COMMAND AND CONTROL OF A LARGE, UNMANNED, UNDERSEA VEHICLE

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Summary. A system incorporating commercial modems and two twisted-pair shielded wires makes it possible to control/monitor a large unmanned undersea vehicle from a surface vessel. This paper summarizes the design, explains the rationale for it, and describes some of the problems encountered and their solution.

Introduction. A system was needed that would make it possible to control and monitor, from a surface vessel, the environment and attitude of a large, unmanned, undersea vehicle. Control of both vertical and lateral movement, as well as of yaw, was necessary through descent and positioning. Movement and surroundings were to be checked and tested through acoustical and optical monitoring. This required a control station topside, with corresponding positions on the vehicle.

After several preliminary designs were studied, the basic system was firmly established as being completely redundant (both on the ship and on the undersea vehicle), and to operate at 9600 bits per second (a commercial modem bit rate). The system transmitters and receivers were commercial modems (modulator/demodulators) operating in full duplex; each redundant system required two twisted-pair shielded wires. The system was designed to be synchronous, with the downlink clock being extracted and used as the uplink clock.

The extreme size of the undersea vehicle made remote stations a necessity for both commands and data. Eight stations were established, two for each of four functions: power, acoustics, sensors and control, and optics. To simplify wiring on the ship, the same scheme was used; however, only three remote terminals were used, the sensors and control position being combined with optics.

Since the system was to control a large, complex vehicle, there was a requirement to prevent reception of all extraneous commands. This was done by transmitting all downlink data twice, with each message containing a single parity bit. The uplink words, delayed from the downlink by 36 bits, contained only a nine-bit address and an odd parity bit (plus the data).

The system required many commands and pieces of data, but the rate per command or data was very slow - one or two per second. There was also a requirement that a computer be able to issue commands at will and monitor and store all up- and downlink data. Although the magnitude of system commands and data requirements was large, it was well within the realm of possibility. Table 1 is a summary of these requirements.

Table 1a
SYSTEM COMMAND AND DATA REQUIREMENTS

Subsystem (2 each)	16-Bit Command Words	Command Bits	80-Bit Data Words	Data Bits
Electrical Power	8 ea	128 ea	5 ea	400
Optics	10 ea	160 ea	6 ea	480
Sensors and Control	12 ea	142 ea	3 ea	240
Acoustics	11 ea	176 ea	8 ea	640
Total	41 x 2 = 82 words	656 x 2 = 1, 312 bits	22 x 2 = 44 words	3,520
System Capability	104 words	1, 664 bits	104 words	8, 320 bits

Table 1b
SDU COMMAND REQUIREMENTS

SDU No.	Bits Required
1	400
2	400
3	240
Test and Control Panel	16
Total	1,056

System Configuration. A simplified block diagram of the system is shown in Figure 1. The heart of the network is the controller, a completely redundant unit. Inside each controller is a 2.4576 MHz crystal oscillator that, after division by 256, establishes the 9600 Hertz system clock. The active of the two controllers supplies the basic timing source for the entire system, both above and below sea.

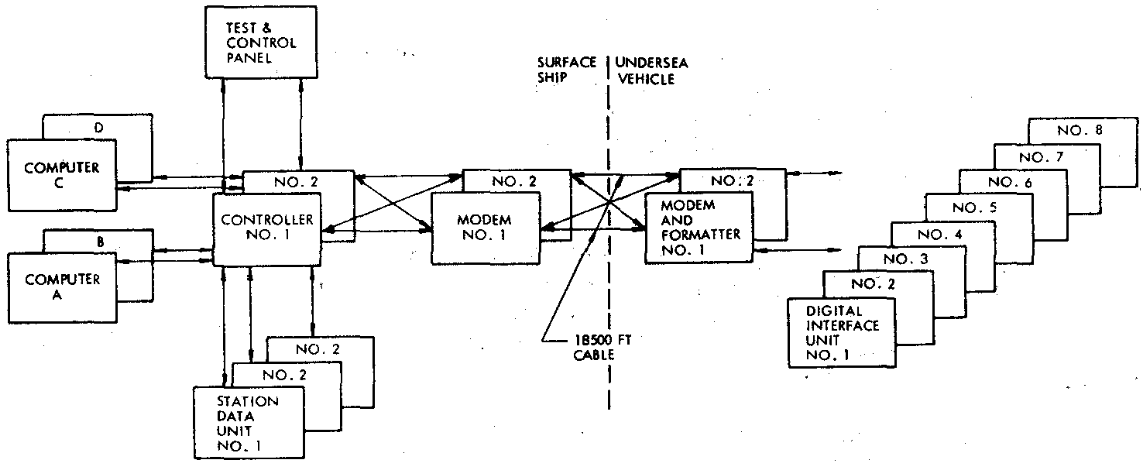

Fig. 1 System Block Diagram

System timing is maintained by pulsewidth modulation of the clock lines as they are distributed to both the surface and subsurface equipments. The clock period, 104.167 µsec, is employed to supply three basic pulsewidths: 25 µsec (short clock) 52 µsec (clock), and 75 µsec (long clock). The 52 µsec clock signal is supplied to the modems and used to sync up the internal modem clock.

