for a particular application and protect it from environmental hazards, trunk cable having various grades of armor is provided. Cable-to-cable junctions (CCJs) are also part of the system and provide the means to connect all the piece parts together.

Shore terminus equipment, which includes the high-voltage power supply and demultiplexer, is also included in the underwater segment. At the shore terminus of the FDS, the optical signal is demultiplexed and converted to baseband electrical signals available at either analog or digital ports. These signals are processed by the shore signal and information processing segment (SSIPS) to detect, localize, and track targets of interest.

In addition to the transmission subsystem described earlier, the FDS has an additional subsystem. It consists of high-voltage power supplies, power-supply grounds, and cable that provides regulated, constant-current power to the MRUs and repeaters.

Performance Drivers for FDS. The basic functions described in the previous subsection are the same as for earlier detection systems. The uniqueness of FDS comes from the high data volume and number of channels required in a typical system. The need for these features is driven by the navy's mission to detect the quiet, modern submarine. Stealth technology has evolved to the point where nuclear- and diesel-powered submarines are quieter than ever before, making them less vulnerable to detection than their predecessors.

To increase the effectiveness of submarine monitoring systems, it was necessary to push acoustic detection methods beyond previous limits. This required an increase in processing gains—that is, additional channels. Even with increased gains, detection ranges were shortened, requiring more clusters to accomplish a given mission.

Both these factors led to the increase of data channels. In turn, the need for additional channels creates other requirements, such as that for smaller and lighter components. The following subsection describes this effect in more detail.

Functional Allocation of Performance. The fundamental challenge to the FDS system is that of *detection.* Physically, the detection problem is governed by the sonar equation:

$$SE = SL - RD + AG - TL - AN.$$

SE is the signal excess, which must be positive for a detection to occur. (This is not strictly true because detection is a stochastic process, but it will suffice for this purpose.)

SL is the source level, which is determined by the navy's mission.

RD is the recognition differential. RD is properly allocated to the SSIPS, and it represents gains achieved through signal processing to exploit the characteristics of the signal and noise field.

AG is the array gain obtained by beamforming—that is, coherently summing the signals on the cluster of hydrophones. The array gain is the responsibility of both the SSIPS and the UWS. The SSIPS influences AG by signal-processing techniques, such as adaptive beamforming that exploit the time-varying directional characteristics of the signal and noise fields. The UWS influences the AG by providing the appropriate number of channels for beamforming, as well as by controlling both the phase and amplitude of the received signals to tight tolerances. Thus, degradations to the received signals that would interfere with the coherent sum are minimized.

TL is the transmission loss of the ocean medium from the source to the receiver.

AN is the ambient noise of the ocean.

To a large extent, an engineer does not control the last two quantities because the environment determines them. Knowledge of their characteristics, however, will influence the design, and the characteristics can be exploited to maximize the signal excess. For example, as mentioned earlier, signal-processing techniques in the SSIPS can be used to exploit the spatial and temporal characteristics of the ambient noise.

Part of the FDS solution to providing adequate signal excess is to minimize TL by shortening the distance between target and receiver. This was effectively achieved by distributing the sensors in a field that requires longer cable runs and more receivers to cover a fixed area of ocean. With a lightwave system, however, these design goals are achievable.

Further provisions derived from the mission requirements described earlier are allocated to system components as follows:

- *High data capacity.* Many channels are needed to achieve high-gain beamforming and desired coverage of ocean areas.
- *Low-power components.* These parts are necessary to achieve system life and size goals in the harsh ocean environment.
- *Small physical size.* This factor allows the cost-effective installation of planned systems using available deployment and transport capabilities.
- *Long system life.* To be more cost effective compared to other systems used by the navy, the FDS was designed to have an extended service life of 24 years.

The Development Process

Two key FDS components engineered to meet the preceding requirements are the *passive variable reluctance hydrophone* and the *cluster.* The challenges faced and successes attained in bringing these components to production are discussed next.

Historical Process—The Need for Reengineering. Initially, the FDS-UWS organization structure was established as shown Figure 3a. This structure supports the traditional type of sequential engineering development processes used today in many organizations.

