Chapter 7.

MISSILE SITE RADAR

Chapter 7.

MISSILE SITE RADAR

The Missile Site Radar (MSR) System was developed in three distinct phases: Prototype (Meck Island Facility - Figure 7-1), Tactical Software Control Site (Madison, New Jersey), and the Tactical Site (Nekoma, North Dakota - Figure 7-2). The three sites were installed over a six-year period. Installation of the prototype system began in late 1967; an MSR receiver and digital equipment group were installed at the Tactical Software Control Site (TSCS), as a software and partial system checkout facility, in 1971; and installation of the tactical MSR site began in 1973. Figures 7-3, 7-4, and 7-5 indicate the schedules for the Prototype MSR, TSCS, and Tactical sites, respectively. The last major milestone occurred on April 1, 1975 [Initial Operational Capability (IOC)], when the tactical system was turned over for military operation.

The MSR, as initially conceived, was a short-range target and missile tracking radar to be used in conjunction with the NIKE-X Multifunction Array Radar (MAR).[1] In this version of NIKE-X, two missile tracking radars were to be deployed near SPRINT missile farms located some distance from the MAR. These two radars were

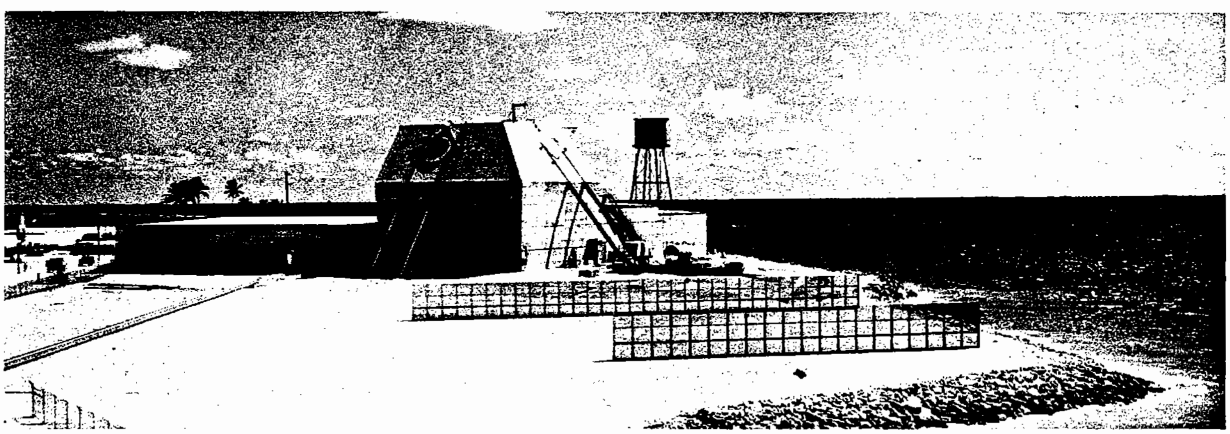


Figure 7-1. Prototype MSR - Meck Island

Figure 7-2. Tactical MSR - North Dakota

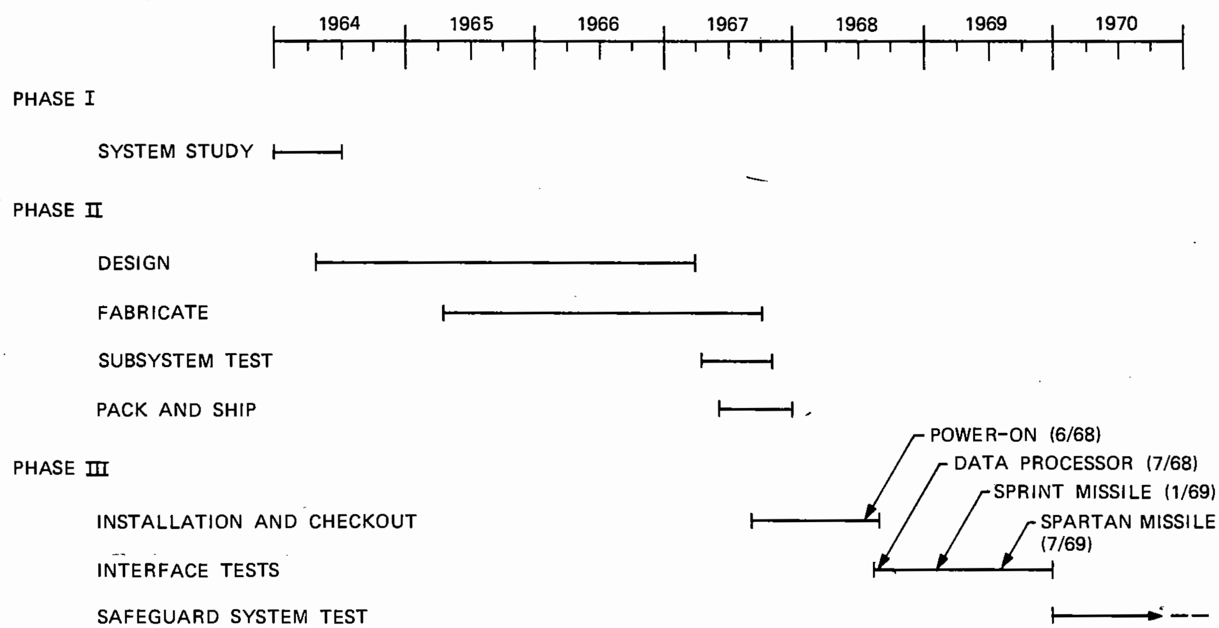


Figure 7-3. Prototype MSR Schedule

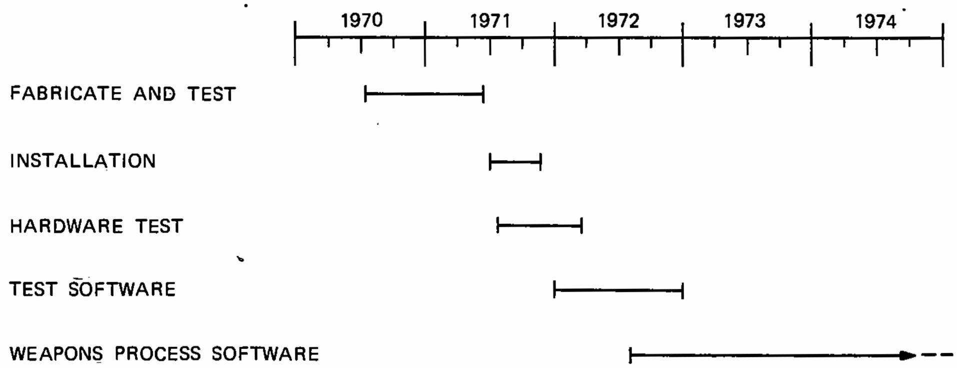


Figure 7-4. MSR TSCS Schedule

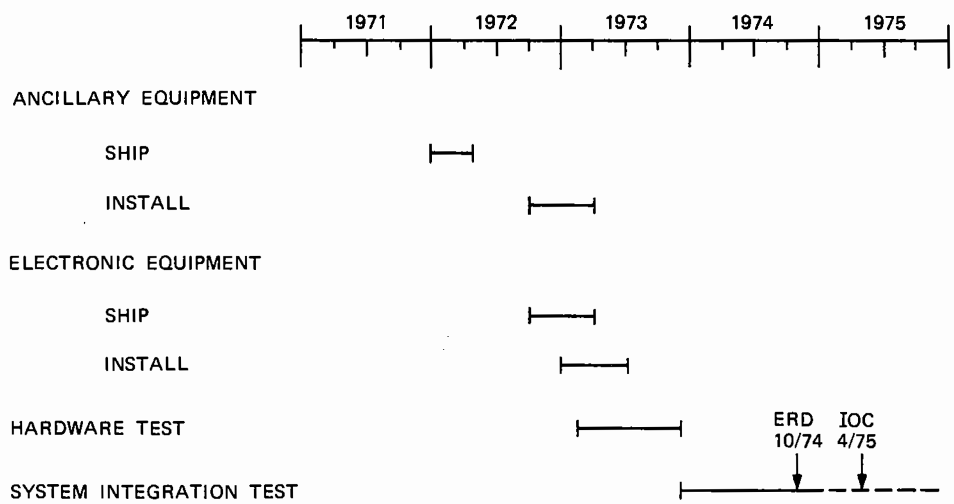


Figure 7-5. Tactical MSR Installation and Test Schedule

to contain a large number of tracking channels for relatively short-range target and missile tracking and, along with the missile tracking capabilities of the MAR, would triangulate the necessary fire power for the proposed NIKE-X System. In this deployment concept, the data processing equipment was to be centrally located at the MAR site.

