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DIGITAL RECORDING AND SIGNAL PROCESSING SYSTEMS FOR HYDROPHONE ARRAYS

APL has completed the development and installation of new digital recording and signal processing systems for studying hydrophone data from submarines. The main objectives of the Sonar Evaluation Program are to assess the effectiveness of the sonar systems, identify contacts that could pose a threat to a submarine mission, establish the potential for improvements both to submarine sonar equipment and to operating guidelines for that equipment, and determine sonar performance norms that can be used to detect equipment degradation.

The nature of submarine patrol operations imposes several constraints on both the recording and the signal processing systems. First, the type of data recorded must permit the most sophisticated signal processing techniques, independent of any processing by submarine equipment. Therefore, it is necessary to record the outputs of entire hydrophone arrays and not of selected elements or channels that have been processed at sea.

Second, the operation of the recording system must have minimal impact on the duties of the submarine crew. This constraint requires the recording system to operate throughout a patrol, approximately 70 days, without major repair and to record the necessary data with no more than two changes of tape per day. Finally, to obtain a complete evaluation of a sonar, the recording system must operate continuously.

Timely evaluation of the resulting large amount of data requires a signal analyzer that can process the data in no more time than is required to record it. Existing recording and signal processing systems could not meet the preceding requirements. Therefore, two new systems were specified by APL and developed by subcontractors: the recording system, termed SPARS (Sonar Evaluation Program Acoustic Recording System), and the analysis system called SPAN (Sonar Evaluation Program Analysis System). This article updates a description of SPARS and SPAN published in 1980.[1]

PASSIVE SONARS

Some background in sonars is helpful in understanding the operation of SPARS and SPAN. Sonars may be of two types: active or passive. In active sonar the user transmits acoustic energy which propagates through the water until it is received or reflected by an object. Active sonars are used for navigation, underwater communication, depth sounding, and localization and detection of targets such as ships or mines. In passive sonar the user listens to signals that are radiated by natural and man-made sources of acoustic energy. Natural sources are wind and marine life; man-made sources are typically ships. The SPAN and SPARS systems were built for the evaluation of passive sonars only.

Passive sonars must be quite sensitive because the acoustic power radiated into the water by man-made sources is very low. For example, an airplane may radiate many kilowatts of acoustic power into the air, but a ship such as the *Queen Elizabeth II* radiates less than 100 watts into the water. It has been reported that a modern submarine operating at a slow speed radiates about 10 milliwatts of acoustic power.[2] Modern passive sonars achieve the required sensitivity by exploiting both the spatial and the temporal structure of the signal field.

Spatial processing makes use of arrays of sensors called hydrophones. A hydrophone is simply a microphone designed to operate in water instead of air. Using arrays of hydrophones rather than single sensors yields two advantages. First, the array can discriminate between sounds arriving from different directions. Second, isotropic or nearly isotropic ocean noise tends to be uncorrelated between the hydrophones of an array. A signal, however, is correlated between the sensors. When the outputs of the sensors are summed in an array, the signal components add and the noise components cancel each other, giving an increased signal-to-noise ratio. The output of an array of 50 sensors can have a signal-to-noise ratio that is 17 decibels higher than that at the output of a single sensor.[3]

In most sonars temporal processing is performed after spatial processing is complete. Generally, temporal processing involves some attempt to estimate the signal power at the output of a sonar array.

SPARS EQUIPMENT

Tape Recorder

The principal component of the SPARS is the RCA Versabit VB-400 digital, transverse scan tape recorder pictured in Fig. 1. This machine is an extension of earlier RCA video tape recorders, but the VB-400 is unique in using an octaplex configuration. In this configuration eight record/playback heads are spaced evenly around a circular headwheel. This headwheel rotates between 9,000 and 18,000 rpm, moving the heads across the tape to record or reproduce the data. Recording at high data rates requires a high relative velocity between the tape and the record/playback heads. By rotating the record heads themselves, the VB-400 can record at high data rates while maintaining a low tape speed of ½ to 2½ inches per second.