A typical work flow for this process is shown in

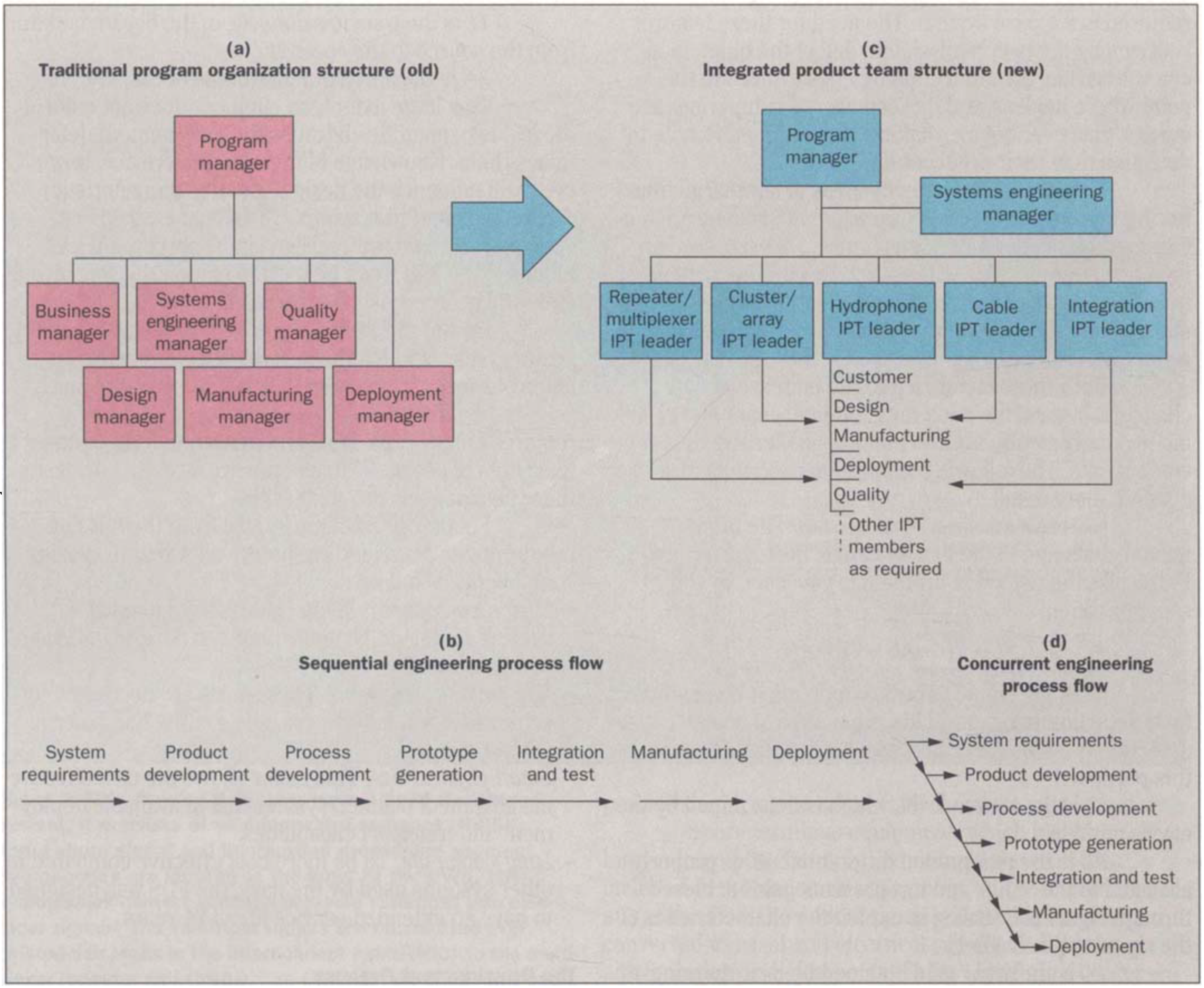

Figure 3. The FDS-UWS organization structure was initially established as shown in Figure 3a. This structure supports the traditional type of sequential engineering development processes used today in many organizations. A typical work flow for this process is shown in Figure 3b. The integrated product team (IPT) structure is shown in Figure 3c. This initial organization was later expanded into a structure of IPTs that report directly to the program manager and embrace a highly disciplined, system-engineering process in support of concurrent engineering. A typical concurrent engineering process flow is shown in Figure 3d.