The requirements of the MSR, as initially conceived, were submitted to prospective contractors during October 1963 in a request for quotation on the study phase of the radar's development program. The proposals were received and evaluated, and the contract was awarded to the Raytheon Company, Wayland, Massachusetts.

Prototype study and definition, Phase I, began in January 1964 and lasted through May 1964.[2] The radar was to be a phased-array type with sufficient power output capability to handle both the size and quantity of planned targets and the large number of missiles in track. To meet this power requirement, a new klystron transmitting tube was designed, which would provide a combination of bandwidth and output power greater than that of any previously available S-band tube. To meet the high availability/reliability requirements, complete channel redundancy with high-speed switching was designed into the transmitter, receiver, and digital radar control equipment.[3]

The prototype development program, Phase II, had been underway one year when the NIKE-X concept was revised to provide an autonomous MSR with much greater target and missile tracking capacity. The revised MSR design was initiated in May 1965 and, among other changes, required a five-fold increase in average power output. After a brief period for redefinition of this larger radar system, development began with the goals of starting the prototype installation at Meck Island (Phase III) in the latter part of 1967, having "power-on" by June 1968, and testing SPRINT and SPARTAN missiles by June 1969.[4] Development continued under this concept for one year until May 1966 when requirements for additional target handling capabilities were placed on the system. With these additional requirements, it was now possible for the MSR to handle the entire engagement and the MAR system disappeared from the NIKE-X program.[5]

In October 1967, NIKE-X was renamed the SENTINEL System, the MSR prototype design was nearing completion, and design of the production version was initiated.[6] The only major hardware design change at this point, which necessitated a new development phase, was converting the digital radar control from thin-film to core memory. All other subsystems were modified as required for quantity production, and necessary final design work and documentation were begun.

In mid-1971, to facilitate the design and testing of software and system related interfaces, installation of the operating consoles and one channel each of the MSR receiving system and MSR digital control system was undertaken at the TSCS. The MSR equipment design was identical to that of the production equipment and was initially used to evaluate MSR test software. Testing of the tactical weapons system software began in early 1972, with the TSCS continuing to support the system checkout and initial operational phase of the Tactical Site.

During the latter part of 1968, when design of the tactical system was well along, consideration was given to increasing the range of the MSR by increasing the diameter of the antenna face. This proposed redesign, known as the Improved MSR (IMSR), was associated with system capabilities that might be required at some time in the future. Studies were made to define the building modifications and antenna support structure that would be required to retrofit a tactical MSR system to the larger diameter antenna. These studies continued until the early part of 1970.[7] The building was then modified so that the larger antenna could be installed. This redesign incorporated a permanently larger antenna-to-feed horn enclosure which could be used with either size antenna, thus eliminating the need for future retrofit. The smaller antenna, as installed at North Dakota (see Figure 7-2), is actually inside a larger annulus which can be removed if the larger antenna is ever needed.

Construction for the North Dakota tactical site began in the Spring of 1970, installation of equipment began in late 1972, and power-on was achieved for all elements of the system in the beginning of 1973. With testing of the tactical radar and tactical software beginning in 1973, the Equipment Readiness Date (ERD) was achieved on September 27, 1974, with Initial Operational Capability on April 1, 1975.

SYSTEM CAPABILITY[8]

The 430-acre MSR site at the Stanley R. Mickelsen SAFEGUARD complex located near Nekoma, North Dakota, is comprised of an MSR and the SPRINT and SPARTAN missile farms (Figure 7-2). Partially underground, the largest structure at this location is the MSR building — 230 feet square and 123 feet high. The visible portion of the building holds the four antenna arrays and their associated equipment. Hardened to withstand a nuclear blast and its radioactive effects, the concrete outer walls are 4 feet thick, slope at an angle of 35 degrees, and rise about 80 feet above the ground.[9,10] Each of the four antenna faces is about 13 feet in diameter and contains approximately 5000 phased-array elements.[11]

Operating at a higher average power than any existing radar in its frequency band, the MSR, with the aid of its associated Missile Site Data Processor (MSDP), processes its own autonomous target data as well as data from the Perimeter Acquisition Radar (PAR), discriminates between warheads and other objects, and launches and guides interceptor missiles on appropriate trajectories via an RF command guidance link to the SPARTAN and SPRINT missile farms. Based on a design concept of two-channel redundancy for major subsystems and multiple redundancy within the antenna system, the MSR is a precision sensor designed for continuous use. (Figure 7-6 is a functional block diagram of the MSR.)

Since the MSR is designed for continuous operation, it contains all facilities for maintaining the electronic apparatus. The redundant transmitter, receiver, and digital systems allow maintenance work on the off-line channel while the radar system is functioning normally using the on-line channels. Each of the subsystems can be checked in the off-line position to assure optimum performance when the off-line channel is switched to the on-line position. Facilities built into the MSR provide rapid and frequent checking of all subsystems while the equipment is performing a mission function. When a fault is detected, the channel is switched off-line and with the use of additional test signals, the malfunctioning chassis is located, replaced with a spare, and checked in the off-line position.

The two output klystrons normally operate in parallel. If one of the klystrons malfunctions, it is automatically switched off-line where further tests can be run. This klystron can then be replaced while the other klystron performs mission functions with a 3-dB lower power output. The replacement klystron can be activated in the