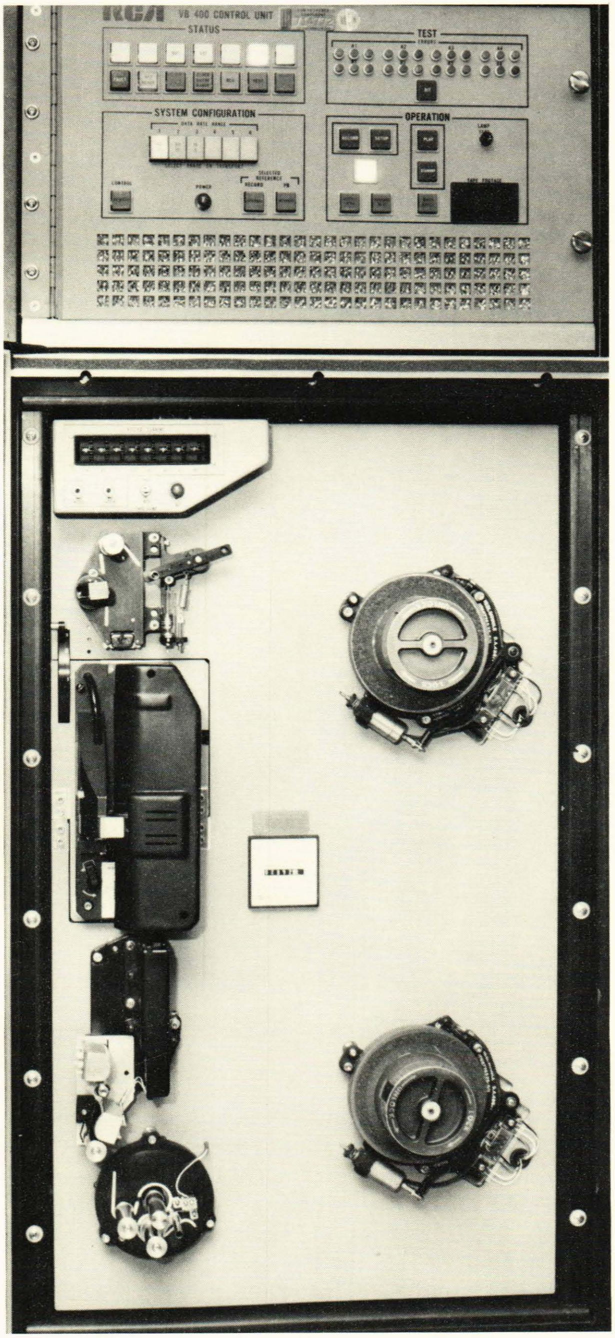

Figure 1 — Laboratory configuration of the RCA Versabit VB-400 tape recorder.

The eight record/playback heads are of a new quarter-track design which allows a bit packing density of 2 million bits per square inch. This density is independent of the recording rate. Instead, the VB-400 recording rate is matched to the input data rate by varying the tape speed and the rate of headwheel rotation. In addition to the acoustic data, the VB-400 also records a control track on each tape. On playback, this control track synchronizes the rotating heads with the recorded data, allowing a bit error rate of approximately 5 per million. The achievement of such a high density and a low error rate advanced the state of the art in magnetic tape recording.

SPARS uses a special magnetic tape made by the 3M Corporation, similar to standard 2-inch-wide video tape, but only 1.1 mils thick. Thus, 9600 feet of tape can be stored on a single reel 14 inches in diameter. At a packing density of 2 million bits per square inch, a single reel of SPARS tape contains 4.6×10^{11} bits. It would require about 1250 reels of standard, 1600-bit-per-inch, 9-track tape to record this much information. SPARS record rates are approximately 9 million bits per second, resulting in a recording time of 15 hours per tape. The VB-400, however, has a record/playback range of 2.2 to 40 million bits per second.

Other Equipment

In addition to the VB-400 tape recorder, the SPARS contains hardware to interface with hydrophone and other signals and to format these signals for recording. Figure 2 shows the relationship of this interfacing and formatting hardware, built by Rockwell International, to the VB-400. For simplicity, the figure omits some SPARS components.

The three acoustic buffers provide the interface between the SPARS and the hydrophones or other sensors; in total, these three buffers supply over 160 acoustic channels. Each channel has isolation circuitry, a seven-pole lowpass filter, an amplifier, and an analog-to-digital converter. The gain of each channel can be programmed individually by plug-in resistors, and each buffer has an automatic gain control to compensate for changes in the ocean noise background. Typical hydrophone quantizing precision is six bits, with a three-bit automatic gain control.

