Solid-State Upgrade for the COBRA JUDY S-Band Phased Array Radar

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***Abstract* - COBRA JUDY S-band is a phased-array data collection radar permanently mounted aboard the USNS Observation Island (Figure 1). Designed in 1976 and first made operational in 1981, the transmitter hardware has become difficult to support and, in some cases, obsolete. In December 2004, Diversified Technologies, Inc. (DTI) was awarded a contract to upgrade the transmitter with solid-state technology.**

Conventional tube-type radar modulators upgraded with switching power supplies and high voltage modulators demonstrate improved performance and significantly extended lifetimes. Employing solid-state technology in high voltage transmitters is cost-effective, improves reliability, and delivers better protection to the RF amplifier than conventional transmitter designs.

In this paper, DTI will present an overview of the CJS transmitter design, key technical drivers, and a summary of progress thorough installation of the transmitter in early 2006.

I. BACKGROUND

DTI has pioneered the replacement of obsolete transmitter vacuum tubes and crowbars with high voltage switches. The company's high voltage switches are built from modules containing from four to twenty individual transistors (typically IGBTs) connected in series. The voltage rating of each module is between 3 kV and 12 kV, depending on the module design, and peak current ratings range from 30 A to more than 5,000 A. Multiple modules are placed in a series assembly to meet the specific transmitter cathode voltage (Figure 2). An external gate drive controls all modules in the assembly simultaneously, with risetimes as low as 30 ns. The modular construction leads to flexibility, economy, and ruggedness, and allows the application of common module designs across a range of transmitter designs.

The radar amplifier tubes driven by the upgraded transmitters are typically either cathode pulsed or mod-anode /grid pulsed. For cathode pulsed systems, a directly connected high voltage modulator (a compact, highly-regulated HVPS and modulating switch) is a viable replacement for "hard-tube", active-switch modulators, and thyratron / pulse forming networks. In normal operation, the cathode switch is closed for the duration of the desired pulse,

Figure 1. USNS Observation Island. The Cobra Judy S- band radar array is located aft of the Cobra Judy X-band dish.

presenting very low impedance between the power supply and the cathode. A cathode modulator provides fully variable pulsewidth (50 ns – DC), adjustable on a pulse-to-pulse basis, and supports pulse repetition frequencies up to 400 kHz. By opening very fast (<1 μs) when a fault is detected, the series switch blocks power from reaching the cathode, without disrupting the power supply. When the fault has cleared, the transmitter can resume operation in microseconds.

In grid or mod-anode modulated systems, this same high voltage switching technology replaces the typical vacuum tubes in the modulator. DTI has built both single sided (pull-down) and push-pull configurations. These switches are typically combined with a cathode series switch for arc

Figure 2. High voltage switch modules.

Figure 3. Cobra Judy X-band DC power supplies and controls installed on-board the USNS Observation Island.

protection (in place of the conventional crowbar), allowing the entire power control interface to the RF amplifier tube to be solid-state.

II. Cobra Judy S-Band Transmitter

The Cobra Judy S-band (CJ-S) radar is a unique system designed to collect dual frequency (S- and X-band), high precision metric and signature data needed for missile treaty verification and strategic and theater missile defense development. Its operation is critical for the foreseeable future. In 2003, DTI installed an upgrade for the X-band transmitters in the Cobra Judy system that included all electronics from ship power to modulating the two 100 kW TWTs (Figure 3).

The COBRA JUDY S-band phased-array radar became operational in 1981. The radar's transmitter hardware is nearly 25 years old, and many of its components have become difficult to support and maintain. In December 2004, based upon the success of the earlier X-band upgrade, DTI was awarded a contract to replace all of the electronics systems in the transmitter between ship's power and the 16 TWTs, to provide greatly enhanced control, fault handling, and diagnostics.

The TWTs in the CJ-S transmitter are grid pulsed designs, operating at approximately 45 kV cathode voltage. Diagrams of the new CJ-S transmitters are shown in Figure 4. and Figure 5. DTI's upgrade retains the top-level transmitter structure, comprised of two identical groups, each supporting eight of the transmitter's sixteen TWTs. The operating goals are to eliminate single point failures, and minimize the impact of a failure on the overall radar performance by limiting that impact to a single TWT. An opening series switch that provides enhanced protection for the TWTs replaced an obsolete, triggered, gas gap-shorting crowbar. In addition, a switching regulator to provide cathode voltage control without extremely large capacitor banks replaced the vacuum tetrode regulator.

The upgrade replaced the existing Power Distribution Unit (PDU), inductrol, power supplies, and filter cabinet, and eliminated the single-point-of-failure grid modulators and associated circuitry in the grid modulator cabinet. The only major remaining transmitter components are the TWTs, their solenoids, the solenoid power supplies and ion pump controllers.

