SPAWAR
Systems Center
San Diego

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A Short History of Navy VLF Solid-State Transmitter Development

R. E. Hammond

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INTRODUCTION

Despite its limitations and the development of competing technologies, very low frequency (VLF) remains the primary means of communicating with a submerged submarine. VLF's distinct advantage is that the submarine can receive transmissions while still submerged. Other approaches require the submarine to surface at least a small antenna and thereby risk detection. One disadvantage of VLF is that its large transmitter stations are vulnerable to sabotage or direct attack and cannot be counted on during an all-out conflict. Another disadvantage is that communication is one-way and is limited to the submarine receiving and not sending information. Despite these limitations, VLF's primary advantage of undetectable one-way communication is unduplicated and irreplaceable.

Given the importance of VLF, the desire for solid-state VLF transmitters is natural. Solid-state transmitters use switching power electronics that are theoretically 100% efficient. In practice, solid-state power amplifiers usually have efficiencies in the 85 to 90% range compared to tube-type efficiencies of 40 to 50%. Efficiency is an important consideration because Navy VLF stations transmit as much as 2 megawatts for the larger stations. Solid-state power electronics do not have the wear-out mechanisms that tubes exhibit. Transmitter tubes have a finite lifetime after which they must be rebuilt or replaced. Solid-state transmitters also do not require the liquid cooling and its associated plumbing that tubes often require. Finally, there is the general perception that tubes are old and antiquated and solid state is the future.

Tubes, however, are not without their own advantages. They can be built to handle large amounts of power compared to the transistors that solid-state amplifiers use. Tubes exist that can handle the power that would require a thousand transistors to process. The tube-type amplifier is simpler and has fewer components. The tube amplifier may be easier to maintain and may not be subject to as many obsolete parts considerations. Tube amplifiers are fundamentally less subject to electromagnetic pulse (EMP) considerations. Although EMP might temporarily disable a tube-type transmitter, it would probably be caused by failure of some of the solid-state support circuitry. The basic power-processing path of the amplifier would most likely remain operational.

The lessons learned from the U.S. Navy's solid-state VLF transmitter development efforts should not be forgotten. The Navy has spent a fair amount of time and money developing solid-state transmitters. The end of the Cold War may change things, but it has been the history of solid-state transmitter development for a new transmitter program to start every 10 years or so. There will probably be another solid-state transmitter development program sometime in the future with new people involved. This document provides perspective and consideration of some of the issues involved in that future development.

HISTORICAL DEVELOPMENT EFFORTS

IN-HOUSE DEVELOPMENT EFFORT

During the late 1970s, it was decided at SSC San Diego predecessor Naval Ocean Systems Center (NOSC), that a demonstration VLF amplifier would be built to determine if solid state was a feasible replacement for the aging tube-type amplifiers. It was known that solid-state switching power electronics approaches would be more efficient and would probably require less maintenance than the existing tube amplifiers. What was not clear was whether it was feasible to build solid-state amplifiers of such high powers to operate at VLF frequencies (15 to 30 kHz). The in-house development effort would answer this question and would also provide engineers with experience in amplifier development for future procurements.

The in-house development effort was to build and test a 100-kW, 15 to 30 kHz, solid-state amplifier that would produce the proper VLF output signal. There were no specifications as to the type of solid-state devices to use or which of many power electronics topologies to use. Figure 1 shows the hardware that was developed. Hardware included a full-bridge power electronic topology with bipolar transistors as the switching devices. Figure 2 shows a full bridge and its output square-wave of voltage. The bridge operates by turning on opposing switches so that first one polarity of the output square-wave is produced and then the other polarity. This topology was chosen because it makes the most efficient use of the switching devices. The transistor makes best use of its current and voltage ratings. This usage is extremely important because the transistors that exist that can successfully operate at VLF frequencies are small compared to the VLF power requirement. Many transistors (and bridges) must be used. The output of the many bridges is summed with the output of the other bridges through series connections of the bridge transformer secondaries. Even though the full bridge efficiently uses the switching devices, there is one continual concern with this topology. This concern is the "shoot-through" action that takes place if two non-opposing switches are turned on at the same time. This action places the DC supply directly across the switches to ground, which destroys the switches from over-current and also any surrounding circuitry. However, protection circuitry can be developed to ensure that this condition seldom occurs.