The mixed conditioner provides the interface to a mixture of different signal types. It contains some acoustic channels similar to those in the acoustic buffers, but it also contains channels for recording status information. These status signals can be of two types: equipment status or ship status. Equipment status is obtained by recording the positions of the various switches on the three sonars. Recording this information allows the analysts at APL to reconstruct the configuration of the sonar equipment for any time during the patrol. Ship status consists of items such as submarine course, depth, or speed. SPARS records this information from self-synchronous machines or synchros. Figure 3 is a photograph of a mixed conditioner.

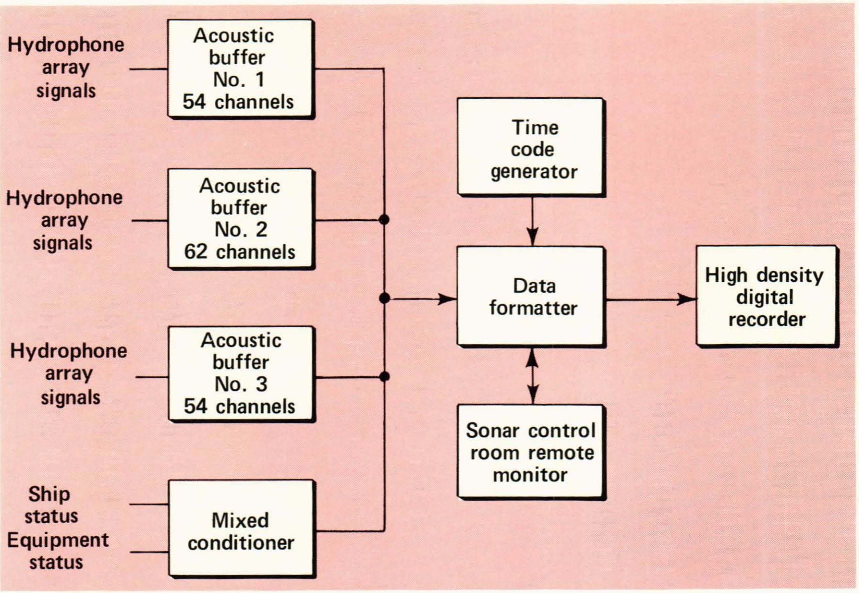

Figure 2 — SPARS block diagram.

Data from the four interfaces are collected and organized by the data formatter, shown alongside the mixed conditioner in Fig. 3. The formatter contains eight programmable read-only memories (PROM's) that determine the sequence in which acoustic and other data are recorded. Differences in equipments or in quantizing precision can be accommodated by changing the PROM's in the data formatter. The formatter also provides timing signals to all the interface units and provides the clock signal that synchronizes the VB-400 to the serial data stream to be recorded.

SPARS contains two other units worth mentioning. The first is a time code generator that provides time of day to the data formatter for recording as part of the digital data stream. The time code generator also provides an analog IRIG-B format signal for recording on an edge track of the SPARS tape. This analog signal is useful in searching the tape and provides a backup to the digital time data. Since the SPARS units may be dispersed throughout a submarine, the sonar control room remote monitor provides the crew with a convenient way to monitor the status of the recording system. This unit also contains a microphone to allow voice annotation of the tapes.