Before system timing is discussed, the system message structure should be understood. The message from the surface equipment to the subsurface equipment is divided as shown in Figure 2. The modem PCM output is bi-phase space (Bi-Ø S), so all idle and resync words transmitted are always sent as zeros, in order to maintain system synchronization. To allow the greatest flexibility in the system, the vehicle remote terminals data interface unit (DIU) identification numbers, and block numbers were stored on programmable read-only memories (PROM) (256 x 1), so that reasonable flexibility could be maintained in the system.

Uplink timing (Figure 3) was divided into the same basic structure as was the downlink, except that the uplink data are displaced from the downlink by 28 bits as a result of the request for data, plus another lag of 8 bits caused by system delays.

Inside the subsurface modem and formatters, a pattern recognizer is alert for the twenty-nine and one that are transmitted at the start of every group of 1200 bits. When this pattern is recognized, a long clock is generated and sent to all eight of the DIUs, then a long clock is generated at bits 14, 28, 34, 62, and 90 for the next 13 words. The exact function performed at these bit times is discussed under DIU’s. A similar set of clocks is generated in the controller to correspond to the uplink and internal control center timing requirements.

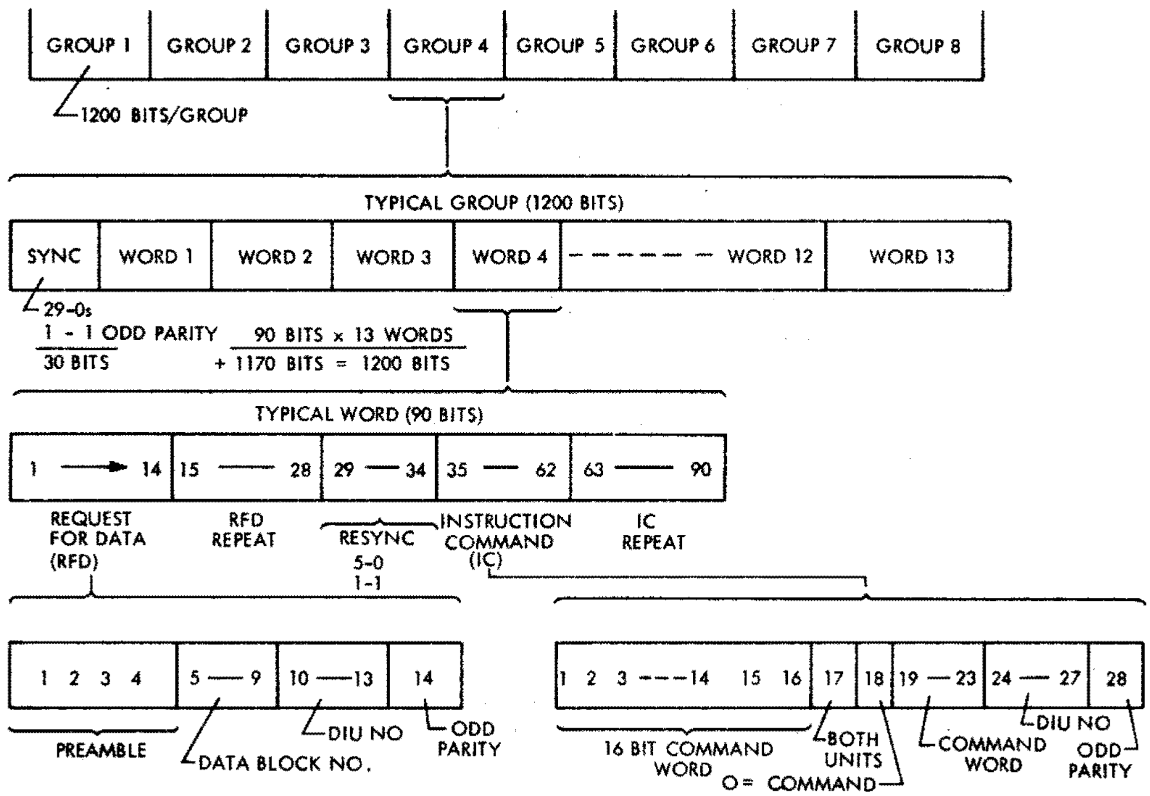

Fig. 2 Downlink System Timing

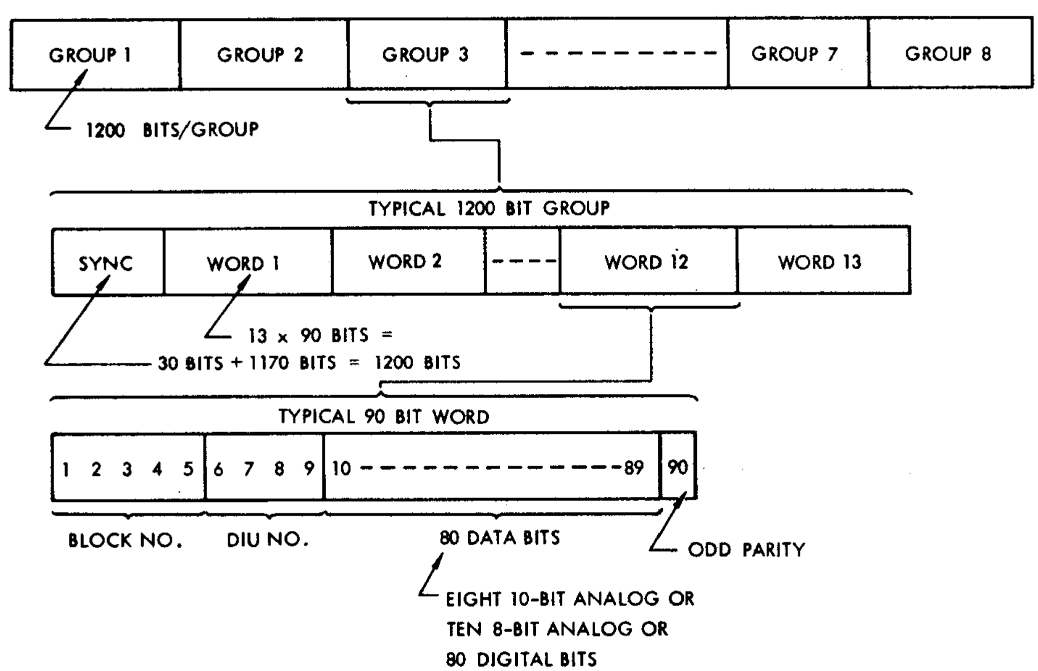

Fig. 3 Uplink System Timing

Control Center Timings. The control center (CC) equipment is under the timing control of the controller. The controller must sort out the uplink data, as well as make requests of the CC remote terminals, the station data units (SDUs) for commands. Three different groupings of consecutive long clocks are used in the control center timing, as described below:

a. 2 long clocks = new uplink word (of 8-, 10-, or 16-bit duration)
b. 3 long clocks = new uplink data group (90 bit long) and a. above
