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HIGH-RESOLUTION TELEMETRY SYSTEM FOR DIAGNOSTIC ROCKETS

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MASTER

Introduction. This paper is concerned with a description of a high-resolution rocket telemetry system developed by Sandia Laboratory for transmission to a ground station of scientific data obtained by sensors in the radiation environments produced by the recent Dominic high-altitude nuclear detonations. The reasons for making diagnostic measurements outside the earth's atmosphere are now a matter of public record.¹ For present purposes it is sufficient to state that radiation (x rays, gamma rays, and neutrons) produced by a nuclear explosion is absorbed in the earth's atmosphere. X rays create electrons in the D region at a height of 80 kilometers (50 miles), while gamma rays and neutrons are absorbed at a height of about 30 kilometers (20 miles). Although indirect diagnostic studies can be conducted from the ground by studies of the attenuation of electromagnetic radiation propagated through these ionized layers, obviously, more significant diagnostic measurements can be made with suitable radiation detectors deployed above the deposition regions.

The basic scientific principles for the production of a nuclear explosion are a matter of common knowledge.² In order to establish a background for bandwidth requirements, it is necessary to recognize that the time interval between successive generations of neutrons in a chain reaction is determined by the average time lapse between release of the neutron and its capture by a fissionable nucleus. This time depends on the energy of the neutron; in general, the interval is of the order of 10^{-8} sec. Therefore a telemetry system specifically designed for transmission of observations on the rate of generation of these neutrons should provide a rise time, then, of at least 10^{-8} sec. The corresponding bandwidth is 35 mc.

1. VELA JCAE Hearings, statement by Dr. Edward T. Pierce, SRI, before the Joint Committee on Atomic Energy, Washington, D. C., March 5-7, 1963.
2. Effects of Nuclear Weapons, S. Glasstone, Editor, DOD/AEC, June 1957, p 10.

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Spectacular effects of the Hardtack detonations on communications, presumably brought about by enhanced electron densities in the D layer, were observed after those events. Moreover, it has long been known that attenuation of a telemetry carrier propagated through ionized media varies inversely with the square of the carrier frequency.³ Therefore the use of high-frequency carriers for real-time telemetry is particularly advantageous. The choice of a microwave diagnostic telemetry system was based on an expected enhancement of the D layer and the high time resolution requirements noted previously. The system described in this report provided a 55-mc (3 db) bandwidth FM microwave telemetry channel (6 Gc). A usable telemetry link was maintained through radiation-induced ionized media over distances of the order of 10^5 meters.

Historical background. The Sandia high-resolution telemetry (HRT) system developed in an evolutionary manner to meet the increasing bandwidth requirements for full-scale nuclear tests. The first efforts to provide high-resolution time measurements used modified 200-megacycle telemetry components. Useful bandwidths on the order of five megacycles were realized. The first wide-band microwave (4 Gc) Sandia ground link telemetry systems, however, were operated experimentally in 1955 on Operation Teapot. Both reflex klystrons and voltage-tuned magnetrons were tested in experimental systems.⁴

The following year on Operation Redwing, diagnostic measurements were made routinely with a 4 Gc system which utilized quarter-watt reflex klystron transmitters, and with receivers which employed a developmental Bell Laboratories low-noise traveling-wave tube and Western Electric 416B cavity amplifiers. The receiver noise figure was approximately 8 db, and useful bandwidths of over 30 megacycles were obtained. The first use of HRT systems in rocket applications was during Operation Hardtack. A quarter-watt klystron and a voltage-tuned magnetron served as transmitters aboard a Redstone missile. Receiving stations used were similar to those used for surface operations; receiving antennas were prepositioned to receive signals during periods of interest in the missile trajectory. Because of limited transmitter power, the bandwidth was restricted to less than 20 megacycles.

3. c.f. E. C. Jordan, Electromagnetic Waves and Radiating Systems, Prentice Hall, Inc., New York, 1950, pp 656-688.

4. R. E. Glass, A Wide-Band Microwave Link for Telemetering, Microwave Journal, July 1960, pp 3-7.

After the development program reported here was determined, it was planned to use the highest practical carrier frequency. After consideration of both the potential performance of systems in various frequency bands which would employ the maximum transmitter power which could be packaged in the rocket payload and the receiver noise figures which were obtainable at these frequencies, it was concluded that the C-band presented the most promising system from the standpoint of availability of components and performance. It was also decided to use an independent channel for tracking purposes. This simplified the antenna system for the rocket and permitted use of available GMD-1B radio-theodolites for tracking. The GMD-1B was modified by adding a servo system to permit slaving the telemetry antenna which was mounted on an SCR-584 antenna pedestal.