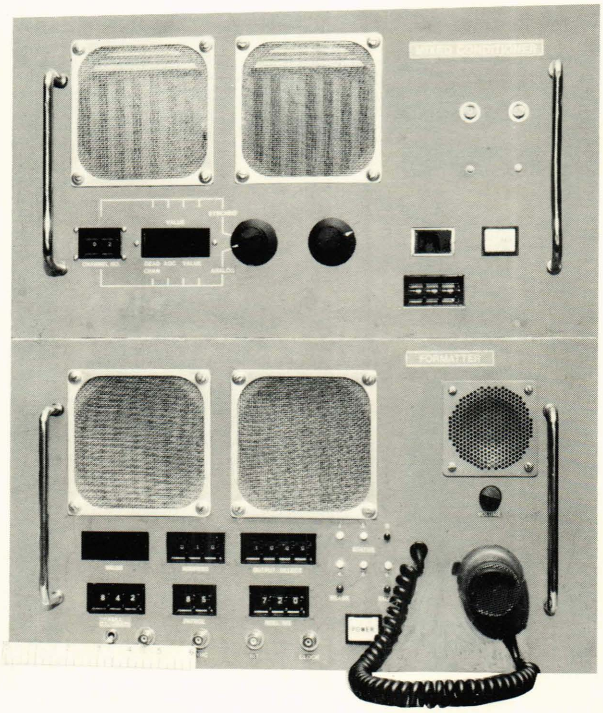

Figure 3 — SPARS mixed conditioner and formatter.

SPAN SYSTEM

Signal Processing

Tapes recorded on SPARS are shipped to APL for processing in the SPAN laboratory, pictured in Fig. 4. Figure 5 shows some of the signal processing functions that the SPAN can perform. These functions allow the program analysts to study the acoustic energy at different bearings around a patrolling submarine. In making their study, the analysts in the Sonar Evaluation Program use a variety of displays, as indicated in Fig. 5. It should be emphasized that the processing functions of Fig. 5 do not necessarily correspond to particular pieces of hardware in the SPAN.

Time domain beamforming is the first operation performed on the hydrophone signals recorded on SPARS. Each hydrophone signal from a particular array is delayed relative to the others, and then all signals are summed. The resulting signal, called a beam, is the variation in time of the energy arriving from a particular bearing. In SPAN processing, multiple beams are formed simultaneously, and each

Figure 4 — The SPAN laboratory, located in the D. Luke Hopkins Building at APL.

beam is fixed in bearing. As shown in Fig. 5, the beam data follow two different paths. In the lower path the beams are used to form estimates of the total power at each bearing. These power estimates are presented to the analysts on an energy-versus-bearing display.

Beam data are also mixed and filtered to select a frequency band for additional analysis. Data in the selected band are transformed to the frequency domain by a fast Fourier transform, and the transforms are squared and then averaged. This process provides the so-called direct method for estimating the power spectrum.[4] The same data are used in more than one transform in order to reduce the uncertainty in the estimate of the power spectrum. The short-term integrator (Fig. 5) performs the averaging of the power spectra.

At this point, the results are used in three different ways. First, the short-term integrated data corresponding to a particular frequency band can be summed across frequency for each beam and the result displayed as a filtered energy-versus-bearing display. Second, the short-term integrated data can be displayed directly. Third, the data can be integrated and presented as a long-term-averaged plot of the power spectrum.

Hardware

Figure 6 presents a simplified block diagram of the hardware shown in Fig. 4. The tapes selected for processing are mounted on the tape playback unit, an RCA VB-400 identical to the SPARS recorder described previously. The remaining hardware in the block diagram is either commercial equipment furnished by APL or custom interfaces designed by Rockwell International. Rockwell International also integrated the initial system. The hardware and software structures of SPAN make it one of the most powerful programmable sonar processors in the world.

Hydrophone data and status data from a SPARS tape are routed to the input/output unit, which provides several internal system interfaces. This unit is programmed with the format used to record the data and with the destination of each data item. From the input/output unit the status data such as submarine speed and depth are sent to the auxiliary control processor, a Data General NOVA 3, for conversion to engineering units. Processing of these status data need not be described further.

Hydrophone data are sent to a hardware beamformer. Each hydrophone signal can also be multiplied by a variable weighting factor to improve the directional discrimination of the beams. The beamformer can produce 64 beams from up to 52 hydrophones, performing up to 200 million operations per second. Beam output can be of two forms: instantaneous data at 8 bits per sample (used for calculation of the fast Fourier transform) or internally detected and integrated data at 16 bits per sample (used for energy-versus-bearing processing). These results are placed on a high-speed data bus for additional processing.