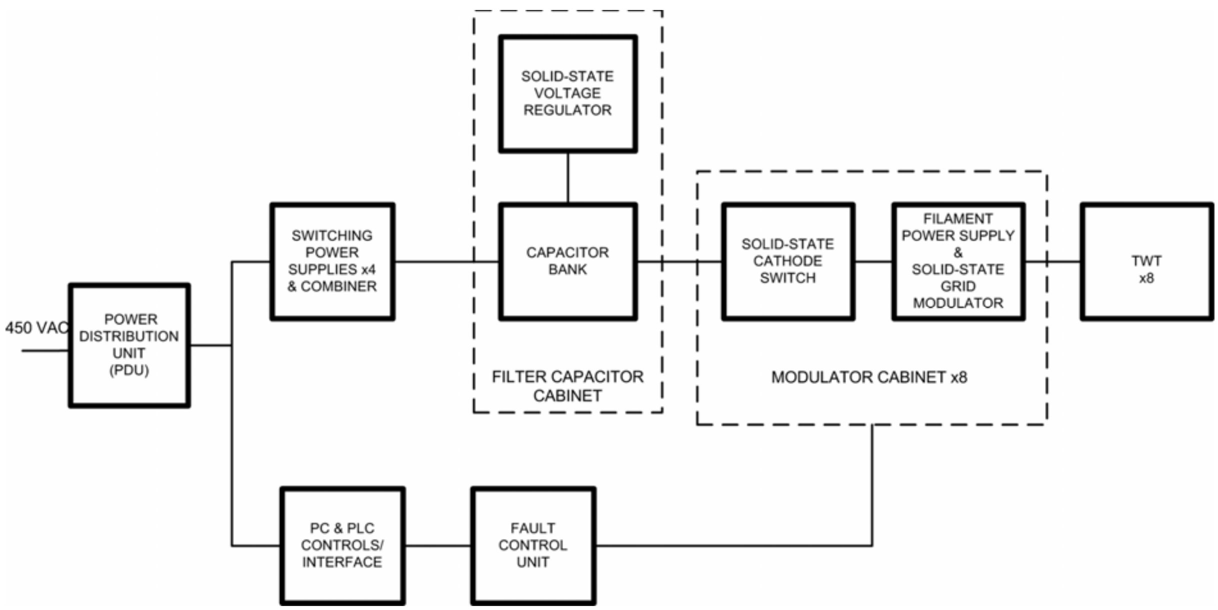

Figure 4. Block diagram of the new CJS transmitter. Diagram represents just one of two identical groups making up the transmitter.

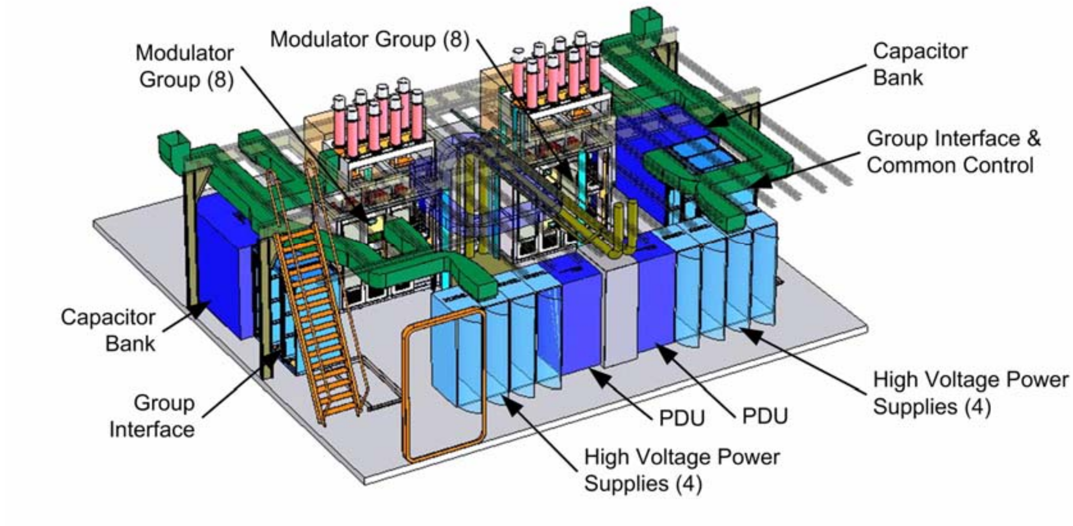

Figure 5. Layout of the new Cobra Judy S-Band radar transmitter. The radar's sixteen TWTs are arranged in two groups of eight, each group having its own electronics. The new electronics for each TWT group consists of one modulator assembly for each of the eight TWTs, two Power Distribution Units (PDU), four (N+1) power supplies, a filter cabinet with a linear voltage regulator, and a capacitor bank.