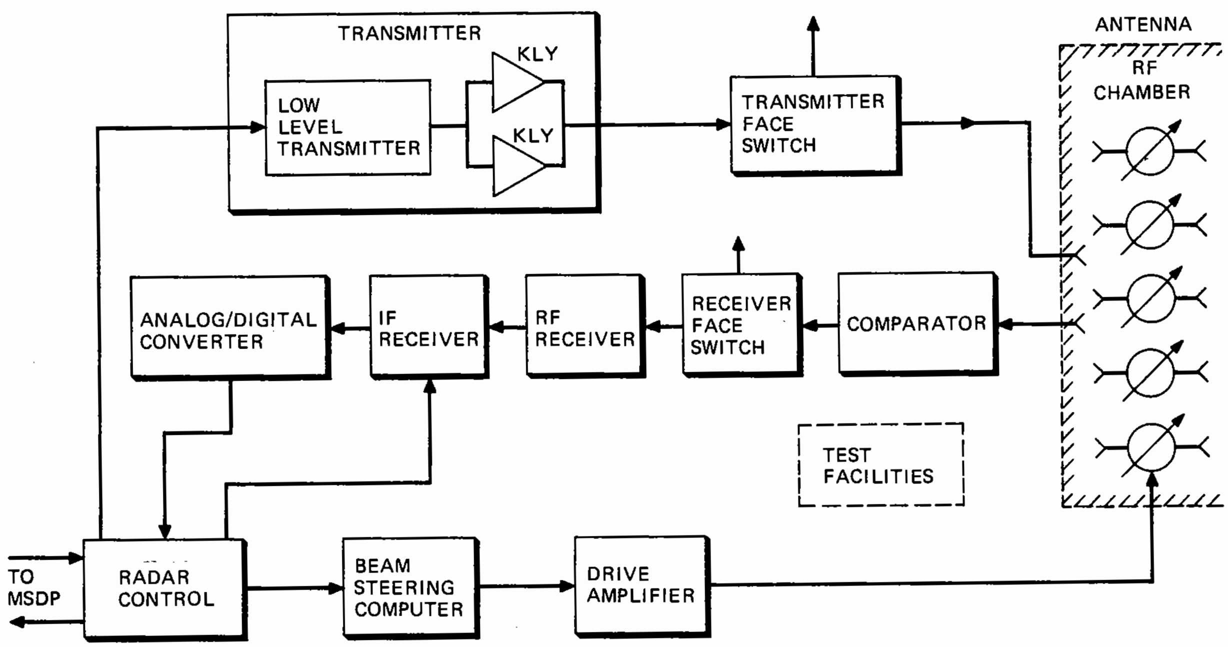


Figure 7-6. MSR Functional Block Diagram

off-line condition, tested for proper operation, and then added in parallel to the transmitting on-line tube.

The 5000 antenna elements in each face are replaced from the outside of the building using an antenna service vehicle designed for this purpose.[12] Very high reliability diodes are used in the phase shifters. This, plus the redundancy inherent in the large number of array elements, results in the need for infrequent maintenance of the arrays. Faulty antenna elements are not changed until a sufficient number have accumulated in each face to warrant removing the system from service and replacing the elements.[13] The replacement operation is quite simple and requires about 2 minutes per antenna element.

A single transmitter supplies power for all four faces by using a high-power face switching network consisting of three high-power waveguide ferrite switches. The switches allow the transmitter energy to be shifted from one face to another in a fraction of a second. (The receiver can be switched from face-to-face considerably faster.) Similarly, to allow maximum use of the large number of track resources that are available for a typical engagement, the antenna beam can be switched in a few microseconds from one position to a newly calculated position.

The MSR provides a variety of radar signals with varying parameters to accomplish the search and tracking functions.[6] Chirp and non-chirp pulses can be transmitted over a wide bandwidth by computer frequency selection. Frequency agility simplifies the separation of the large variety of acquisition and tracking functions, including the frequencies dedicated for communications to SPRINT and SPARTAN missiles.

Operation of the MSR is controlled by the MSDP through the radar control interface.

ANTENNA DESIGN

The antenna subsystem of the tactical MSR provides hemispherical coverage with four 5000-element phased arrays. A single-element Q-channel, located adjacent to each array, rejects signals received on the array sidelobes.[14-16] The MSR arrays are space-fed rather than corporate-fed; each array uses a separate transmit and receive feedhorn located at its focal point. Corporate-feed (as used in MAR) was rejected primarily due to its mechanical complexities in the dimensions inherent in a phased-array antenna at S-band.

Each array element consists of a rear horn, diode phase shifter, and front radiating element containing a beryllia window. As shown in Figure 7-7, the phase shifter and front element can easily be removed from the front of the array for replacement and repair. Development and manufacturing controls of the array components have produced a failure rate of less than 2 antenna elements per day and a PIN diode rate of less than 100 fits (100 failures in 10^9 component-hours).[17] The phase shifter consists of PIN diodes appropriately spaced in a coaxial RF structure to provide the required 4 bits of phase shift in sixteen 22.5-degree segments. The prototype system was designed with 30 diodes[18,19] per phase shifter. The development program[20,21] successfully reduced the number of diodes to 16 for tactical antenna elements.

The Beam Steering Computer (BSC) of the radar control equipment computes the orders for each bit in each of the 5000 phase shifters per array. These orders are processed by drive-amplifier cards, which generate the forward and reverse bias for the phase shifter diodes.

For a space-fed array to be practical, a simple method must be used to test each element in place. To avoid an RF cable connection to each element, a system using the BSC was devised.[22] The antenna is pointed at the test pole, which radiates an RF signal. To test an element, its bits are individually modulated at a 10-kilohertz rate by the BSC. The phase modulated signal from the element under test and the unmodulated signals from all the remaining elements add in the receiving feedhorn and are amplified by the

MSR receiver in the normal way. A sample of the receiver IF signal is fed to an antenna test set, which recovers the 10-kilohertz phase modulation and compares its phase with that of the original BSC 10-kilohertz signal. By proper control of each bit, an actual phase measurement can be made. Six phase measurements are made on each element to test the four bits of each phase shifter.

Measurement of antenna elements, like other test capabilities provided in the MSR, is interleaved with the normal surveillance functions under software control. The antenna element test software computes the value of each bit from the six phase measurements of the element and compares the value against acceptance limits. If out-of-limit, the test is rerun at another frequency; if still out-of-limit, the element number and bit values are "printed out" for use in fault location and repair. The antenna element test software can measure ten elements per second. Measurement of the 5000 elements of one array face typically requires about 20-minutes elapsed time. This antenna element test can be run at any time and is initiated manually. The test is automatically terminated if the system is required for potential battle engagement.

The area behind each array and its feedhorn assembly is enclosed in an RF chamber for personnel protection. The Meck prototype chambers included an RF absorber, which provided very low sidelobe levels. Studies of the clutter levels predicted for the tactical MSR site indicated that under the expected conditions, a higher sidelobe level could be tolerated. As a result, the RF absorber was eliminated from the tactical design. However, provision was made for mounting a high-power absorber material around the periphery of the arrays to improve the far-out sidelobe level by about 6 dB, should it become necessary.[23,24] Figure 7-8 shows the interior of one of the Grand Forks RF chambers.