Figure 3b. The chief advantage of this process is that it allows an orderly progression of the product through the various phases of the development effort. However, it suffers from one problem—some involved organizations do not adequately communicate about the design early enough in the product life cycle. As a result, such key issues as manufacturability, maintainability, and system life-cycle support might not be fully addressed until the product has reached a late stage in its development. Then, any changes required as a result of these down-stream activities frequently are difficult to make and very costly.

Reorganization into Integrated Product Teams. About midway through the FDS-UWS development program, it became evident that the design could pose significant manufacturing difficulties. As a result, integrated product teams (IPTs) were formed, involving both the design and manufacturing engineers in the transition to manufacture. Through participation in the IPT, the manufacturing engineers gained a better understanding of the product. Thus, they facilitated the development of special tools, test-equipment facilities, and training.

The IPT structure is shown in Figure 3c. This initial organization was later expanded into a structure of IPTs that report directly to the program manager and embrace a highly disciplined system-engineering process in support of concurrent engineering.

The U. S. Department of Defense defines concurrent engineering as "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support."[5] To accomplish concurrent engineering as determined by this definition, teams are created that continually provide input on the integrated design of product and process throughout an entire product's life cycle.

The fundamental advantage of such a team structure and concurrence of effort is that many issues are addressed simultaneously, resulting in much shorter development intervals. A typical concurrent engineering process flow is shown in Figure 3d. By drawing members from all relevant functional disciplines, this team structure eliminates barriers present in the old structure—that is, inadequate communication as a product moves from the design stage to manufacturing, and then to testing and the field. Thus, the concurrent-engineering IPT embodies the concept that the fastest and least expensive way to advance a product from the design stage to manufacturing is to assemble—at the beginning of a project—all the professionals who will be involved in any part of the process.

A core ingredient in the success of this process is the development team itself, which should be made up of a multidisciplined group of experienced professionals. Typically, such a team includes representatives from design, engineering, customer, management, and supplier groups.

A crisis resulting from the failure of an underwater cluster unit provided an unexpected major test of the effectiveness of this reengineered program structure. The crisis occurred well into the program-development phase. The details about how this crisis was addressed and the program-development effort itself are discussed next.

Development Process Successes

This section presents a more detailed look at two component-development projects within the FDS program. The first project discussed, the *variable-reluctance hydrophone*, illustrates the benefits of involving manufacturing early in bringing a product developed in a research environment into production. The second project, *cluster redesign*, illustrates the advantages of the IPT approach in the rapid development of a comprehensive requirements set to provide an easier to build, lower-cost product.

Hydrophone Development. Early on, project management decided that an unpowered hydrophone would be used in the FDS design. In addition to saving power, the passive hydrophone has an inherent advantage in reliability, does not require a preamplifier, and allows all circuitry to be housed in a single pressure vessel. These features outweighed those of a powered ceramic hydrophone in providing improved channel similarity. Research conducted prior to the FDS-UWS contract award indicated that a unique variable-reluctance hydrophone would be the best choice. Such a hydrophone uses electric current generated by a plate moving in a permanent-magnet field to convert sound pressure into an electrical signal.

To apply this concept to FDS, the size and number of parts in the experimental hydrophone had to be reduced to make it suitable for manufacturing. Figure 4 shows an exploded view of the resulting hydrophone assembly. Even though the original program was not organized as IPTs, the hydrophone development project assumed one crucial characteristic of a multidiscipline team—the early involvement of manufacturing.

The manufacturing organization became involved initially because of its acknowledged expertise in polyethylene molding, gained during development of the earlier LUSC and SD-C systems. Polyethylene molding is extensively used in both commercial and military underwater cable systems because of the material's excellent long-term undersea survival characteristics. It is a crucial technology in which AT&T has special knowledge.