c. 4 long clocks = SDU load pulse, and a. and b. above

To explain the timing, the following example is given:

a. Bits 35, 36, and 37 are always long, indicating that this is the start of a new group of data.

b. In some words, Bit 33 may be long if a SDU command load is desired.

c. The following bits are long for a data word rouping of eight 10-bit words; 46/47, 56/57, and 66/67, 76/77, 86/87, 6/7, 16/17, and 26/27.

All of the long clocks above are generated by PROM (256 x 1), so that maximum system flexibility can be maintained.

Controller. The controller generates all system timing, performs error checking on uplink data, acts as the assembler of command data from the SDU, and is the interface between the four system computers.

When command data are desired from an SDU, the controller generates four long clock pulses. At the leading edge of the second short clock after the four long clocks, all three SDU's and the test and control panel respond by loading data into shift registers. The SDU's transmit data in 16-bit blocks, corresponding to the 16-bit command words in the DIU. The first 16-bit word of the message is a control word, where the first bit = 1 and the second bit = 0; the next 14 bits control the messages to follow. The SDU command inputs are supplied from switches, each of which represents a specific command bit. Even though all three SDUs are commanded to load their registers and transfer their data to the controller, the controller accepts only the data it wants, through use of PROMs. The data selected are checked for a 1/0 transition on the first two bits and then loaded into random access memories (RAMs). The data are read out of the RAM's and combined with the DIU number and block number previously stored on the PROMs. This method of commanding allows 104 words of 16-bit length (1664 bits) to be transferred from the control center every second. Most 16-bit words are sent only one time per second, but a few are sent twice. The system processes many low-speed commands, because the subsurface equipment is so very large and slow it requires low command rates.