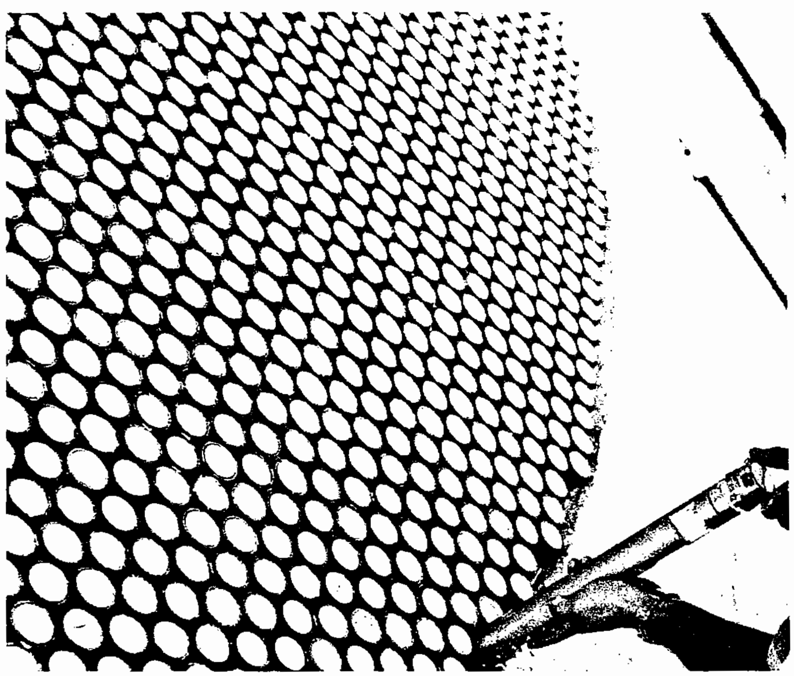
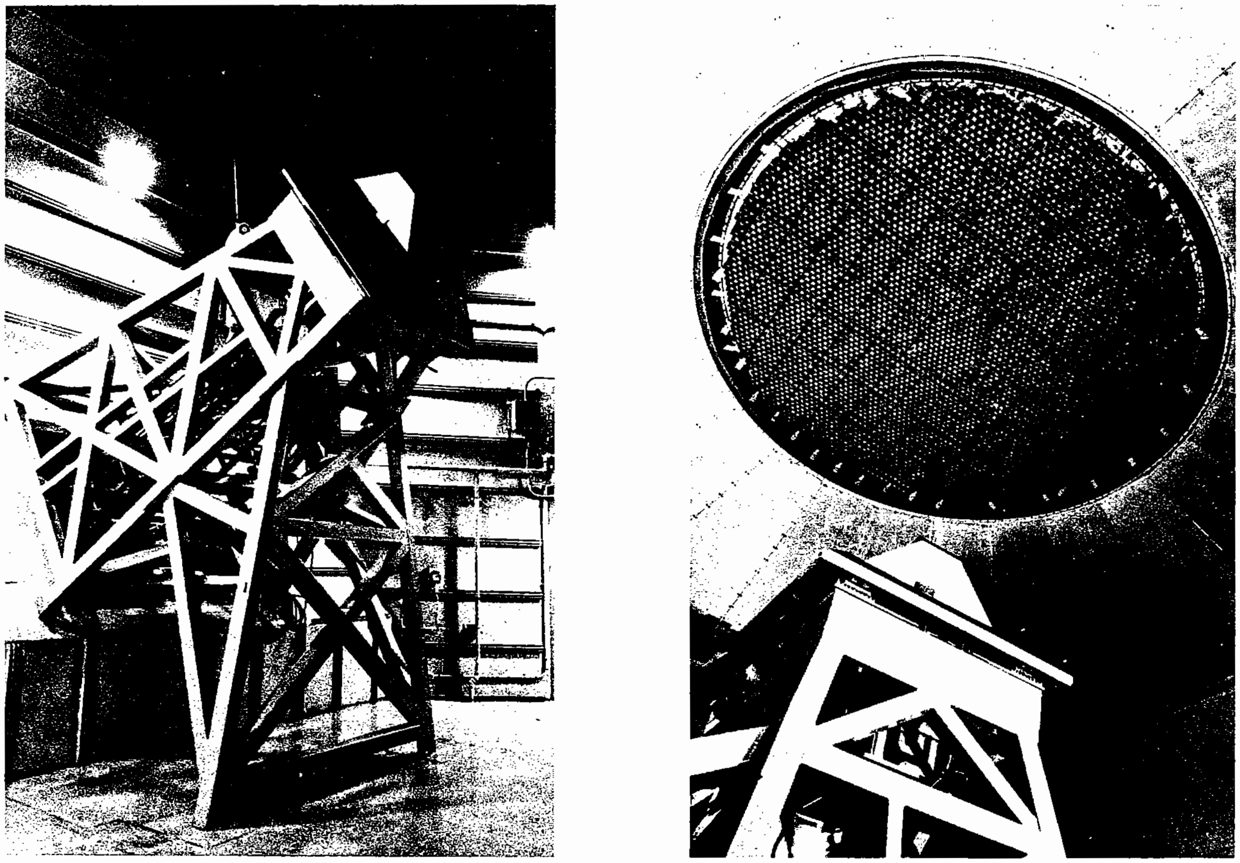


Figure 7-7. MSR Array Element Installation



A. MSR Feedhorn and Chamber *B. MSR Feedhorn and Array*

Figure 7-8. MSR RF Chambers

Techniques, such as mechanical and optical array surveys, accurate location of the receive feedhorn on the array normal axis, and use of satellite tracks for final correction, have been developed to accurately "boresight" each array.[25,26] Motion sensors are mounted in the antenna turret to detect any long-term structure motion and derive correction factors to the stored software constants pertaining to array orientation.

RECEIVER DESIGN[6]

The basic concept of the MSR receiver and signal processing stemmed from earlier work done in connection with the NIKE-ZEUS Target Track Radar (TTR) and Discrimination Radar (DR). In many areas, the MSR receiver design was a modification or refinement of the earlier designs. For example, the cooled parametric amplifier uses a closed-cycle helium refrigerator based on an Arthur D. Little design for cooling the ZEUS TTR maser. The 30-megahertz IF limiters and logarithmic amplifiers were based on similar designs in the ZEUS DR. Some of the 30-megahertz IF amplifier module designs in the MSR were unchanged from those in the ZEUS DR.

The MSR receiver consists of two functional groups: RF and IF. The RF portion receives three signals [sum (Σ) channel plus two difference channels] from the antenna comparator. These signals are amplified by a multichannel cooled parametric amplifier and double-converted to the 30-megahertz intermediate frequency. A fourth channel, the Q channel, is also implemented in the RF and IF receivers to provide antenna sidelobe blanking.[15] Automatic gain control functions are also included in the RF and IF receivers to ensure that the received signal is always within the overall receiver dynamic range.[27,28]

The IF portion continues the four-channel processing of the 30-megahertz signals delivered by the RF receiver. Figure 7-9 shows the IF receiver area. The first portion of the IF group employs the matched-filter concept of signal processing. High-speed electronic switches pass the various waveforms through signal paths that have an optimum response to each waveform. Significant variations of gain and delay (due to the different matched filters) are normalized by including appropriate attenuators and delay sections in each matched filter. Residual relative gain and phase changes [due to changes in operating frequency, Automatic Gain Control (AGC) level, etc.] are automatically compensated with binary controlled amplifiers and phase shifters.[28] After the matched filters, the signals are passed through logarithmic amplifiers, dechirp networks, and equalizers to conventional video signal processors to extract target data. Analog-to-Digital (A/D) conversion is applied to the signals for transfer to the radar control digital circuitry.

Complete MSR redundancy is utilized in the RF and IF receivers to maintain operational capability in the presence of any possible fault environment. Faults in the RF portion of the receiver are detected by amplitude monitoring at the inputs of the IF portion of the receiver. These monitors respond to test pulse signal inputs to the active and redundant channels through directional couplers, which precede the TR tube receiver protectors. The test pulses are gated into the receiver from the RF test set by computer control. Improper amplitude values and other faults will initiate redundancy switching. Other characteristics are displayed on control-monitor panels to allow manual control and to aid in fault isolation and calibration.

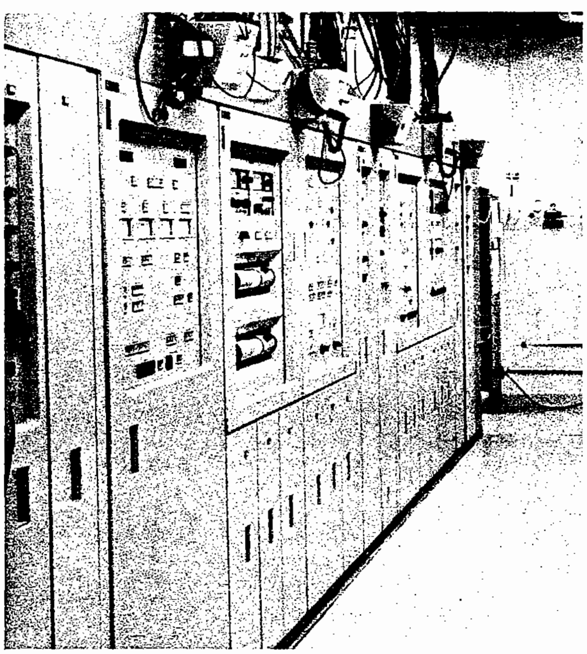
Figure 7-9 IF Receiver

The IF portion includes monitors that respond to these test pulses. The response of the receiver to these test signals is used to determine the IF channel status. Failure in the on-line receiver initiates redundancy switching, after which, off-line maintenance is performed on the faulty equipment, restoring it to normal operation.