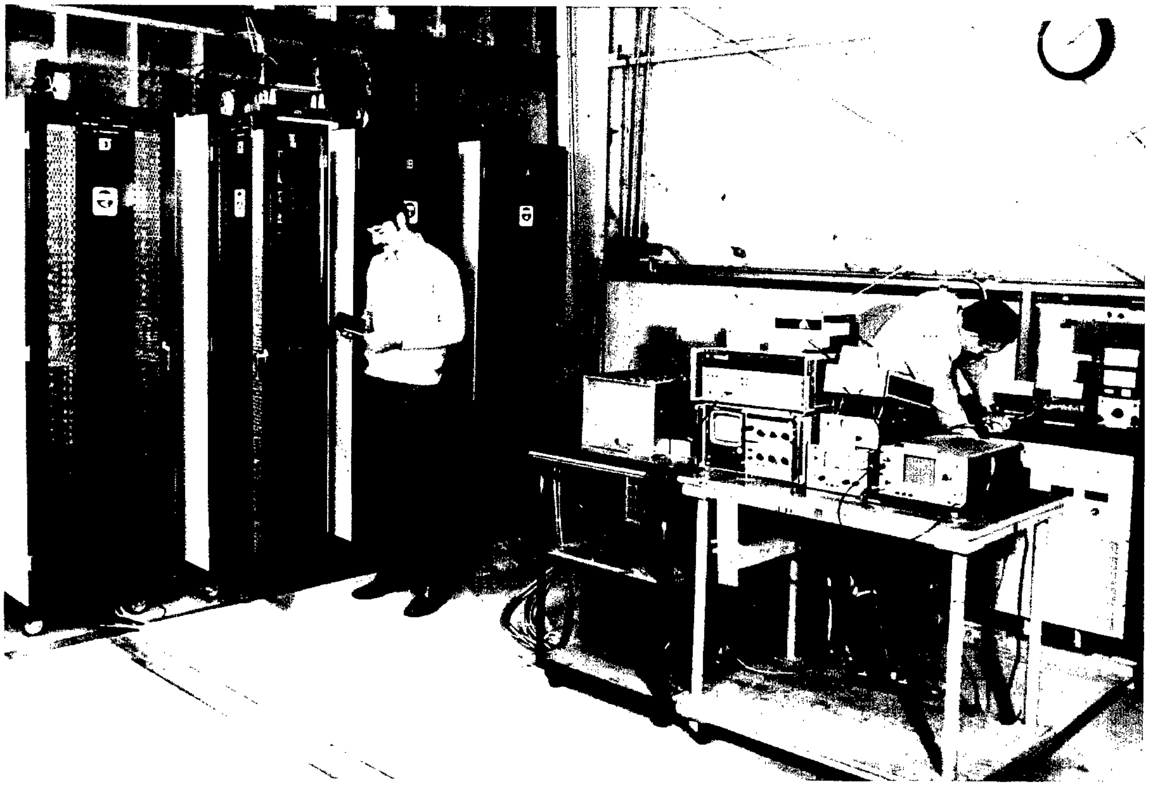


Figure 1. In-house development transmitter.

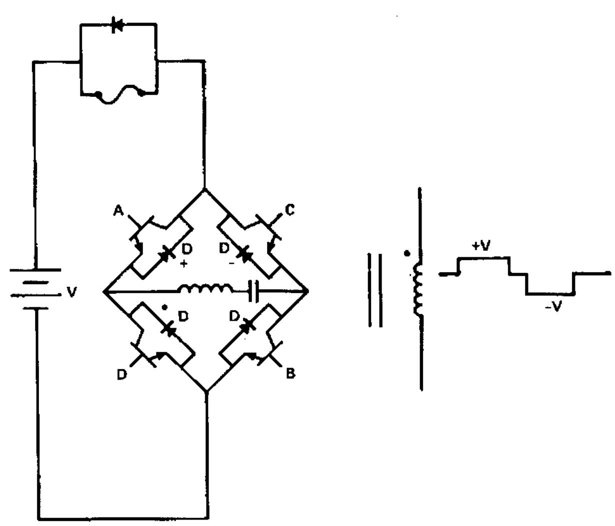


Figure 2. Basic full-bridge circuitry.