A molded polyethylene boot had to be designed

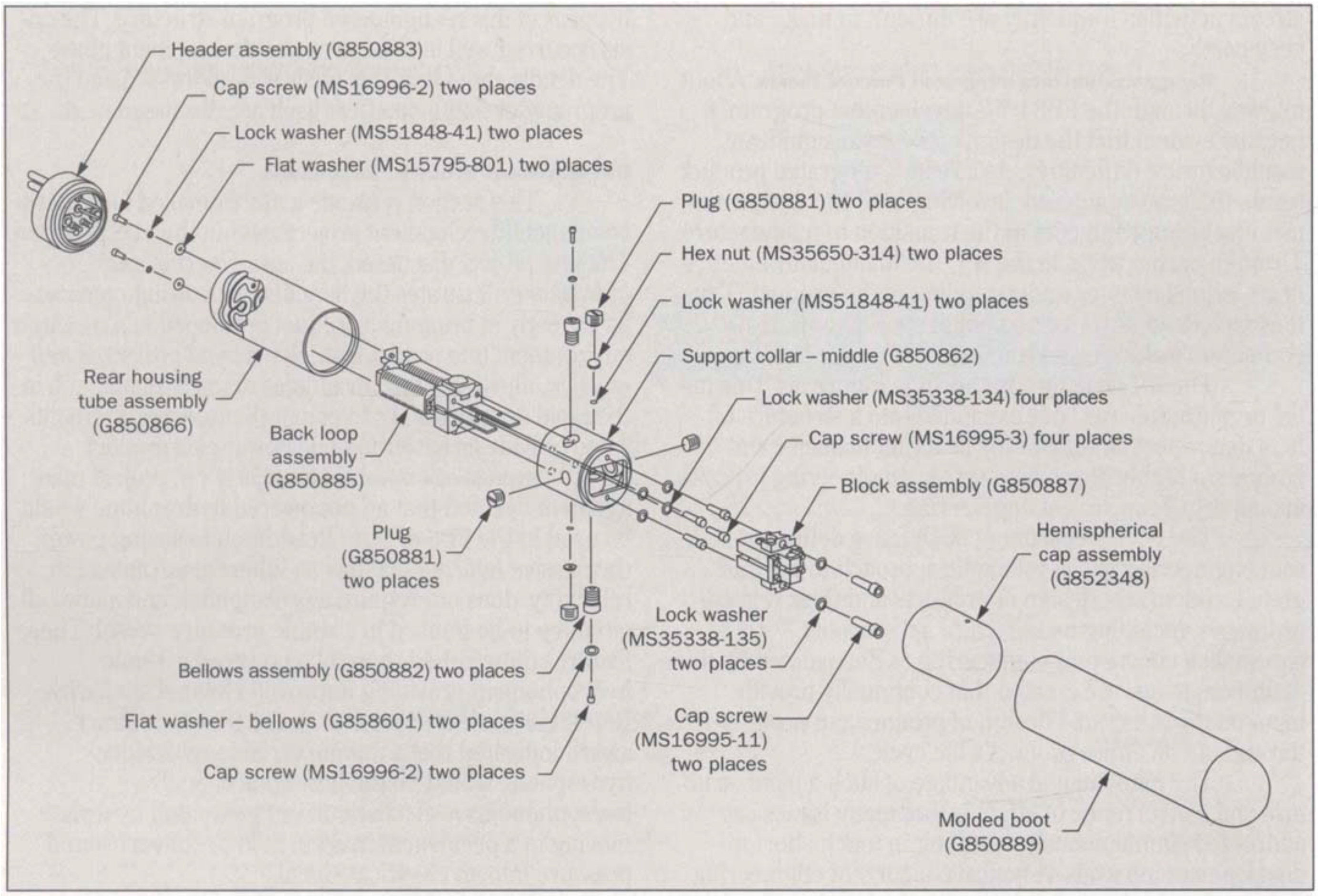

Figure 4. In the fixed distributed system, the size and number of parts in an experimental hydrophone had to be reduced to make it suitable for manufacturing. This exploded view depicts the resulting hydrophone assembly.

to make the hydrophone watertight. Project management realized that manufacturing could design the necessary molds most efficiently. Therefore, that organization needed to participate in the design process. Thus, the manufacturing engineers were provided with the early product drawings, and they worked directly with the product designers, making suggestions and concurrently developing the necessary tooling for testing and production.