The controller is capable of sending computer-generated commands. The requirement is for the computer to be able to interrupt the command downlink data at any time. The computer generates an interrupt pulse, and when the controller receives this pulse it sends out the computer generated command word at the first available opportunity. It does this by extending the number of words per group from 13 to 14, which causes the last word to be lost. In retrospect, the real requirement was that the computer need only send a command every 1 or 2 seconds, which would have greatly simplified the design of the controller and prevented much unnecessary worry during the initial phases of operation.

The controller can also send commands generated by the test and control panel. By the use of multiple function digital (up to 16 functions) switches, any DIU can be addressed and any 16-bit message sent. Once a second, at a preassigned time, the system can accept a word from the panel and send it downlink.

While all four computers are connected to the system at one time, it is possible to inhibit their command capability. Each computer is wired to both the command and data bus, and 16-bit data transfers are made to all four computers. All data are transferred to all four computers regardless of whether or not they are enabled to command. The interface was parallel, because the computers used were parallel machines; but in retrospect the interface should have been serial, with the serial/ parallel conversion being made at the computer. That would have made for a cleaner and simpler system and would have effected a saving of parts and wires.

The uplink data are received at the controller, where they are checked to see whether the “echo back” of the DIU number and block number are correct, as well as to check for odd parity. If everything is correct the data are transferred to the three SDU’s and the test and control panel, as well as to the computer. If either the DIU number, block number, or parity is incorrect, the data are inhibited from going to the SDU’s and T&C panel, but are flagged as being in error and transferred to the computer. At the same time the data are flagged as being in error, a counter is advanced so that a count of the total number of errors can be maintained; additionally, a red light flashes, indicating which DIU was in error (later, the eight lights were recorded, as a diagnostic tool).

Station Data Unit. The SDU’s are the operator interfaces to the system. They are rather simple devices, having only shift registers for commanding and light drivers or analog (sample and hold) circuits for the data function.

The interface with the controllers, which is very simple, is shown in Figure 4. One of the major system requirements was to keep each unit a separate entity and not tie the system grounds or power supplies together. To accomplish this goal, solid-state relays or optical coupled isolators were used as the primary interface devices. Each unit was powered from the 110V 60 Hz lines, but since the power supplies - as well as all inputs/outputs - were isolated, there were no ground loops between any two boxes.