TRANSMITTER DESIGN

The MSR transmitter achieves its high power output from two parallel high-power klystrons. The combined output from these tubes is supplied to the space-feed system of the antenna via a microwave waveguide system. A space-feed system powered from a single transmitter source can provide more transmitted power at a lower tube cost than a corporate-feed array using multiple amplifying tubes. Other advantages include fewer total components and the potential of higher reliability.

Four stages comprise the entire transmitter: exciter, buffer, driver, and final. The exciter and buffer are known as the Low Level Transmitter (LLT);[29] the driver and final stages are known as the High Level Transmitter (HLT). The solid state exciter generates the required transmitter frequencies for the HLT, as well as all local oscillator frequencies needed by the receiver. The buffer is a Traveling Wave Tube (TWT), which drives the HLT and also provides the required RF test signals. The LLT is completely under the control of the radar control equipment, changing frequency under computer command.[30] The various waveforms are generated in the IF receiver at 30 megahertz and fed to the LLT for frequency up-conversion to RF. Output power and other monitors are provided in the LLT to initiate an LLT redundancy switch when a failure occurs. The LLT equipment is physically located with the receiver equipment. Figure 7-10 shows the LLT on the left and Radar Monitor and Test Consoles



A. Low Level Transmitter

B. Radar Monitor and Test Consoles

Figure 7-10. MSR Low Level Transmitter and Consoles on the right. The LLT output is fed by waveguide to the driver stages in the transmitter control room.

The HLT occupies six rooms, comprising a major portion of the equipment space in an MSR building. Two locked rooms contain the high-voltage power supplies. The driver and control equipment occupy a room in which all HLT operation is controlled and monitored. A specially designed room houses the two klystrons mounted in large oil tanks. The remaining area contains the extensive ancillary support equipment for the transmitter, including units involved in the purification, filtering, circulation, and heat exchanging of the high purity water, dielectric oil, and dielectric gas used by the transmitter.

A matrix of waveguide switches and dummy loads provides the redundancy switching capability of the driver stages. Either driver stage can be connected at its input to the LLT output or to the output of built-in test equipment used for alignment and trouble location. The output of either driver stage can be connected to a dummy load or to the final-stage klystron input. Switching is controlled either automatically by built-in fault monitors or manually for test purposes. A specially designed waveguide switch provides millisecond switching times. Fault monitors in each driver stage detect low power output, TWT arcing, low coolant flow, etc. The driver high voltage cabinet is equipped with interlocks for personnel protection. A crowbar, using a vacuum spark gap, fires in case of TWT arcing, interlock operation, or other faults requiring rapid removal of high voltage. Opening the cabinet door operates the mechanical shorting bars to ground high voltage connections.

The 35-kilovolt power supply for each driver occupies a corner of the nearest high-voltage power supply room. These solid state, regulated power supplies are fed by 480-volt three-phase power supplies through conventional switch gear adjacent to the high voltage rooms. Control cabinets adjacent to the driver cabinets operate the driver stages as well as each final amplifier. The built-in test equipment located here includes the RF signal generator, RF power meter, attenuators, etc. needed to align the transmitter and locate faults, as well as power distribution circuit breakers and control switches for all equipment. All logic required for fault indication, crowbar initiation, and system control is in a single cabinet.

Each high power channel includes a Varian Associates VA-144 klystron developed for MSR use. This tube has a wide bandwidth high peak power output, and a high duty cycle and resulting average power output capability. Power varies no more than ±0.7 dB across the band. The tube operates with a 150-kilovolts beam voltage, A modulating anode controls the beam pulse. Physically, the VA-144 is about 8 feet high.[31,32]

As mentioned previously, the klystron is mounted in a tank containing 3500 gallons of high dielectric-strength transformer oil. Two identical tanks are mounted in the klystron room as shown in Figure 7-11. The shock-mounted construction protects the final amplifier equipment from damage in a nuclear battle environment.

All components needed to pulse the modulating anode are immersed in the oil tank. The low level modulators, in cabinets adjacent to each tank, couple to the immersed equipment through a pulse transformer, which provides high voltage isolation between the external equipment at ground potential and the equipment in the tank at -150 kilovolts. The floating-deck modulator uses two Litton L5033 switch tubes, one on the off-deck and one on the on-deck, that are cooled by circulating the tank oil.

The final amplifier room also contains 14 power supplies, seven of which supply focus solenoid current to each klystron. A lead shield weighing about 2-1/2 tons encloses each klystron to protect personnel from X-ray radiation. The room is a high bay area equipped with a crane to handle the lead shield and klystron when tube changes are made. The crane also is used when the modulator on-deck or off-deck needs maintenance or replacement.

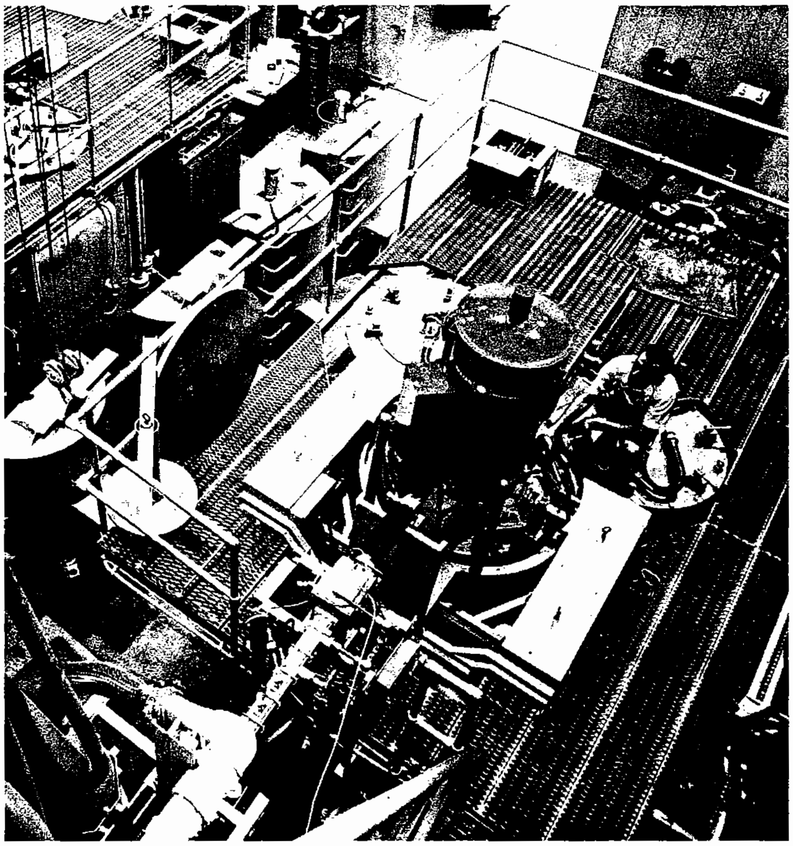


Figure 7-11. Klystron Room

Each klystron output connects through a high power waveguide to a high-power ferrite circulator and then to a high-power waveguide switch matrix to permit control of the output RF power from each klystron. These outputs can be combined and fed to the antenna, the normal condition, or into parallel high-power dummy loads. If a single channel malfunction occurs, the combining hybrid is automatically switched out and the remaining channel is connected directly to the antenna. For test purposes, the matrix can be manually controlled to connect any channel to either its own dummy load or the antenna, or to connect the combined output into either a dummy load or the antenna.