The in-house development effort was successful. It did lack the protection circuitry necessary to make it an operational transmitter at a site. However, it showed that a solid-state VLF amplifier could be built and produce efficiencies of 80 to 90% compared to the tube-type amplifiers' 40 to 50%. The full-bridge topology selected was used in all subsequent VLF transmitter developments. The bipolar transistors that the in-house development used were replaced with the field-effect transistors (FETs) developed later. The in-house development was quite successful and paved the way for the next procurement effort.

HIGH-EFFICIENCY SOLID-STATE AMPLIFIER (HESSA)

The follow-up procurement effort was the High-Efficiency Solid-State Amplifier (HESSA) program. This development effort was started during the early 1980s. The objective of this program was to develop a 500-kW solid-state transmitter for use at one of the existing VLF stations. Technically, there were few specifications on the exact nature of the transmitter as to the type of switches used or the power electronics topology. A minimum efficiency of 80% and a radiated harmonic current limit of 60 dB were specified.

The contractor selected for the HESSA program was Continental Electronics. They proposed developing a full-bridge amplifier very similar to the in-house developed amplifier. Continental Electronics' bridges would use FET switches instead of bipolar transistors. Continental had an excellent reputation for building tube-type VLF transmitters and also tube-type AM and FM radio transmitters. However, the company had no experience building solid-state transmitters, and this lack of experience was evident in their proposal. While the development program contract was a cost-plus contract, Continental had the lowest cost proposal. This proposal was enough for them to win the contract, despite their lack of experience in this technology.

Continental's effort to develop a solid-state amplifier was not successful. After several cost and time extensions in the program and a dedicated effort by Continental, it was evident that there were still difficulties with the hardware. Their lack of experience in solid-state power electronics was too large a hurdle to overcome during the relatively short period of the contract. Even after the HESSA program, Continental did not successfully develop solid-state transmitters for the commercial AM/FM market. They lost market share to companies like Harris Transmitter, which did produce solid-state transmitters. By 1999, Continental's main market in transmitters was smaller South American tube-type AM and FM radio stations.

It might be argued that the Navy was at fault for selecting a minimally qualified low bidder for HESSA. This was false economy. The initial low cost on the cost-plus contract was soon greatly exceeded. Not only did Continental not produce an amplifier for the U.S. Navy, the experience it acquired during the contract did not help it transition from tube to solid-state transmitters in the commercial marketplace.

FRT-95A SOLID-STATE TRANSMITTER DEVELOPMENT

The FRT-95A solid-state transmitter was a unique development effort. The procurement effort was intended to produce replacement tube-type FRT-95 transmitters and was a firm fixed-price contract. However, the Navy was surprised when one of the contractors proposed a solid-state version that would be form, fit, and function compatible with the FRT-95. This proposal was selected and eventually led to the Navy's only fully operational solid-state VLF/LF transmitter system.

The FRT-95A was based on a full-bridge power amplifier that already existed as a product of Instruments Incorporated (II). II is a small San Diego-based company that had previously built sonar power amplifiers for the Navy. The program's main contractor was Electrospace Incorporated (ESI), a general defense contractor and a subsidiary of the Chrysler Corporation. ESI performed amplifier integration with the computer control and monitoring system and the antenna system. There was very little technical risk in this program as the power amplifiers essentially already existed, and there was little doubt that the integration was technically straightforward. However, there was schedule risk. The program had management difficulties and ESI changed program managers at least six times during the program. The Navy was very particular, at least initially, about program reporting, control console layout, and other technical details. At the end of the program, ESI was out of money in the fixed-price contract and went into a slow-motion, cost-reduction mode.