This data bus is one of the key structural features of the SPAN. The bus is unidirectional and operates at a data rate of 50 million bytes per second. Data on the bus are in the form of 64-bit messages. The first 32 bits of the message identify the destination and

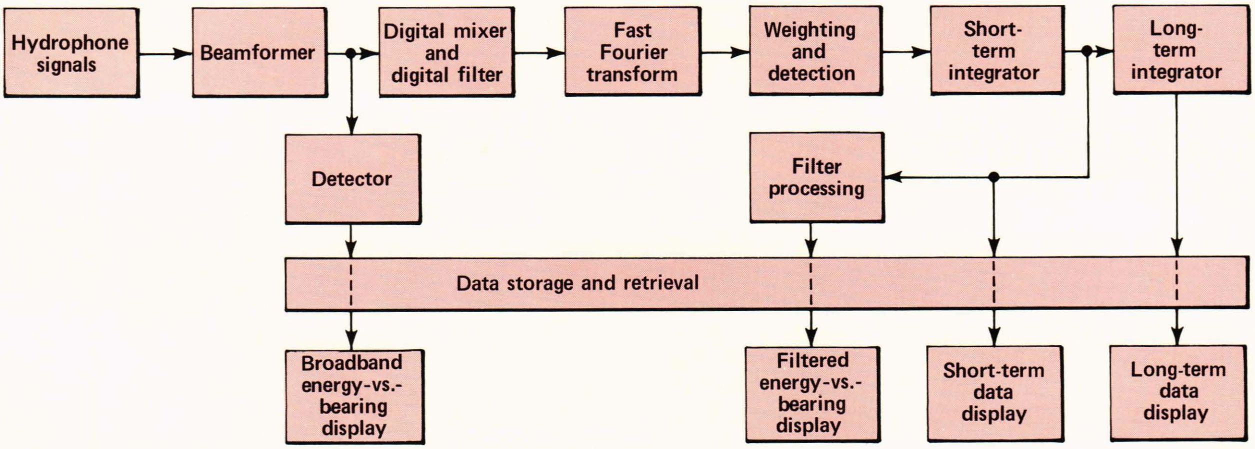

Figure 5 — Simplified SPAN signal flow.

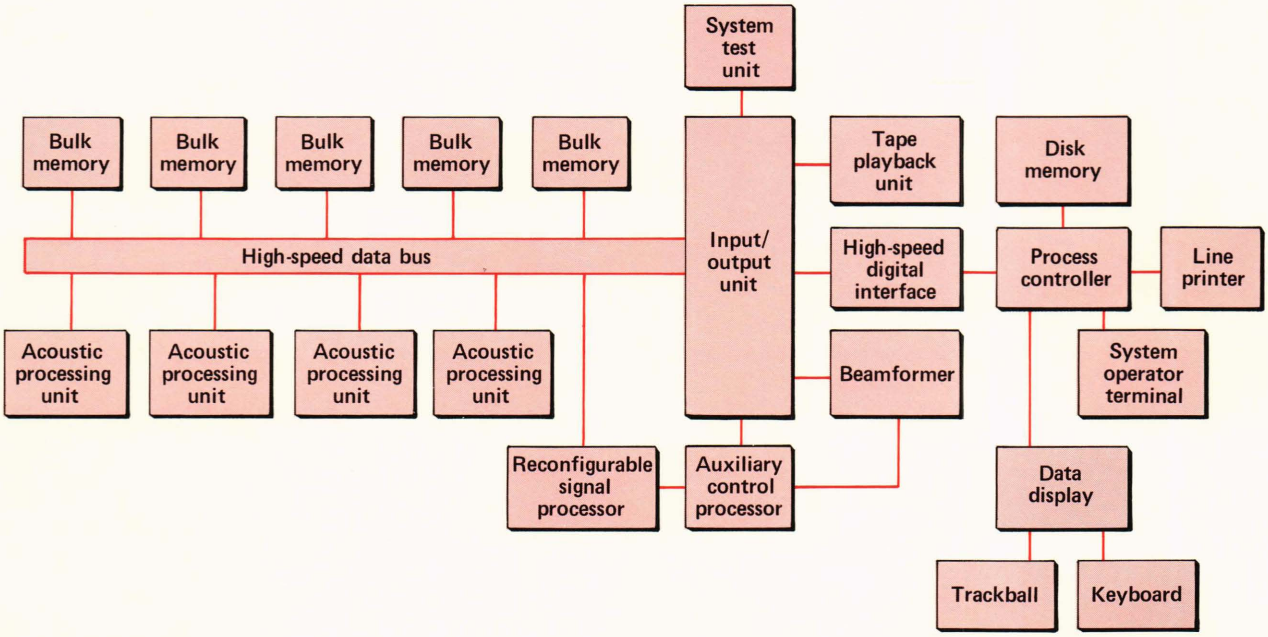

Figure 6 — SPAN hardware block diagram.

sending unit, the data type, and an address. They allow any unit on the bus to send data to any other unit. For example, the integrated beam data are typically sent to bulk memory, but the instantaneous beam data are routed to the reconfigurable signal processor. The remaining 32 bits contain the data.