The mechanical waveguide switch used to handle the transmitter full power output is of special design. It is water cooled and operates in less than 100 milliseconds. The high power waveguide also is water cooled. Extensive investigation took place in the laboratory, using a high power resonant ring structure,[33] to determine the mechanism of waveguide RF breakdown, which occurred in the Meck prototype system at high average power levels. In many cases, breakdown occurred at the high power waveguide flange joints. These had been designed for the high RF currents involved but proper assembly was not always achieved. Providing suitable assembly tools and minor changes in flange design resolved this. However, arcing still occurred at random locations in the waveguide. It was noted that the power level at which unstable arcs occurred in the resonant ring was a function of the physical length of the ring. From these data, it was deduced that the RF pulse duration after an arc forms was the controlling factor. Analytical work showed that, at the long pulse length and high average power levels of the MSR, a random arc would cause the copper waveguide wall to melt.[33] This melting created copper particulate matter, which would be heated by the high average power resulting in more RF breakdown and continuous arcing. The system remedy was to shut off the RF pulse as quickly as possible after an arc formed, preventing the generation of more particulate matter. This technique is known as "early-off."

The early-off circuits also protect the transmitter feed horn window.[34] Air circulates on one side of the window to minimize the deposit of dust particles, which could cause an arc. The early-off operation prevents damage to the ceramic window when an arc does occur. With this addition to the transmitter arc detection logic, stable operation at maximum average power and pulse length was readily achieved.

In the event of particles either in the waveguide or on the transmit feed window, the early-off allows the particles to be vaporized by the arc without creating additional particles. The effect of early-off on the system is similar to that of a missing pulse. As missing pulses regularly occur from target scintillation, etc., early-off has no effect on system performance since the software is designed to bridge gaps in data input.

A bank of three single-pole, double-throw high power RF "face" switches is used to connect the combined output of the final amplifier stage to one of the four antenna faces. One of these face switches is shown in Figure 7-12. These switches are controlled through the radar control equipment and consist of four parallel sets of ferrite phase shifters. These are fed by splitting hybrids that send one-fourth of the power to each set of phase shifters. The outputs are recombined through short slot couplers, which direct the energy to one of two outputs depending on the input phase. Each phase shifter is switched by a suitable modulator connected to its magnet coil. The switch has minimum loss and all microwave parts are water cooled.

Each klystron channel is supplied with the required high voltage from a power supply in an adjacent room. This power supply is completely solid state and uses a three-phase full-wave diode rectifier. It is regulated to within 3 percent by silicon controlled rectifiers in the 4160-volt ac supply line. A total of 250,000 coulombs of energy is stored in the capacitor bank to supply power during the klystron beam pulse.

Elaborate safety precautions are used. A Kirk key system protects personnel against exposure to high voltage components, X-ray radiation, and RF radiation. Fault monitors protect the equipment against klystron arcing, waveguide arcing, low coolant flow, high coolant temperature, out-of-limit solenoid current, etc.

Experience with transmitter operation at the Meck test site indicates all reliability objectives have been met. Tube life data available to the end of 1974 indicate the design objective of 20,000-hours mean life will be achieved for the driver TWT and final amplifier klystron.

After the tactical site transmitter had been in operation about six months, the pressure drop in the VA-144 klystron collector cooling channels increased from a normal 130 psi to as much as 180 psi. This phenomenon had never occurred during the operation at Meck. For seven months, an intensive investigation was conducted.[35] During this interval, site operation was maintained by periodically flushing the collectors with citric acid, which removed the copper oxide deposits and generally restored the pressure drop to near normal. Flushing was needed at intervals varying from a few days to two weeks.

Extensive analysis established that considerable particulate matter existed in the cooling water, although the particles were very small. A set of 0.45-micron absolute filters was installed in the collector cooling line at each klystron tank. These substantially reduced the particulate matter but did not correct the problem.

Small quantities of bacteria were also detected. To prevent possible growth in the collectors, a sterilizing lamp was added to the water purification unit. This also did not change the phenomenon.

Chemical analysis of Grand Forks' high purity water versus samples from Varian, Meck, and the high power test station at Raytheon's Spencer Laboratory (Burlington, Massachusetts) showed no essential differences. Impurities were at extremely low levels (in parts per million). However, only the Grand Forks water showed small traces of sulfides. As these were known to increase copper oxide formation rates, considerable attention was given to a remedy. Sulfide removal was attempted by the temporary use of copper pellet scavengers and sulfide removal resins but had no effect on the pressure increase. An investigation of copper oxide corrosion rate versus sulfide and oxygen concentration showed no significant rates at the concentrations detected at Grand Forks.

Finally, it was possible to disassemble one klystron's collector, which had exhibited the pressure drop change at Grand Forks. This showed a roughening of the copper oxide in the

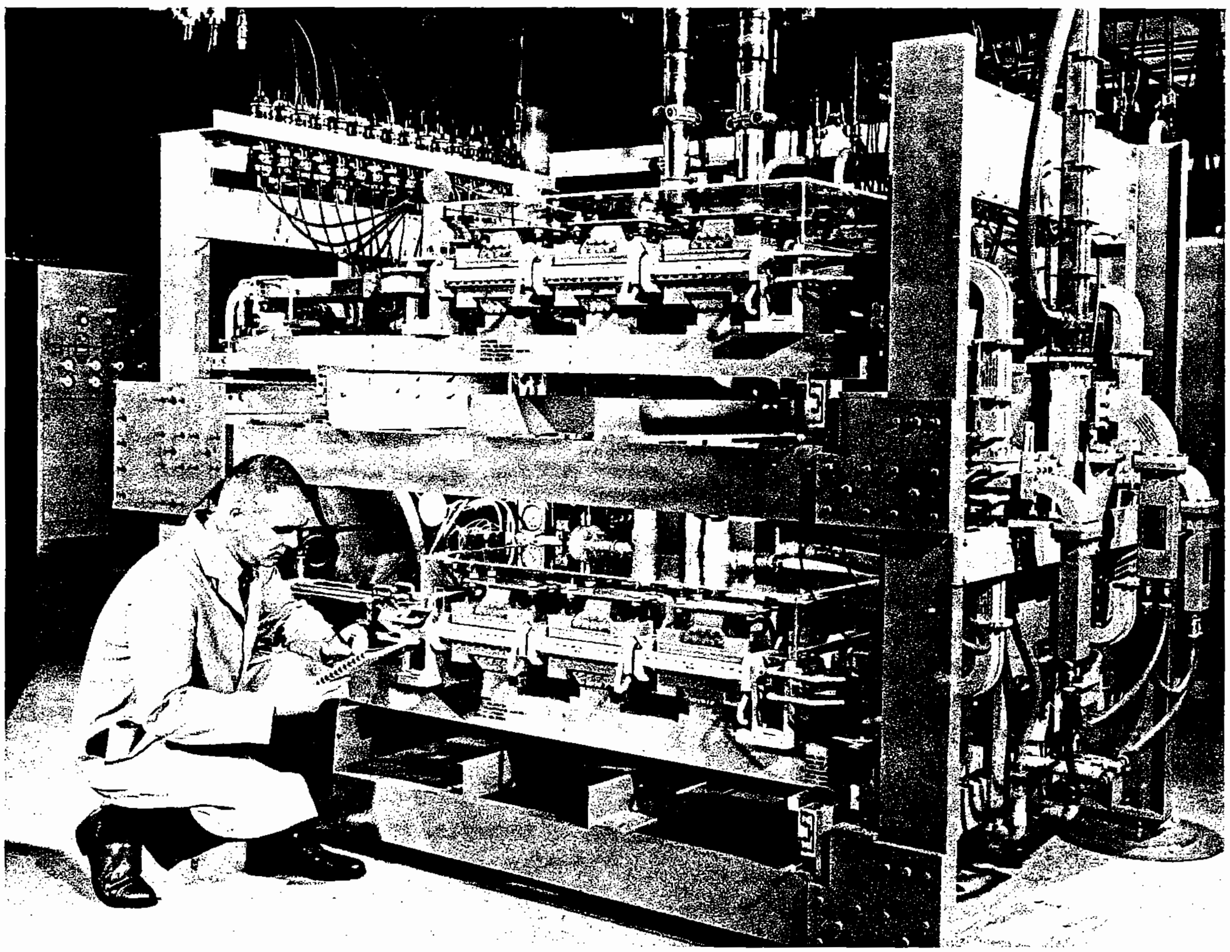


Figure 7-12. Single-Pole, Double-Throw High-Power RF "Face" Switch

conical region. Earlier calculations had shown that such roughening could cause the pressure drop increase. Analysis of the oxide on the Grand Forks collector and on a collector that had operated only at Meck showed no chemical differences. It was postulated that the oxide formed in the normal way but was roughened by hydraulic differences.