After significant delay, the FRT-95A transmitter was fielded and operated at four sites. However, there have been some relatively minor maintenance concerns. The most significant was an optical coupler integrated circuit used in the bridge circuitry. It was initially unknown that these devices degrade over time and affect circuit operation. This device has been replaced with a small transformer drive circuit that has no such degradation mode. Overall, the FRT-95A is a simple, maintainable, and successful solid-state transmitter system. It was produced without an elaborate cost-plus development contract and without initial intent by the Navy.

SOLID-STATE POWER AMPLIFIER PROGRAM (SSPAR)

The objective of the Solid-State Power Amplifier Program (SSPAR) was again to replace the aging VLF tube-type transmitters with a solid-state version. There were six respondents to the request for proposal (RFP), including several foreign companies. Although they did not have the best technical proposal, Rockwell Dallas did have acceptable technical and cost proposals. This contract was also a cost-plus contract, and even during proposal evaluation it was decided that Rockwell's program costs were understated.

Rockwell's technical approach was based on the full-bridge approach with some new developments. However, there were three aspects that were substantially different from what had been tried in the past. First, a high-power bridge was to be used. Solid-state switch development had not yet produced higher power FETs. Though the bridge used basically the same FETs as switches that HESSA had a decade earlier, 16 FETs were to be paralleled in each switch position to make a large bridge that would handle 30 kVA of power. Next, instead of relying entirely upon series power combining, Rockwell would also use parallel power combining. Lastly, the entire transmitter would use extensive computer control and monitoring, much more than had been tried in the past. Figure 3 shows the SSPAR transmitter amplifier.

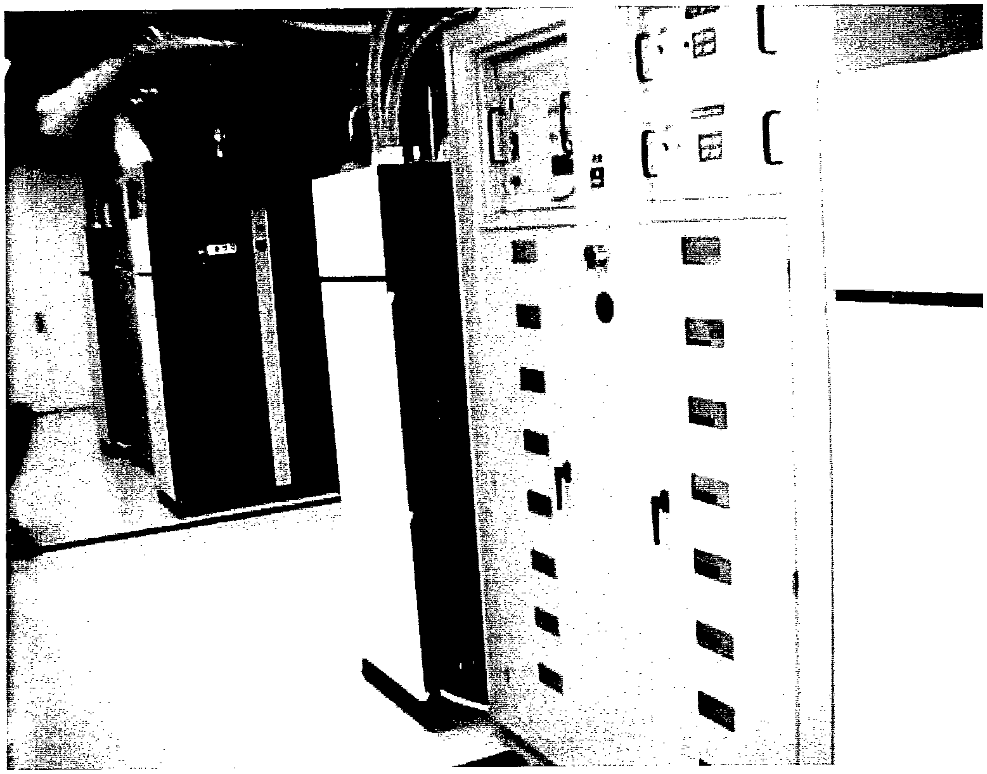
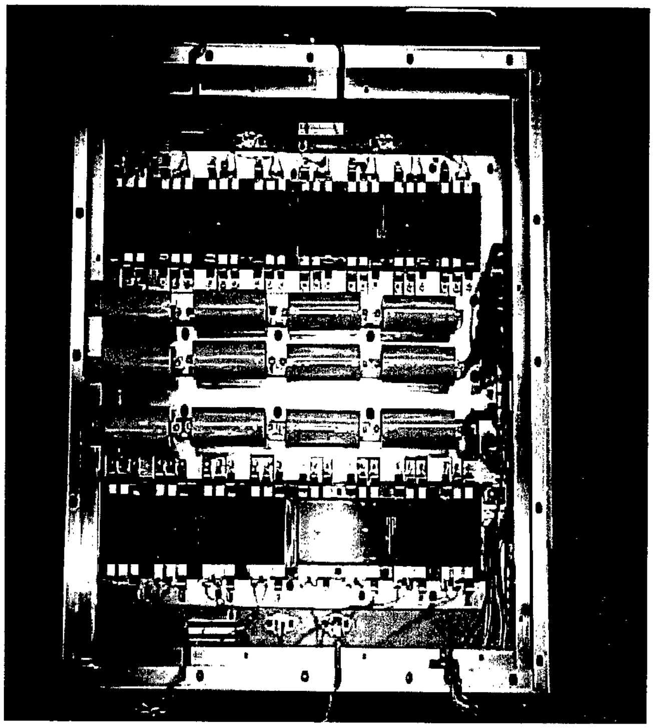