The reconfigurable signal processor is a programmable, special-purpose unit for performing spectral analysis. The unit, pictured in Fig. 7, employs a modular design,[5] pipelined architecture, and fixed-point arithmetic to achieve a theoretical computation rate of 46 million multiplications per second. In operation the unit achieves 97% of this value. A more detailed description of the unit is available.[6]

Table 1 gives the specific signal processing functions performed by the unit, but the unit's essential purpose is to estimate the power spectrum of an input signal by the direct method. As shown in Table 1, the processor can also perform a frequency domain adaptive filter.[7] This type of filter can be used to remove interference from signal channels of interest.

The reconfigurable signal processor performs only the particular function of spectral analysis. The four acoustic processing units provide most of the general computing power in SPAN. Each of these units contains an interface with the bus, a Data General NOVA 3 control processor, and a Floating Point Systems AP-120B array processor. Table 2 gives the hardware details of the control and array processors. The four AP-120B's operate simultaneously and together can perform up to 24 million floating point multiplications per second. The actual operating rate is less than this because of overhead operations such as reading the data into the array processor. Assembly language programming coupled with the efficient SPAN software structure enable the array processors to achieve 70% of the theoretical multiplication rate.

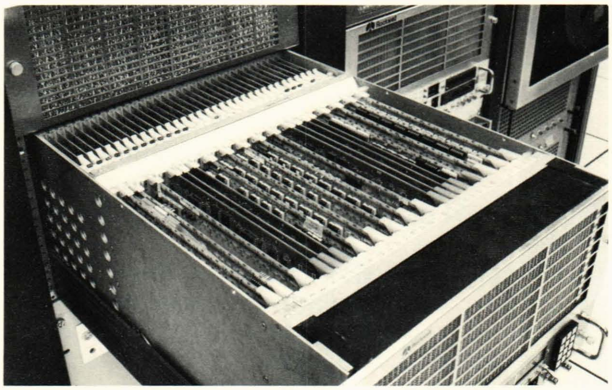

Figure 7 — The reconfigurable signal processor.

Table 1—Characteristics of the reconfigurable signal processor.

a. General Characteristics	
64 Input channels	
Fixed point arithmetic	
b. Performance Characteristics	
Function	*Multiplications/second*
Digital mixer	3×10^6
Digital filter	20×10^6
Fast Fourier transform	10×10^6
Adaptive filter	11×10^6
Detector	2×10^6
Total computation rate	46×10^6

The bulk memory stores the intermediate results from the SPAN processing. It consists of five National Memory Systems NS3-1 MOS random access memory units. Each unit contains 65,536 words, each with 32 data bits and 7 bits of error correction code.

Table 2—Descriptions of the SPAN components.

Unit	*Number*	*Model*	*Word Length (bits)*	*Memory Size (words per unit, K = 1024 words)*	*Cycle or Access Time (nanoseconds)*
Mainframe processor	1	Gould SEL 32/77	32	128K	600
Control processor	5	Data General NOVA 3	16	4 to 8K	800
Array processor	4	Floating Point Systems AP-120B	64	1 to 16K 2K program 8K data 1K table	167

Each bulk memory unit has an input/output rate of 1.54 million bits per second. Each acoustic processor puts data onto the SPAN bus using an address generator that operates at 390,000 bits per second. Therefore, a bulk memory unit can serve three acoustic processing units simultaneously.

Upon completion of the signal processing, the data are sent back to the input/output unit for transfer to the process controller, a Gould SEL 32/77 minicomputer. This processor formats the data for display and stores it on a 300-million-byte disk, which also holds all the system software. In addition, an operator can initialize the hardware and control the processing of acoustic data from a terminal connected to this computer. Finally, the process controller contains several programs designed to automate the analysis.