The initial teamwork on the molded boot's design led to interactions in other areas. The manufacturing engineers suggested alternative components based on ease of procurement. They also worked with the designers in building test models. This interaction resulted in improvements to the manufacturing process, as well as to the design of the factory's tooling. The testing and manufacturing tooling thus developed was used to fabricate final product models, after which it was transferred to the factory floor. This process resulted in few design changes once production began, as illustrated by the bar graphs in Figure 5.

One of the challenges faced in this mode of operation is keeping track of design changes and ensuring that the appropriate tradeoffs between system-level requirements are considered when design changes are made. This requires that all team members have a clear understanding of how their activities affect other teams and the rest of the system. The project required constant

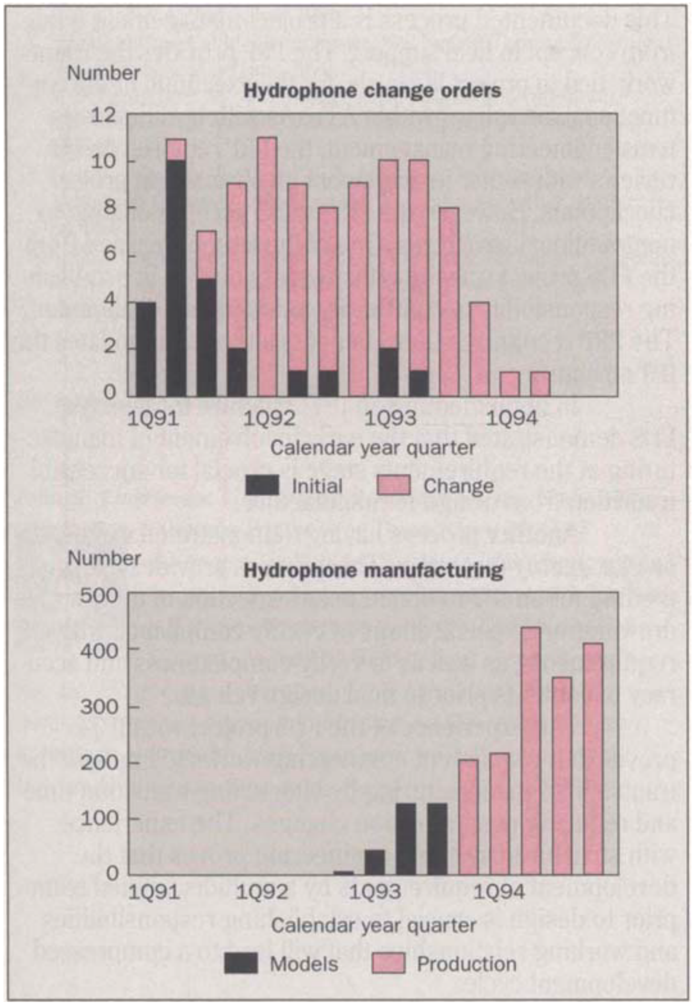

Figure 5. These bar graphs illustrate both the number of hydrophone change orders issued and units manufactured. Early establishment of drawing structure and manufacturing involvement in model building and testing led to a smooth transition to production with few design changes once production began.

interaction between the hydrophone designers and the designers of the electrical channel that consists of the ICC and MRU input-signal conditioning circuitry.

An ideal way of accomplishing tradeoff studies is to have a mathematical system model realistic enough to capture the essential performance parameters. The electrical channel had a fully developed mathematical model with a *Monte Carlo feature* to estimate manufacturing variability. A Monte Carlo model is a mathematical model having random features built in to simulate uncontrollable statistical variations in the modeled process. Using the combination of physical measurements and the Monte Carlo model facilitated making the necessary trades.