A. Structure of the Cobra Judy S-Band Transmitter Upgrade

Each of the two groups has five major subsystems: (1) controls and fault diagnostics; (2) a Power Distribution Unit (PDU), (3) four switching DC power supplies, (4) a single filter cabinet, and (5) eight TWT modulator assemblies (one per TWT). The eight TWT modulator assemblies are grouped in a single cabinet (Figure 6) that also contains a series cathode switch, filament supply, and solid-state grid Modulator for each TWT.

Figure 6 Eight TWT modulator assemblies are located in these cabinets. The eight TWT cathodes will be located directly above this cabinet in the final installation. Each modulator assembly has its own fault control panel as shown in Figure 9.

The designs of most subsystems in this upgrade are sourced from the previous CJ-X and Gray Star X-Band transmitter upgrades. They include the PDU, power supplies, Fault Control Unit (FCU), filter capacitors, PLC/PC control system, and solid-state switches. The grid modulator and solid-state voltage regulator are new subsystems built specifically for the CJ-S transmitter. Additional displays and controls allow operation and monitoring of both TWT groups from one location.

1) Power Supplies

Each of the eight TWTs operates at approximately 40 kW (38 kV x 18 A x 6% duty). Four 45 kV, 150 kW switching power supplies (HVPS) replaced the old Induction Voltage Regulator, HVPS, and electronic voltage regulator for each of the two transmitter groups. The new supplies (Figure 7) provide N+1 redundancy, and are combined and controlled so that if one supply fails, its transmitter group will continue to operate at full power. These supplies are similar to DTI's commercial switching power supplies, modified for shipboard operation.

2) Voltage Regulation

In the original CJ-S transmitter design, a beam voltage regulator tube and separate power supply ensured that the cathode-body voltage remains stable. Since the TWT collector is depressed, all of the capacitor droop then occurs between cathode and collector during each pulse, where it did not affect the RF characteristics of the TWTs.

Figure 7. Four, 45 kV 150 kW switching power supplies drive one of two 8-TWT groups. The power supplies in each group have N+1 redundancy, allowing full power operation if one supply is off-line.

Figure 8. Solid state cathode switch assembly (modulator).

In the upgraded system, a DTI switching voltage regulator further modernizes the transmitter, compensating for capacitor bank droop during the longest pulses. This solid state regulator controls the combined ripple, pulse-to-pulse stability, and droop of the TWT cathode voltage to ± 10 V (± 0.025%) for all normal radar operating conditions. By comparison, the cathode voltage sag alone would be over 1,000 V during the pulse without this regulator.

B. Modulators

Each TWT has its own modulator assembly that provides the electrical connections to the TWT itself. All eight of the modulator assemblies for each group are located in a single cabinet, shown in Figure 6. Each modulator assembly consists of a series opening switch and gate drive tied to the cathode (Figure 8), a filament supply, and a grid modulator. Each modulator assembly also contains the isolation transformer and power supply for the cathode-referenced filament power supply and grid modulator, as well as the controls and monitoring interface for each individual TWT. The assembly, rated at 55 kV, 50 A, is located between the capacitor bank and the TWT cathode. Typically it is closed during radar operation. If a fault occurs in its associated TWT, this switch is commanded to open, fully removing power from the TWT in <1 µs. Cathode power can be reapplied immediately upon clearing of the fault.

The modulator assembly provides simplified and independent diagnostics and maintenance, and minimizes the impact of any single TWT failure on the group's performance. The radar can run with a single TWT off-line, with negligible impact on its performance. In contrast, the previous system shared a crowbar and large grid and filament power system among all eight TWTs. In the event of a fault within any TWT or the common supplies, the entire group of eight was taken off-line, resulting in a direct 3 dB loss in sensitivity.

C. Control System

A multi-level fault handling, and diagnostics system controls and monitors the transmitter. The first level provides fast response using hard-wired fault detection with safety shutdowns and first fault latching. In addition, local readouts are provided at each major hardware element for operator direct monitoring and rapid troubleshooting. Each modulator assembly, for example, includes a display panel (Figure 9) which shows overall modulator status, displays the filament and grid voltage and current levels, and includes fault indicators with first fault indication, to identify where a sequence of TWT faults was initiated. This panel also includes BNC outputs of critical signals within the modulator. All of these can be accessed directly, without requiring access to high voltage areas.