The principal SPAN display, indicated as *data display* in Fig. 6, is a GENISCO GCT-3000 Programmable Graphics Processor with trackball and keyboard. The resolution of the display system is 1024 × 1024 points (called pixels), with eight gray levels per pixel. Such resolution is required to make the display compatible with the number of data points available. Even though it contains approximately one million points, the entire display can be changed in less than 2 seconds.

Some idea of the SPAN throughput can be gained by noting that a time series that fills a standard tape 10 inches in diameter, recorded at 1600 bits per inch, would require just 20 seconds for spectral analysis on SPAN.

Software

The specific processing functions performed by SPAN are defined by software that executes in the array processors, the NOVA computers, and the SEL 32/77. Figure 8 gives the hierarchy of this software, which, as shown, is divided into two categories. The top-level mode structure software controls the SPAN processing. The programs in the basic software perform the processing and allow the user to control the operations. The software architecture described in subsequent paragraphs is unique to SPAN and permits its fast operation.

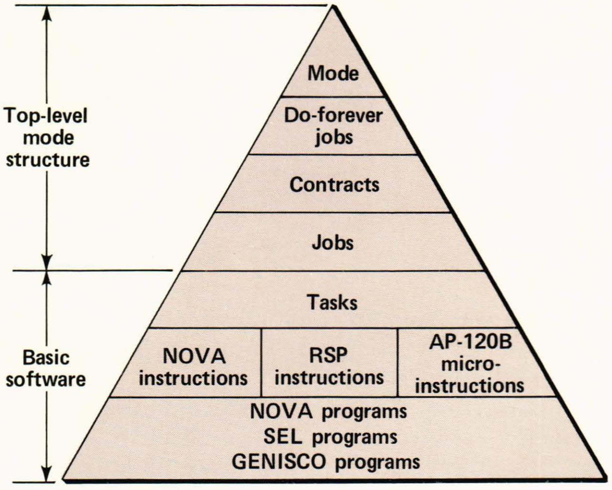

Figure 8 — SPAN software hierarchy.

At the base of the hierarchy are the programs for the NOVA, SEL, and GENISCO units. These programs, which constitute most of the software, annotate the displays, store and retrieve data, and convert binary values into engineering units. The next level contains the assembly language instructions that process the signal. The assembly language instructions are grouped into subroutines that perform specific operations such as computing a fast Fourier transform. Each of these subroutines is called a *task*, which is the basic element of SPAN signal processing.

In typical applications, tasks must be used in groups rather than individually. For example, in spectral analysis it is necessary to transfer the data into an acoustic processing unit, calculate the fast Fourier transform, square the transformed data, and then write the result into bulk memory. A *job* is a collection of tasks that run in a single SPAN processing unit. Since SPAN contains several processing units, several jobs can execute simultaneously. All jobs that are running simultaneously are grouped into units called *contracts*. In other words, for each SPAN processing interval a contract specifies the jobs to be executed in each processing unit, the order of the jobs (if more than one is to be run per unit), and the data to be processed by each job.

Next above the contracts in the hierarchy are *do-forever jobs*. These programs synchronize the SPAN processing to the playback rate of the SPARS tapes. The do-forever jobs count the number of data samples read off the tapes and send out a new contract