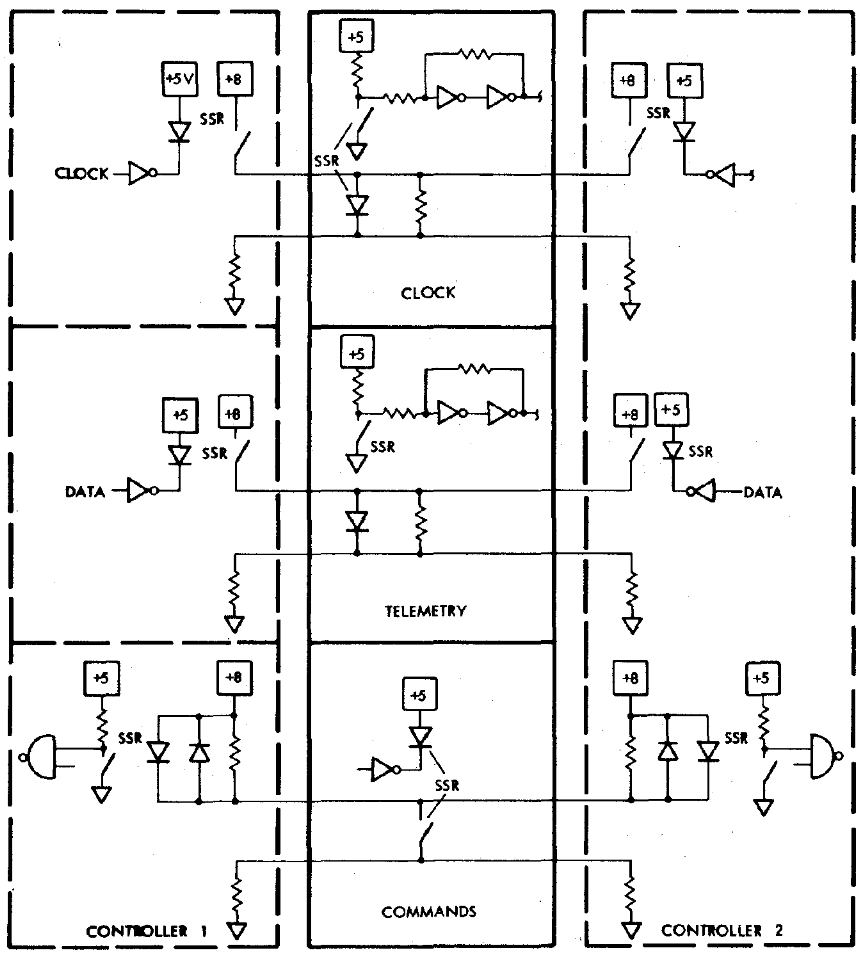

Fig. 4
Controller to SDU Interface

The command interface is very simple. Figure 5 shows that the operator just depresses a switch (momentary or alternate action) and, when four long clocks come (and go), the data are transferred into a shift register and then to the RAM in the controller, to be combined with the proper DIU number and Block number.

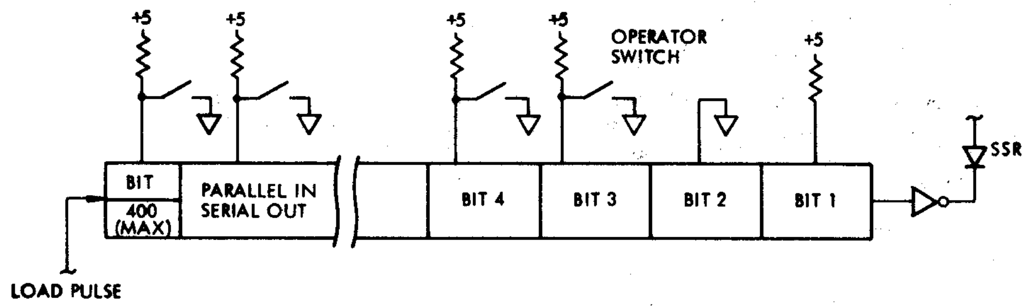

Fig. 5 SDU Command Interface

The data from the controller are processed in either of two ways: analog or digital. The digital data are switched to processing cards in 8-, 10-, or 16-bit groups, depending upon the source of the data. The processing cards do many things, from merely lighting lamps to converting and scaling the data for readout on seven-segment LED displays. For the analog data, all data, including the digital, are routed through a digital-to-analog converter, where they are converted into pulse amplitude modulated data and routed to sample and hold circuits for display on µamp meters; Figure 6 shows these circuits.

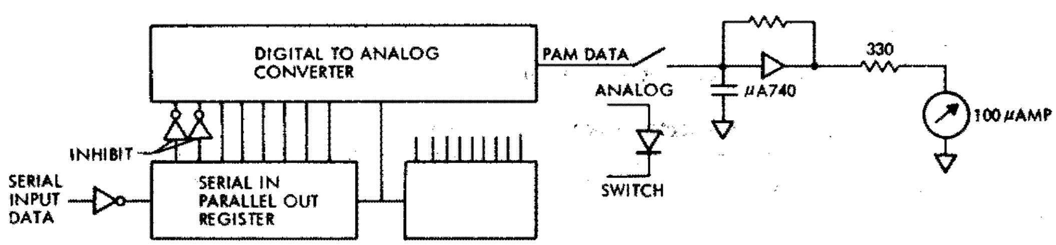

Fig. 6 SDU Data Processing

Modem. The modem interfaces with the controller on the surface ship and with the modem and formatter via the electromechanical cable on the subsurface vehicle. The modem selected was not a very sophisticated device, but worked reasonably well after being modified several times. The unit was expected to have a 600-ohm output, but the two units Initially tested had a Zo that was nearer 65 ohms. A matching network was made to increase the Zo to equal the line impedance of 87 ohms (two 11-ohm resistors). Later it was found that there were really some 600 ohm units, so it was necessary to change their output transformers; this presented some difficulty, since it had to be done on the ship (although in port). It developed that the units with 600 ohm outputs also had different filters, which also had to be changed.

Once the changes were made it was found that the method being used to generate the subsurface clock was not practicable, so a crash program was initiated to design and build a more stable phase-lock loop.

The interface from the controller to the modem consisted of the following:

a. Command line to modem
b. Clock line to modem
c. Data line to controller
d. Request to send -basically modem on/off
e. Carrier present - to diagnostic light

All circuits shown on Figure 7 were identical to the one, being nothing more than transistor/transister logic (TTL) to level shifters/line drivers and back to TTL. It would have been better if SSRs had been used, but the modems already had the level shifters installed.