The second level provides supervisory automatic controls and average response fault detection with safety shutdowns via a commercial programmable logic controller. The third level enables operator control using a personal computer with a color touch screen. Using this control system, all

Figure 1. Modulator assembly fault control panel. Filament and grid voltage and current readings are displayed, along with system status and fault indicators. BNC outputs are provided for monitoring of time varying parameters within the modulator.

settings, fault monitors, and operating parameters can be displayed, monitored, and controlled from the PC terminal. The PC also provides data logging and trending to record performance, and extensive diagnostic information to minimize down time. Finally, a remote touch screen in the Operations Control Center (OCC) allows control of the transmitter to be transferred between the transmitter room and the OCC (Figure 10). Backup hardware switches in each group allow the radar to be manually operated without the PC, if necessary.

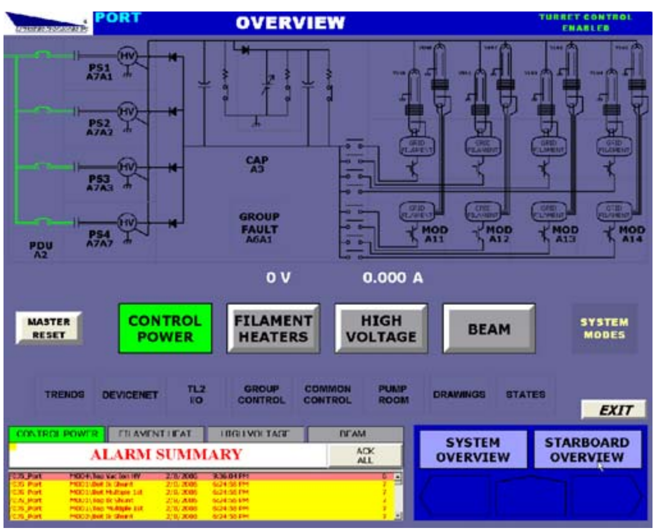

Figure 10. CJS PLC control screen. This is one example of a nested set of control screens, allowing the operator to view and control system operation. Multiple levels allow the operator to rapidly zoom from this overview of one group, to details of each elements' settings and performance.

III. STATUS AND SUMMARY

The CJ-S transmitter construction and in-plant testing is complete. At DTI, two GFE TWTs were used to test each segment of the transmitter, albeit sequentially. By utilizing, for example, one power supply and two modulator assemblies, full power testing of this subset of the transmitter was accomplished, through operation of the transmitter into two TWTs at a time (Figure 11). This testing was then repeated until all elements had been tested.

The system is awaiting installation on-board the USNS Observation Island during its next major shipyard period. On-board testing will allow the entire transmitter to be operated as a complete system.

The design of the CJ-S transmitter is directly applicable to the upgrade of other large phased array radar transmitters with grid pulsed TWTs, such as PARCS and Cobra Dane. Major elements of this design are also used in the new Haystack Ultra-Wideband Imaging Radar (HUSIR) transmitter currently being installed at the MIT Lincoln Laboratory (MIT-LL) Haystack Observatory in Westford MA, and the new Transportable X-band radar transmitter just awarded to DTI by MIT-LL.

The replacement of obsolescent, conventional switch tubes and components by modern, solid-state technology has significantly increased the performance and reliability of numerous radar systems – both in new radars and upgrades of older transmitters. Over the last decade, DTI has shown that typical RF amplifier VEDs, including magnetrons, CFAs, klystrons, TWTs, and gyrotron-based systems can be successfully driven using a combination of highly regulated, switching power supplies and switches. This capability has proven applicable to all of the major transmitter topologies, including cathode, mod-anode, and grid pulsed system.

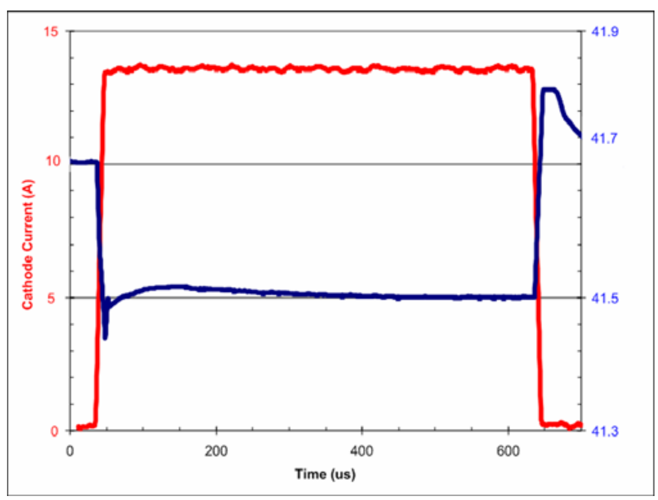

Figure 11. Cathode voltage and current pulse into a single TWT.