Tubes were subsequently flushed at Grand Forks using sulfuric acid to assure more complete removal of oxide. The static pressure on the collector was also increased by throttling on the return line. Since then, no further pressure drop increase has occurred. It is believed that at low pressure, incipient cavitation begins causing rough erosion. Once started, the roughening propagates, causing a pressure drop increase. At a higher static pressure, cavitation does not occur, precluding roughening of the oxide. Meck had always operated at the higher static pressure, hence the phenomenon was never seen there.

RADAR CONTROL DESIGN

The MSR is controlled by the Missile Site Data Processor (MSDP). The MSR Weapons Process (MW) software specifies the mode, frequency, antenna beam direction, transmitter power level, waveform, range gate width, minimum range, type of data needed, etc., for every transmission and every receiving interval.[30,36-41]

The function of the radar control equipment is to accept and store, until called, 68-bit words from the MSDP containing the desired action and the time it is to be taken. At the specified time, the words are decoded and the necessary control signals are generated and sent to the transmitter, receiver, and antenna. The receiver output is transformed from analog to digital signals and sent to the radar control equipment, where it is formatted with related information and stored to be transferred to the MSDP when requested.[8]

The radar control function is implemented by equipment called the Digital Control Group (DCG).[39] Like the receiver and the transmitter, the major portion of the DCG is redundant, with each portion called the Digital Control Unit (DCU). Besides the two DCUs, the DCG includes the Switch Rack and the Beam Steering Computer (BSC).[40] The Switch Rack monitors each DCU output and performs redundancy switching when a fault occurs.

The DCG uses standard SAFEGUARD logic and has eleven logic racks and eleven power supply racks. Some of the DCG logic racks are shown in Figure 7-13. Each DCU has three racks: input, output, and control. The BSC has two control racks and three register racks. The Switch Rack completes the complement.

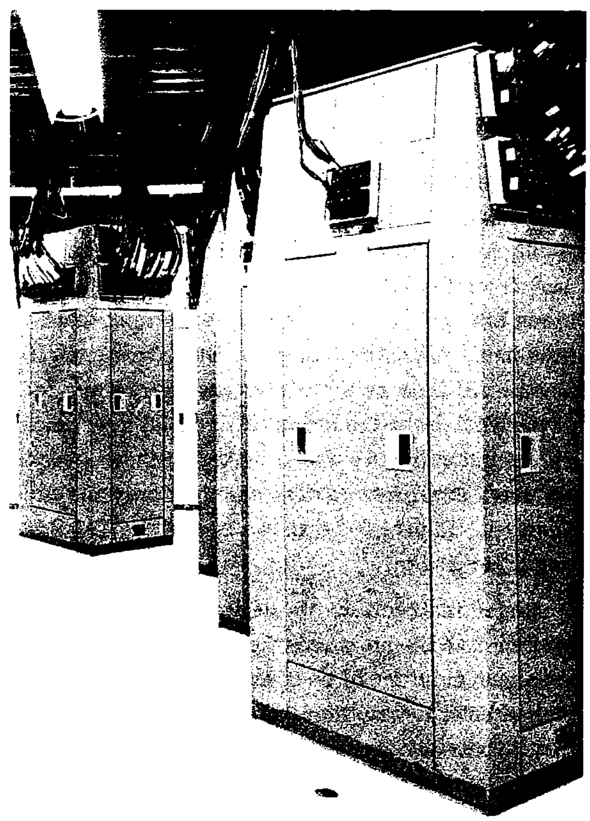


Figure 7-13. Digital Control Group Logic Racks

About 110,000 integrated circuit packages are used in the entire DCG.

To steer the antenna, the phase setting of each phase shifter must be calculated from the steering angle instructions. This is accomplished by the BSC,[40] which has two sets of registers; one holds the array in its last position while the second is being set for the next position. When the beam is to be repointed, the new phase shifter values are "jammed" from the second register to the first one. The beam steering calculation not only determines settings for the desired beam direction, but also corrects for the fact that the wavefront at the array face from the feedhorn is spherical. The constants for this correction are stored in a wired memory, which is part of the BSC. Calculation primarily involves incrementing a fixed phase shift from element to element. This is accomplished in functional logic blocks called accumulators. The element phase values therefore ripple through the registers as they are calculated. At jam time, all values are simultaneously transferred to the output registers.

The phase shifter diodes require 250-volts reverse bias or 150-milliamperes forward current. Each phase shifter has a drive amplifier to convert from the logic level of the registers to the diode bias level. In a four-face system, each face has a full complement of 5000 drive amplifiers. All four sets of drive amplifiers are fed in parallel from the output of the BSC. A face-select indication provided by the BSC fans out to all drive amplifier cards, enabling only the face desired. Figure 7-14 shows one of the 144 drive amplifier racks.

Radar instructions in the form of groups of four or five 68-bit words flow from the MSDP to the input memory of each DCU where they are stored until instruction time. The words are then subdivided by the input controller and fed to the various other controllers. Four controllers convert the digital information into pulses at the proper time to control analog parts of the MSR (i.e., the transmitter, IF receiver, video receiver, and test controllers). The BSC controller sends the instructions in digital form to the BSC for its calculations.

The set of output pulses from each DCU to the other portions of the MSR are continually compared in the Switch Rack. In case of a noncompare, software tests identify the faulty DCU. Redundancy switching takes place as needed.

The data output of the receiver is in digital form from the encoders. Because receiver data must be taken in real time as radar return signals occur, it is loaded into temporary storage (Receiver Data Buffer) for a brief time until it can be transferred in blocks to the output memory. The Output Memory Controller performs

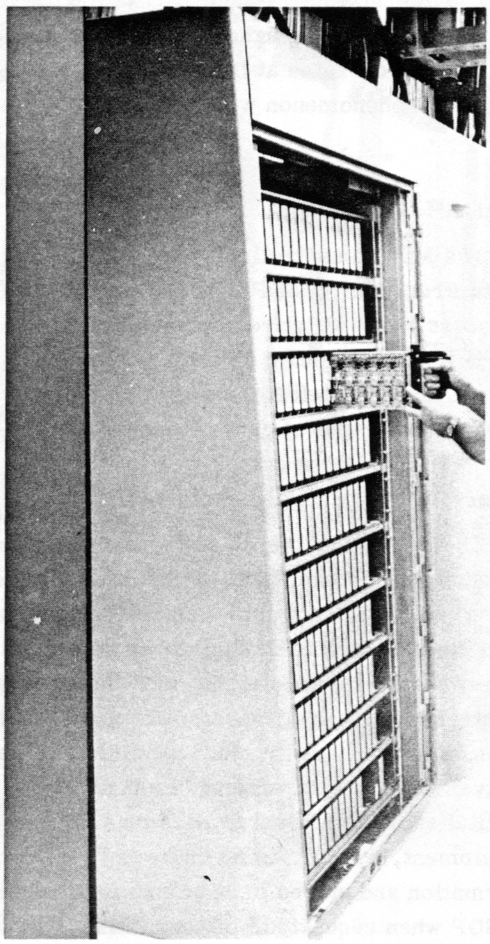


Figure 7-14. Drive Amplifier Racks

this transfer as well as transfer of data from the Output Memory to the MSDP when requested.