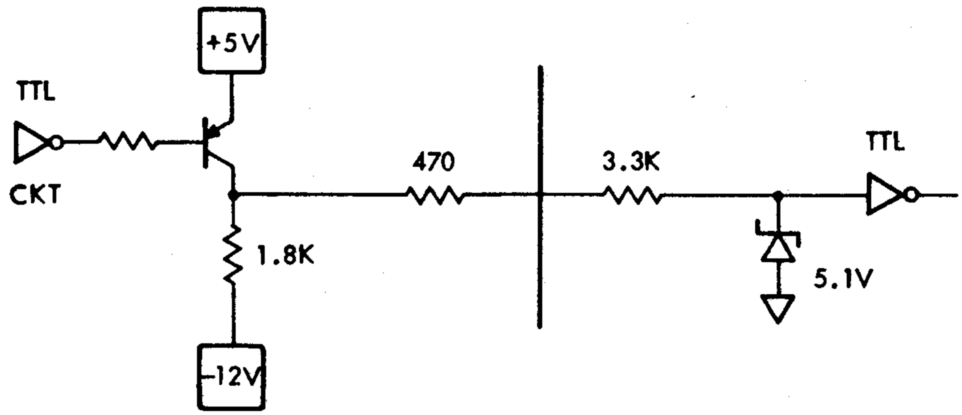

Fig. 7 Typical Modem/Controller Circuit

The interface from ship to subsurface equipment is shown in Figure 8. The system only ties the four shields to ground on the surface ship. During testing the other three ways to tie the shields to ground were tried, but the single-point ground at the ship worked best.

The systems, as mentioned, were completely redundant, and during the later stages of test a multiple-pole switch was installed so that the modem-to-controller interface could be reversed, if required. While not indicated in Figure 8, it was also possible to switch from either modem to either modem formatter.

Modem Formatter. The modem formatter (M/F) was the interface to the ship as well as to the eight subsurface DIUs. This unit was originally conceived as utilizing just the downlink clock, then turning it around and using it as the uplink clock. This worked reasonably well during testing, but when the two parts of the system were mated with the long EM cable, quite a bit of jitter (about 5 μsec RMS) was observed at the output of the subsurface modem, which when passed back up made the entire system so bad it was unusable. Emergency measures were taken to reduce the jitter by redesign of the phase-lock loop that was installed. Fortunately the new design worked and the system quieted down.

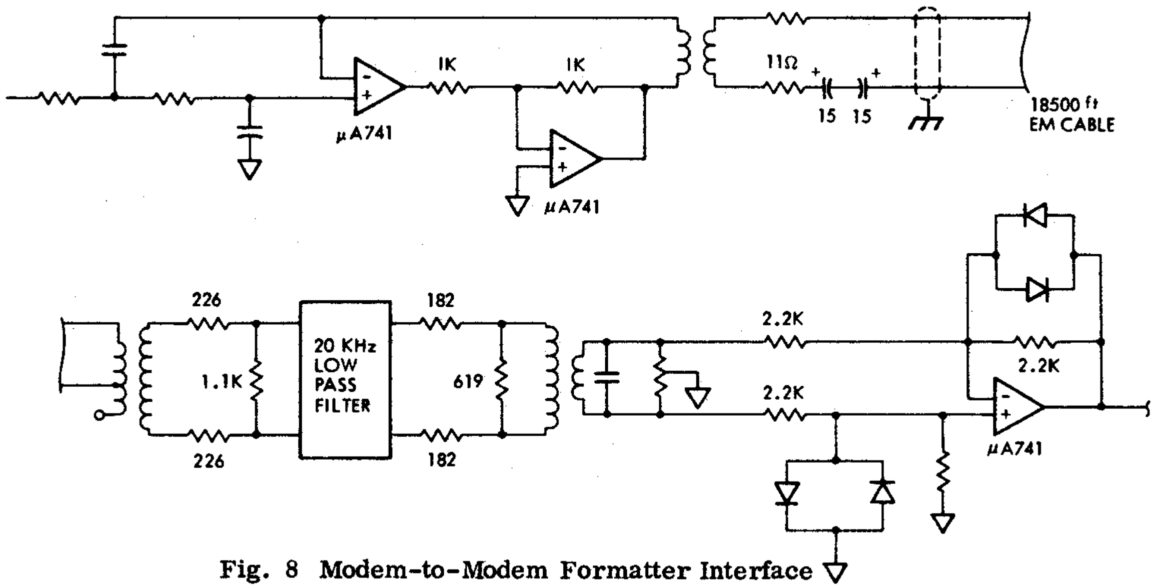

Fig. 8 Modem-to-Modem Formatter Interface

The DIU clock line was reconstructed by the formatter, which searched for the twenty-nine 0's and a 1 that were used for the system sync. When it recognized this pattern it put out long-clock pulses during each word at bits 14, 28, 34, 62, and 90; by this means the DIUs checked the following:

a. Correct parity (odd) at bit times 14, 28, 34, 62, and 90
b. Two identical words at bit times 28 (2 each 14-bit words) and 90 (2 each 28-bit words)
c. This DIU at bit times 14, 28, 62, and 90