Figure 3. SSPAR transmitter amplifier at La Moure, ND.

Each of these three new developments can now be evaluated with 20/20 hindsight. Whether the big bridge is a good idea is dependent upon the relative failure rate of the bridge. If the failure rate is high, a larger proportion of output power is lost with each failure and the cost to repair the larger bridge is also higher. If, however, the failure rate is low, there is a benefit from reducing the number of times each bridge's support circuitry (protection and monitoring) must be replicated with each bridge. Thus, the transmitter can be made somewhat more compact, with fewer parts to statistically fail. After several years of operation of Rockwell's transmitter at La Moure, ND, this seems to be the case. However, obsolete parts are yet another aspect of the transmitter that should be considered. With an operational VLF transmitter, the Navy would probably want 20 to 25 years of use before replacement. If individual piece parts in the big bridge become unavailable, the cost of redesign may be unacceptable. Smaller and simpler bridges may ultimately be more maintainable. Additional time should provide this answer. Figure 4 compares the physical bridges used in the SSPAR and FRT-95A.



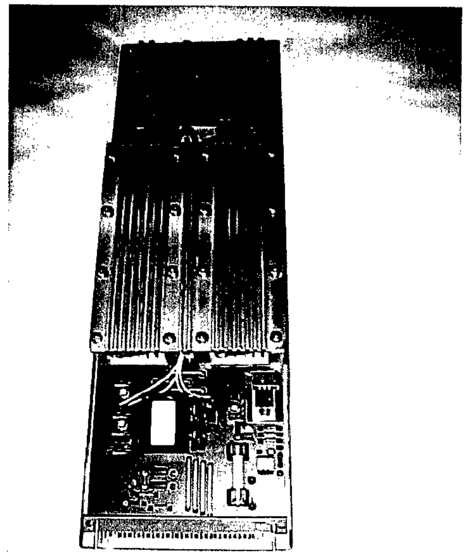


Figure 4. SSPAR (left) and FRT-95A (right) bridge.