The DCG, therefore, is a wired logic decoder for input data and a formatter for output data. There are, of course, a number of important test capabilities. It has parity checking in critical places and also continuously monitors each DCU operation. In summary, the DCG provides the interface between the Data Processor and the analog parts of the radar. It is redundant and automatically switches when a fault occurs. It is maintained by test software via a control console provided for that purpose. This test software also provides monitoring and trouble location for the entire radar equipment.

DCG testing, overall MSR fault indication, and continuous performance checking are accomplished by test software included in the Weapons Process. This software is controlled from the Radar Monitor Console.[42] Three classes of tests are made: Class A, Class B, and Class C.[43,44]

Class A tests create test pulses, which run continuously under all system operating conditions. These cause the hardware monitoring equipment in the receiver to function. The entire signal path, from the Low Level Transmitter to the Receiver A/D encoders, is monitored. The High Level Transmitter is internally monitored exclusive of software. On failure of a Class A test, redundancy switching can occur or man is informed of the trouble. Man then can isolate the difficulty using Class B tests. These run interleaved with the Weapons Process and displace a small number of search channels of the radar template. In the event of a real or simulated engagement, the Class B tests are automatically terminated by software.

The Class B tests provide fault location in the DCG.[44] In most cases, they can isolate failures to within three logic chassis. The Class B tests also provide periodic testing of all antenna elements. The remaining Class B tests permit performance evaluation of the receiver and overall system. Sufficient flexibility is available to permit operator selection of test conditions where appropriate.

To prevent interruption of normal system operation, the flexibility of Class B tests has to be limited. The Class C tests allow complete flexibility under test conditions and perform function tests that can only be accomplished with the entire MSR out of service. Normal MSR operation can be rapidly reestablished from a Class C test condition, however.

COMPARISON OF PERFORMANCE OBJECTIVES AND RESULTS

The performance of both the prototype MSR installed at Meck[4] and the tactical MSR installed in North Dakota,[45] came very close to that specified in the work statement[2,46] prepared at the beginning of the development period. (See the Classified Supplement.) The development of each critical item — the antenna, transmitting klystron, low sidelobe chirp lines, and the like — produced components with performance that equaled or exceeded the specification. The antenna, since this was one of the first phased-array systems, was a distinct challenge. The thoroughness in testing the prototype antenna design ensured achieving the required MSR performance and provided sufficient detailed information to compare the theoretical performance of a phased array with the realized performance of an as-built array. This type of data can be utilized by designers of future arrays to evaluate the need for expensive antenna pattern measurements.[47]

The operation of the prototype system at Meck since mid-1968 has provided a wealth of information concerning the reliability of the radar. Accurate records on component failures have been kept since that time. Following the typical and expected high initial failure rates, the rate of failures in the entire complex quickly reached a level of less than one per day except for the high-usage drive amplifier and phase shifter diodes.[48] These items are replaced periodically after a sufficient number of failures have occurred to warrant change. The integrated diagnostic system has simplified locating and repairing each malfunction to a degree comparable with much smaller and simpler radars.

The system has demonstrated the ability to run continuously for long periods of time and shows no abnormal wearout in any section of the apparatus. The failure rate of the solid state components, such as transistors and high-power phase shifter diodes, is equal to or better than the design objectives.

The original design did not contemplate an Electromagnetic Pulse (EMP) requirement which subsequently evolved. All elements of the MSR were then designed to meet this requirement and, in many instances, were tested specifically to demonstrate this.[49,50] The results of the antenna hardening, particularly in the beryllia antenna element window, were most encouraging. See Chapter 6 for more information on hardening.

The tactical system in North Dakota afforded an opportunity to observe the installation of this massive amount of electronic equipment. The ease with which the apparatus was installed, wired, and tested confirmed an adequate tactical design. Of particular interest was the simplicity of installing the space-feed antenna systems compared to the usual complex and time consuming corporate transmission system network.

The beneficial capabilities of a phased-array antenna beam have been demonstrated during the prototype firings at Meck Island. The MSR provides data on a very large number of reentry objects over a large area, and the comparison to previous "dish" antenna radar systems is quite dramatic in this regard.

MAJOR CHALLENGES AND INNOVATIONS

One of the major challenges to the MSR system was the development of a space-feed antenna having sufficient beam agility, low loss at S-band, accurate tracking capability, and ease of installation and maintenance. The resulting design has met all of these objectives and has performed well in the very severe environmental requirements at Meck Island and North Dakota.

The very low far-out sidelobes were achieved without resorting to special fabrication techniques requiring high precision. The long life of the high-power phase shifter diodes was achieved after a lengthy development period. This was the first application for diodes in this power range. The performance of the transmit feedhorn window was achieved after a long period of design and testing. Its performance has been proven by both the Meck and North Dakota operations. The low failure rate of the antenna components and the very rapid antenna element checking system reduces the maintenance task on the phased-array antenna to a once-a-month or less often operation. The development of an antenna service vehicle simplifies even this maintenance task. The performance of the beryllia antenna element window both electrically and from the EMP standpoint was a significant achievement resulting from extensive development and testing.

The development of the high-power klystron transmitting tube probably represented as severe a challenge as any item in the entire radar. The very high average power output in S-band, as well as the wide frequency bandwidth, were objectives never before achieved. In fact, the S-band klystrons available at the beginning of the development period provided roughly an order of magnitude less average power output than the subsequent MSR klystron. This development has produced RF power at the S-band frequency at a lower cost per watt of power than that produced at any other frequency. In addition, the requirement of only two tubes produces a transmitter design of high reliability and low maintenance cost.

Utilizing the high power from the klystrons created problems with the power-handling capability of the S-band waveguide transmission system connecting the transmitter to the antenna. These problems required considerable development effort since average power levels of this magnitude had never before been attempted with

S-band waveguide and waveguide components. Final solutions were readily achieved and several years of operation, including operation of the installation in North Dakota, has verified their effectiveness.

The klystron collector cooling channel design was marginally able to cause cavitation-related erosion. This did not appear until the Grand Forks equipment was inadvertently operated at low static pressure.[35] When the roughness was completely removed by a sulfuric acid flush and high static pressure was maintained, no roughening occurred due to erosion. The high pressure apparently prevented the nitrogen entrained in the water from forming bubbles at low pressure points in the collector. Such bubbles led to the rough erosion.

Installation and test of the radar digital control equipment at TSCS permitted early detection and correction of design deficiencies. Tests with system software of increasing complexity turned up logic and timing problems of increasing subtlety. As the DCG is a wired logic computer, the solution of these problems required logic changes. It should be noted that logic design changes could be expeditiously implemented due to the highly automated design process used for SAFEGUARD digital equipment. Solving problems at TSCS resulted in required performance at Grand Forks, showing that reproducibility was easily achieved. However, as TSCS was a partial, nonredundant DCG with only a skeleton Beam Steering Computer, residual problems did occur during Grand Forks testing particularly where DCG redundancy was involved. These problems were corrected on site.

Of particular importance was achieving the availability and reliability objectives for the radar system. With the success of the entire engagement dependent entirely on a single radar complex, attaining these requirements was mandatory. Several years of operation in a firing program at Meck Island has established that the MSR with its redundancy can meet the very stringent availability and reliability requirements. Redundancy switching of receivers, transmitters, and radar control equipment has been demonstrated during engagements, including those with an interceptor missile in flight.

The requirement for very low-range sidelobes in the chirp system used in the MSR was important. The very small target size of the incoming reentry vehicle in relation to its surrounding objects mandated a solution to this problem. The delay lines resulting from the development program did meet these requirements and exhibited such excellent stability that performance could be obtained on a day-to-day basis over a long period.