Telemetry package. The HRT telemetry package and sensors were installed in the payload section of a Nike-Apache instrumentation rocket (see Fig. 1). Physical disposition of the major components of the telemetry package is shown in Fig. 2. Sensors were housed in the ogive section of the payload. The telemetry package proper contained a klystron oscillator, traveling-wave-tube amplifier (TWT), GMD beacon, timer control circuitry, power supplies, and battery. The output of the TWT was fed through a pressurized connector to a horn antenna mounted on the pressure bulkhead between the payload section and the motor. An explosive bolt arrangement provided in-flight separation of the payload and drive sections. The horn was mounted so that it radiated toward the receiving station after separation if the missile executed its planned trajectory.

Thermal design considerations affected the physical arrangement of the telemetry package. It was assumed that the total operational period of the telemetry package would be limited to about 15 minutes. Consequently, the thermal capacity of the telemetry package was sufficient to limit the internal temperature rise, and provisions were made only to provide good thermal paths from the points of highest dissipation to the body of the package. Approximately 200 watts were dissipated at the collector of the TWT, and special attention

was given to improving the efficiency of the thermal path between the collector and the heat sink. A special conducting grease, consisting of a silicone suspension of finely powdered aluminum, was developed to ensure a good thermal bond. The temperature rise of the TWT during a 15-minute period at full power output was limited to 100 degrees F. Finally, a fiberglass insulating sleeve provided thermal insulation from the high skin temperatures reached during the launch phase.

Outputs from the radiation sensors were fed to the oscillator, a Varian type VA-248 klystron. Modulation was obtained by superimposing the sensor output on the klystron repeller. This klystron has a nominal deviation sensitivity of 2 mc per volt, with a nominal "in-mode" (second) frequency deviation of 50 mc. The center frequencies (nominal 6000 mc) used were arbitrarily chosen. No provision was made in the klystron input circuitry to prevent the klystron from being driven out of mode in the event sensor outputs exceeded predicted values. The input impedance of the klystron circuit consisted of a 1-megohm resistance shunted by a 4- μ f interelectrode capacitance. Total stray wiring capacitance was 12 μ f. The driving impedance of the radiation sensor housed in the ogive section was sufficiently low (10 ohms) that the only limitation on rise time was imposed by the telemetry channel bandwidth. In the field the overall system rise time was limited to 10^{-8} sec.

The klystron output was fed through a wave guide to coaxial transistion and a variable attenuator to an Eitel-McCullough X-1020, periodically focused TWT. The amplified radio-frequency output (nominal 20 watts) was fed to a horn antenna. Typical specifications for these antennas (nominally 6 Gc) are a VSWR of 1.17, nominal 3-db beam widths in the E and H planes of 28 degrees, and a nominal gain of 15 db. Surrounding metallic surfaces were recessed from the horn in order to minimize perturbations of its radiation pattern after separation. During the preseparation period, horn radiation was absorbed by a 5/8-inch layer of RF absorbent attached to the head cap of the second stage. The absorbent terminated the horn in its characteristic impedance and prevented reflections which would damage the TWT.

As mentioned above, physical configuration of the integrated test vehicle prevented ground station prelaunch monitoring of EM radiation from the horn. In order to circumvent this difficulty, an E-polarized quarter-wave probe was inserted between the horn and absorber. The RF signal induced in this probe was fed through the skin by a short length of coaxial cable to a quarter-wave stub antenna normal to the axis of the vehicle.

Internal power for the transmitter was provided by a 28-volt battery fabricated from silver-zinc cells. Klystron power was supplied by a solid state DC-to-DC converter which provided regulated beam, repeller, and filament voltages. The TWT power supply (3 kv at 70 ma and 6.3 volts at 590 ma) was also a special DC-to-DC converter.

The telemetry package included a continuous-wave radio-frequency signal source for use in conjunction with the GMD-1B radio theodolite tracking unit. The transmitter was a nominal 1680-mc, grounded-grid, tuned-plate, tuned-cathode, single-stage oscillator. A solid state converter provided plate and filament power. Output of the oscillator was fed to two quarter-wave stub antennas spaced 180 degrees apart and inclined 45 degrees to the test vehicle longitudinal axis. The 3-db antenna beam width was roughly 80 degrees and the gain was about 2 db. Radiation was directed primarily along the axis of the vehicle.

Ground station system. The HRT ground station system was placed behind protective barriers situated about 800 feet from the HRT rocket launchers (see Fig. 1). The receiving complex provided tracking, receiving, and data-recording facilities for monitoring several rocket flights. Each receiving station consisted of a GMD tracking unit and a "stripped-down" SCR-584 van containing the telemetry receiving antenna, associated antenna drive circuitry, a receiver, and data-recording equipment. A small trailer served as a maintenance shop for both stations. This trailer also contained an FM tape recorder to record low-frequency signal components.

A detailed description of the AN-GMD-1B radio theodolite is given in the Rawinset manual.⁵ For tracking purposes, the meteorological data-processing

5. "RAWINSET AN/GMD-1A", TM 11-271A, DOD, August 1954.

equipment was removed and the GMD tracking antennas were slaved through a servo link to the mechanical drive systems of the HRT receiving antennas. In practice, the GMD antennas were manually prepositioned at the rocket launch azimuth and elevation. Automatic tracking modes were activated as the GMD units detected beacon radiation from their respective rockets. The design autotrack acquisition angle was ± 6 degrees, with a tracking error of ± 0.05 degree rms for elevations greater than 12 degrees. The over-all system tracking error was estimated to be less than 0.5 degree rms.