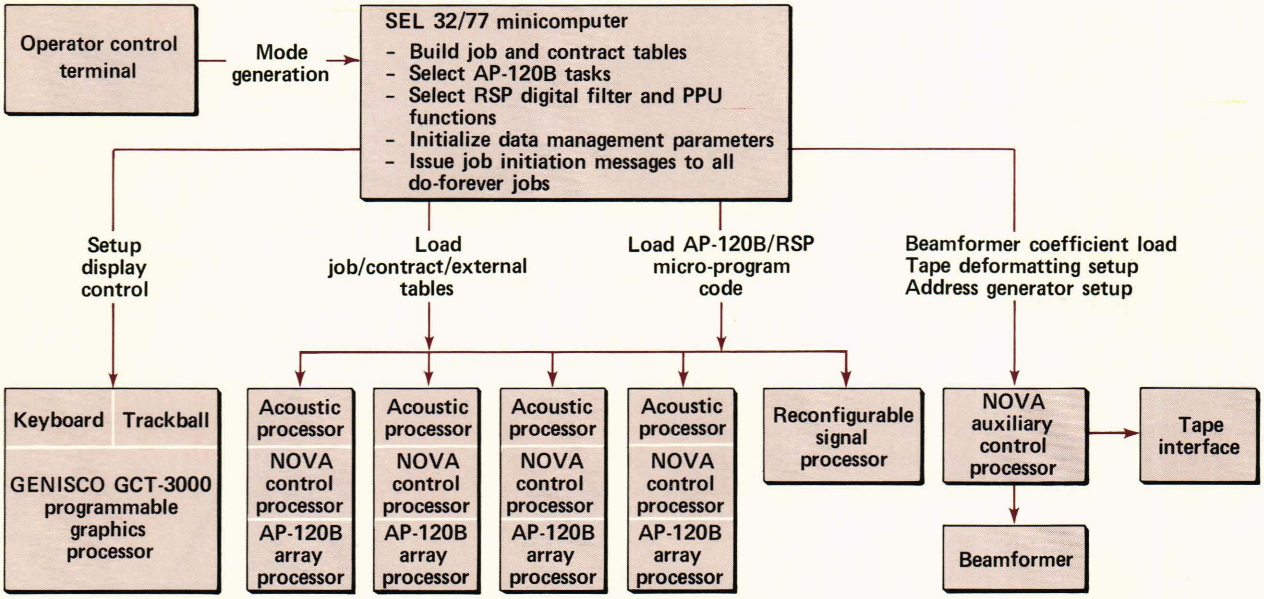

Figure 9 — SPAN processing initialization.

whenever a certain number of samples has been read. The entire set of all contracts, jobs, tasks, and do-forever jobs is called a *mode*.

This structure provides high speed and important flexibility. New functions can be added by writing new jobs or, in some cases, new tasks. SPAN processing can be tailored to specific types of data, making the system a valuable tool for the development of signal processing algorithms. Further, the subdivision of the overall effort into contracts and jobs provides the control needed for efficient, parallel operation of all SPAN processing units.

Figure 9 illustrates the initialization and control of the SPAN processing. The operator selects the mode and certain options, such as hydrophone weights for the beamformer. The mode and the options are input to the SEL 32/77 minicomputer via a terminal. Programs in the SEL 32/77 then set up tables of contracts and jobs to provide system control and transmit the AP-120B, NOVA, and RSP programs to the appropriate units. Next, the beamforming coefficients, SPARS tape format, and data addresses are sent to the auxiliary control processor, which loads the beamformer and the input/output unit. Simultaneously, the SEL programs initialize the GENISCO display. The SPAN is then ready for operation. All these steps occupy less than a minute.

CURRENT EFFORT

Developmental signal processing work in the SPAN laboratory currently falls into three areas. The area of greatest importance is the development of automated analysis techniques for acoustic data. Staff members of the Sonar Evaluation Program, working in conjunction with members of the Research Center, are developing rigorous, comprehensive requirements for automated analysis. In a parallel effort, the techniques of pattern recognition are being applied to extracting useful features from acoustic data. A second area of investigation concerns the use of adaptive filters in reducing interference. Finally, an IR&D-funded effort is under way to apply Walsh, Haar, and other transforms to the analysis of sonar data. Successful application of these transforms would increase SPAN output and enhance the ability to recognize some types of signals.

Both SPAN and SPARS have been in operation since January 1979. During this time several thousand hours of hydrophone data have been collected, processed, and analyzed to provide an unprecedented understanding of the acoustic environment of patrolling submarines.

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ACKNOWLEDGMENTS—The Strategic Systems Projects Office, Department of the Navy, funded the work described in this article. The development of both SPAN and SPARS was supervised by J. L. James, L. P. Montanaro, and R. C. Morton. The systems could not have been built without the efforts of many subcontractors to the Laboratory. Particularly important was the work of D. H. Wurster of RCA and of R. H. Jackson, P. M. Brewer, and W. D. Ashcraft of Rockwell International. Finally, one of the reviewers suggested several improvements in the style of this paper.