In contrast to the electrical channel, no accurate mathematical model of the hydrophone was available. The model that had guided the research effort described the hydrophone operation as analogous to an electrical circuit with lumped elements, such as resistance and capacitance. This model was inadequate for describing the detailed behavior of the scaled-down version. Furthermore, building an accurate model was extremely difficult because the variable reluctance mechanism has inherently nonlinear magnetic properties and complex geometry with unpredictable flux-leakage effects.

Instead of improving the mathematical model, small runs of preproduction hydrophones were made. Careful measurements were taken on these physical models to understand both the average properties and expected manufacturing variabilities. The capability to turn around experimental models and measurements rapidly caused design improvement to become a continuous process with constant feedback. As a result of these efforts, the hydrophone reached full production ahead of any other cluster component and required few design changes once into production.

Cluster Redesign. The catalyst that led to a critical test of concurrent engineering was the mechanical failure of a cluster during sea trial design-qualification testing. Analysis of the root cause of the failure indicated that although individual components were designed to meet stress requirements, the completed assembly had failed at the interfaces.

Rather than repair the immediate problem and proceed, both the customer and program management decided that a total audit was needed to determine if other crucial requirements were overlooked at the interfaces. The FDS program was already well-established, having firmly established production and manufacturing timetables. The problem, therefore, was to accomplish the audit within a tight schedule and limited budget. The best solution was determined to be the application of concurrent engineering. An IPT was established and given full responsibility for this effort.

The program included the following main features:

- Subject matter expert team members were identified and given clear goals for schedule, responsibilities, and interfaces.
- No redesign work was started until requirements and interface agreements were established.
- Each design engineer had full authority to make decisions within a defined area.
- During the requirements definition phase, a document was produced for capturing the requirements for each component and interface.
- Manufacturing engineers, as well as logistics engineering experts, were involved from the beginning to capture manufacturing-suitable and life-cycle functional requirements.

As design proceeded, manufacturing was kept abreast of developments through the efforts of the design-engineering services group, which converted engineering sketches into drawings that were examined concurrently by manufacturing and procurement engineers. These team members provided feedback to the designers to ensure that the designs were neither too difficult nor too costly to manufacture; that they could be constructed of readily available materials; and that the designs could meet quality, pricing, and delivery-schedule guidelines.

The result was a product that was easier to build with fewer people, and one that had a lower hardware cost and fewer design drawings. Savings were estimated to be over $2.5 million resulting from a reduction of manufacturing effort; $700,000, from a reduction in the cost of parts; and $600,000, from drawing simplification.

Lessons Learned

The recognition that disciplined system engineering is critical to the ultimate success of any project is the heart of the lessons learned from the FDS program. ATS' engineering process was developed directly from experience gained during the execution of the FDS project. The development of the process has resulted in ATS being designated as the lead AT&T business unit for the systems engineering process.[6]

In addition, the most important lessons that have emerged from the FDS-UWS project have been incorporated into the ATS product realization process (PRP).[6] This documented process is a project-management guide from concept to field support. The PRP provides the framework, tied to project life cycle, for the execution of the core, functional disciplines within ATS. As with traditional systems engineering management, the PRP requires design reviews with senior management involvement at project checkpoints. However, the PRP is also accommodating to nontraditional structures. One of the lessons learned from the FDS project was the effectiveness of IPTs in establishing responsibility and authority for product development. The PRP recognizes these benefits and accommodates the IPT structure.

In implementing an IPT structure for a project, FDS demonstrated that the early involvement of manufacturing at the requirements stage is crucial for successful transition from design to manufacture.

Another process having demonstrated value is *in-process quality inspection*. This process provides a formal method for an IPT to obtain peer inspection of design drawings and specifications to certify compliance with requirements, as well as to verify completeness and accuracy of contents prior to final design release.

The experience of the FDS project with IPTs proves that concurrent engineering works to improve the transition to manufacturing by shortening transition time and reducing post-transition changes. The experience with structured systems engineering proves that the development of requirements by a multidisciplined team prior to design is crucial to establishing responsibilities and working relationships that will lead to a compressed development cycle.

Acknowledgments

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