Parallel power combining also had potentially good and bad aspects. It avoids one of the difficulties associated with exclusively using series power combining. With series power combining, the output voltage of each bridge is stacked upon one another, which leads to very high voltages at the end of the stack. This voltage is especially a concern with larger 2-megawatt VLF stations. Arcing and potential destruction of circuitry is a definite concern. With parallel power, combining the voltage from a number of bridges can be fed into the simple inductor capacitor inductor T, which then functions to convert what was a voltage source into a current source. Figure 5 shows the circuitry used in the combining T. Current sources are easily paralleled, so overall transmitter power can be increased in this way. The potential downside of parallel power combining is that some previously unknown fault mechanism would be introduced. This does not seem to be the case, as observed at the LaMoure site. However, LaMoure only parallel combines two subamplifiers. The larger French SSPAR-type transmitter outside Paris parallel combines four subamplifiers and should be investigated as to whether any problems are encountered.

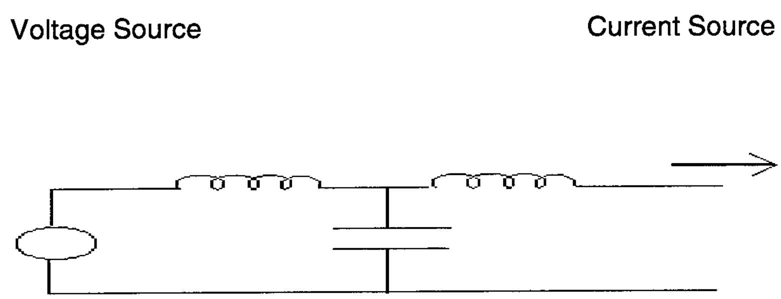


Figure 5. Subamplifier parallel power combining T.

Extensive computer control of the transmitter has advantages and disadvantages. On the positive side, when things are working well, control and monitoring of the transmitter is simple and clearly presented. Indeed, the information on the transmitter's control screen can be remoted and monitored or used for control there. On the negative side, the software used to accomplish this convenience must be maintained. This maintenance amounts to another full-time employee who understands the software and is available to make changes or correct glitches as they are discovered. If this individual becomes unavailable, a much larger expense will be encountered in training other people to understand the software and make changes. Essentially, an evaluation must be made in future situations as to whether the convenience associated with extensive computer control warrants the continual maintenance expense.

Ultimately, it was cost, not technical merit, that decided the fate of SSPAR. Cost was an issue from the beginning of the contract when it was decided that Rockwell's costs were too low. However, bidding low on a cost-plus contract is a winning strategy. Bid too high and the contractor will fail to get the contract and, if it is at the end of the Cold War, go away. This is what happened to two of the contractors who were previously active in the VLF arena, Electrospace Inc and Westinghouse. Costs are essentially always increased during the course of a cost-plus contract. What was not anticipated was that the costs of the production contract would be twice ($120 M versus $60 M) what was anticipated and budgeted. In Rockwell's defense, Rockwell built a Cadillac of VLF transmitters. Given a choice, the Navy's technical people would rather have additional transmitter capability or features. However, costs increase with the added complexity and capability. Financially, the Navy had more of a Chevrolet version in mind.

CONCLUSIONS

The final VLF solid-state transmitter development may not have occurred. Yet if this is true, it is important not to forget the lessons learned from past development efforts. Solid-state transmitters have sizeable advantages in their ability to process reactive power and efficiency. Tube transmitters still have significant advantages for the largest VLF sites. Technology will continue to advance, but solid-state switch development is presently slow. The multiplicity of circuitry required for high-power, solid-state VLF sites brings up reliability, maintainability, and obsolete parts concerns. The feasibility of the big bridge versus small bridge has not been completely decided. Computer control brings added convenience, but brings cost and maintainability concerns. The cost of solid-state transmitters will likely remain an issue because of the limited number of contractors competing in this area. If custom transmitters with additional features and capabilities are developed, cost will increase. Finally, initial contractor selection is critical and issues that are noticed during proposal evaluation do not go away.

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This document provides a short history of Navy VLF solid-state transmitter development at SSC San Diego and its predecessor organizations. Lessons learned in these developments and issues involved in future developments are discussed.

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