The M/F interfaced to the DIUs and SSRs, just as on the ship equipment. Figure 9 shows the interface configuration. Inside the M/F, on the receiving end, was a digital gate that allowed only the DIU that was to respond to enter data into the uplink. This circuit was not necessary, but it was installed to provide backup if either of two possible failures occurred: one is a failure in the DIUs that would allow them to respond to all DIU addresses; the other was an SSR failure, in either the DIU or the M/F, that would lock up the circuits.

Digital Interface Units. The underwater equipment was partitioned into four fully redundant subsystems, each housed in a pressure vessel. Each unit had a DIU in it for command and data. The controller put out a message that was received by all 8 DIUs, but only the DIU being addressed responded. The DIU received commands in groups of 16 bits and put out data in 80-bit groups.

The DIUs were designed to receive commands in 16-bit broups, with DIUs 1 and 2 having an 8-group capability (128 bits) and DIUs 3 through 8 being wired for 12 groups (192 bits). The message was received, checked for duality (two identical words, as it was

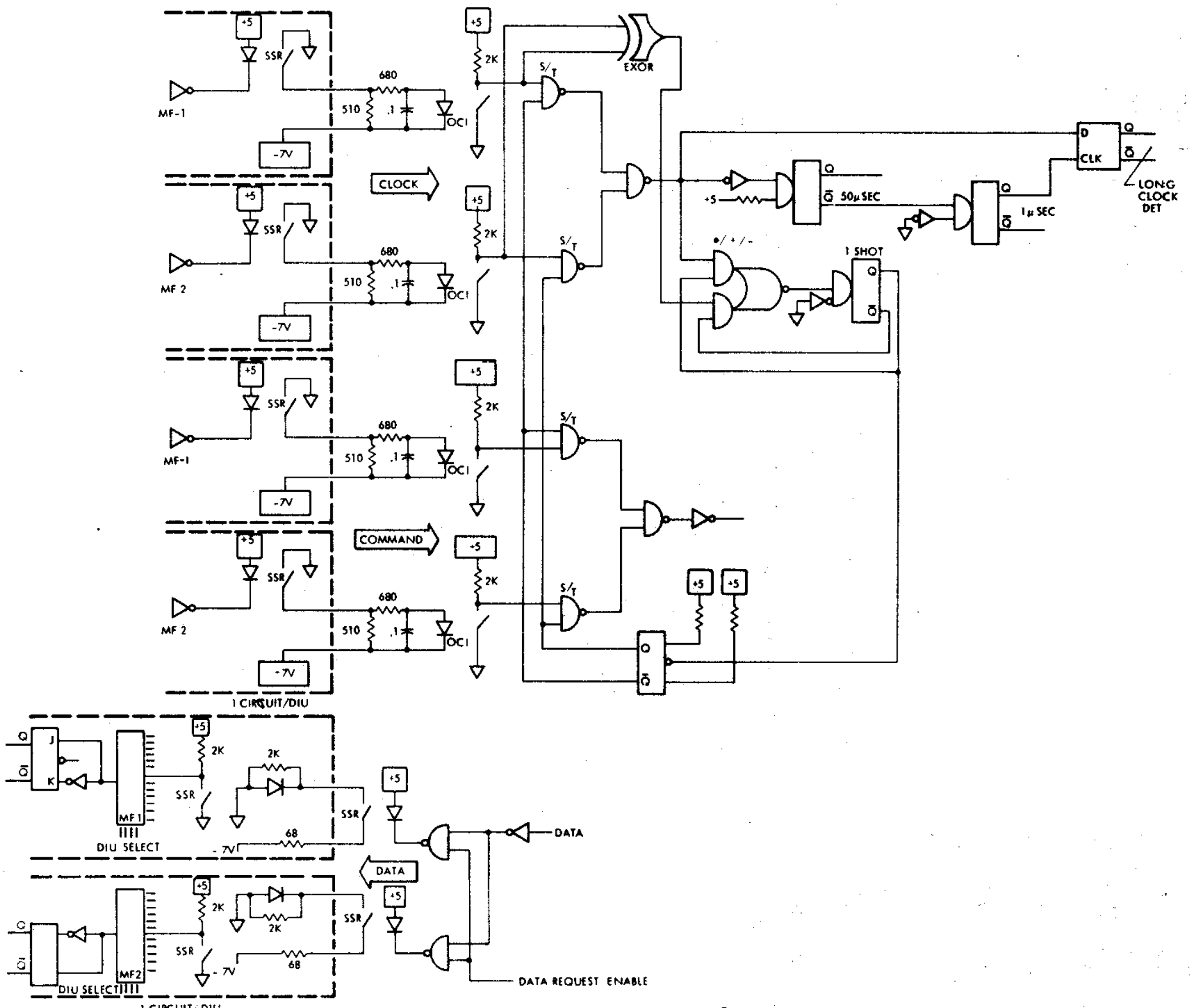

Fig. 9 Modem Formatter to DIU Interface

better to do nothing than to execute a wrong message), and parity; then, depending upon the block number (up to 32), a 16-bit word was output through a parallel-in/ parallel-out register -the output bits being held until the next time the command block appeared. For the most part, the DIU outputs drove solid-state relays that controlled 110v loads; the SSRs were the type that turned on/off at the zero crossing of the AC line. This system of control caused no EMI and was virtually failure free.

The data portion of the DIUs was capable of putting out any one of the following:

a. 80 digital bits
b. Eight 10-bit analog words
c. Ten 8-bit analog words

Each DIU contained two 80-bit digital multiplexer cards, identical in the SDU for command bits. if a digital word is requested, the data are transferred into the 80-bit register at one time and shifter out of the DIU in serial.

The DIU also contains an analog multiplexer card with three 16-channel multiplexers (48 inputs total). Depending upon the block of data requested, a group of either 8 or 10 consecutive analog gates is sampled; the PAM data are digitized by an A/D converter and shipped out serially. A considerable amount of trouble was experienced with the 16-channel multiplexer, since the first group purchased had the undesirable characteristic of turning on all 16 gates at one time, then getting very hot.

The analog multiplexers were all replaced with units from the same vendor (at $80 each, or $2400 for all the units bought); even these new units were found to malfunction, but in a different way. Another $2400 was spent for some different units from Harris (excellent performance) that were used as replacements as the other (newer) units continued to fail.

Test and Control Panel. A test and control panel used to monitor system health and status had the following control capability:

a. SDU 1 through 3 enable/disable
b. Controller 1 or 2 select
c. Modem 1 or 2 select
d. Modem formatter 1 or 2 select
e. Computer A through D enable/disable
f. Test and control panel command enable and execute

The monitoring capability was a vital factor in ascertaining system status. Monitors included the following:

a. Two 16-bit dial up words for data display
b. One command dial up word display
c. DIU 1 through 8 error lights
d. SDU error lites (failed 1/0 transition)
e. Parity error counter
f. Four computer enable/active lights

Conclusion. The system ran very well after it was debugged; however, since every design was committed to production, with little testing, and since there was inadequate time to fully test cards and boxes, bringing the system on line was very difficult. If a problem identified was not critical it would go on a list of things to be resolved on a weekend, if immediate repair was urgent, it was done on the spot. The lack of good design partitioning was a problem, as most troubles had to be found in the units because the cards had too many inputs and outputs (110 pins per card) to allow easy testing on the card tester.

Two problems were especially difficult. One was isolated by means of the Kepner Tragoe approach to problem analysis. The other, which was high-frequency noise getting through a low-frequency solid-state relay, was finally isolated by a less formal method: It was evident that high-frequency noise was present, but it was so infinitesimal that it could not be detected on the oscilloscope; however, with the scope connected, there was no problem. Therefore, the cable length was measured; the number of feet of cable was multiplied by 13; and a capacitor with a pf of the magnitude indicated was added. Unorthodox, perhaps, but the problem was eliminated.

Once the system was declared operational, it worked exceedingly well. In two of the trial cruises the system was operated 4 consecutive weeks the first time and 3 weeks the second. The number of errors and the bit error rate were as follows:

a. 28 days, 11 errors, $BER = \frac{11 \text{ errors}}{9600 \times 86400 \times 28 \text{ bits}} = 4.736 \times 10^{-10}$

b. 21 days, 1 error, $BER = \frac{1 \text{ error}}{9600 \times 86400 \times 21 \text{ bits}} = 5.741 \times 10^{-11}$

Note: All 12 errors were parity errors which was considerably better than the original BER design requirement of 1×10^{-6} or even the 1×10^{-8} which was the design goal.

Acknowledgments. The design for the control center and undersea vehicle was the responsibility of Ed Stoeckert; Charlie Braasch was responsible for the digital data link; Bill Marmom for the SDU, DIU, and Controller; and Dion Dillon did the modem and the modem formatter. Ray Feldman and Ted Axton helped greatly in debugging and repairing the system.