Figure 3 is a block diagram of the HRT receiving and data recording station. The diagram shows the processing of a signal from its reception at the antenna through a succession of low-noise amplifiers and attenuators to a balanced discriminator where it is demodulated and fed to an array of oscilloscopes. Successive stages of amplification and attenuation were used to obtain limiting action. For unity power output, the dynamic range of the system was approximately 50 db. The receiving system gain was roughly 160 db, with a noise figure of 5.2 db. The system bandwidth was 50 mc.

With the exception of the input stage, traveling-wave tubes were used for amplification. The input preamplifier was a specially designed Texas Instruments parametric amplifier having a nominal noise figure of 3 db at 20-db gain. The receiving antenna was an 8-foot parabolic dish with the following nominal characteristics at 6000 mc: gain, 41 db; beamwidth (3 db), 1.5 degrees; VSWR, 1.2; polarization, circular.

The demodulated output of the discriminator was displayed on three oscilloscopes, each equipped with a double-mount camera bezel. Fixed film Polaroid and 35-mm moving strip-film cameras were used for recording. The strip-film recording rate was 20 feet per second; total run time was 5 seconds. All cameras were actuated manually from the voice countdown. The same basic recording scheme was used for radio-frequency signal-strength measurements. The output of the second-stage amplifier was fed through a single-ended, crystal detector to a fourth oscilloscope.

In addition, the outputs of the two detectors, together with 1-msec time marks, WWVH time signals, and GMD signal-strength measurements, were recorded on both magnetic tape and paper.

System evaluation. The inherent resolution of the system, excluding the sensor, was determined to be within the 10-nsec design specification. Resolution measurements were made through the ground station by applying a 100-nsec pulse from a Spencer-Kennedy Model #503 fast-rise pulse generator to the klystron of the rocket package.

Each unit was statically and dynamically calibrated through the complete system. Static calibrations were made by varying dc repeller bias and recording discriminator voltage output. Dynamic calibrations were made by varying the amplitude of the pulse from the Spencer-Kennedy fast-rise pulse generator. Reproducibility of the absolute bench calibrations was generally within 20 percent for a saturated receiver input.

In addition to the calibration checks which were run on each unit, additional evaluation studies were conducted on representative packages. Since the HRT package differed significantly, both mechanically and electrically, from payloads previously flown, an extensive preflight evaluation test study of the package was made. These tests were primarily environmental: namely, mechanical and radiation. The mechanical tests consisted of acceleration and vibration studies of the whole package in addition to special tests on individual components. In making radiation vulnerability studies of the package, the Sandia Pulsed Reactor Facility (SPRF) and flash x-ray facility were used.

No mechanical defects were noted in an acceleration test in which the payload was spun on a centrifuge. In this test the horn antenna was subjected to a 50-g acceleration for 3 minutes. Components forward of the horn experienced a smaller acceleration, but no component was subjected to an acceleration of less than 40 g's. Additional mechanical tests included subjecting the unit to a 5-g load varying from 20 cps to 2 kc to 20 cps over a 14-minute period. These tests revealed no major defects. Minor defects were easily rectified.

Vulnerability of the telemetry package to radiation was a subject of grave concern. Therefore the SPRF source was used in conducting free-field radiation tests. In order to simulate operational conditions, both a representative telemetry package and the reactor were tower-supported (see Fig. 4). Distances between the package and the reactor were selected to produce neutron-flux densities at the package of the order of 10^{10} neutrons (above 0.2 Mev)/cm²/burst. (Neutron-sensitive film badges sheathed in lead were used for dosimetry.) A "stripped-down" version of the basic HRT ground telemetry receiving station was located roughly 1800 feet from the reactor. Although these tests indicated that the unloaded telemetry package (i.e., basic package less sensor) was markedly sensitive to a radiation environment, modifications in the klystron repeller bias circuitry, including insertion of a load simulating the radiation sensor source impedance, reduced the peak transient frequency deviation resulting from SPRF irradiation to an insignificant level.

After sensitivity of the basic telemetry package to SPRF irradiation had been established, further tests were conducted in which the 200-kv flash x-ray facility was utilized. The object of these tests was to determine susceptibility of the package to very short-duration transient radiation. In this test, the output of the TWT transmitter was fed directly through an attenuator to a balanced discriminator. Representative sections of the telemetry package were exposed directly to a 2×10^5 r burst. Results indicated that radiation-induced transients were reduced significantly by the modifications described previously.

At the conclusion of the radiation environmental studies, the telemetry package was rechecked. No permanent damage to any component was detected. The telemetry package was operated on internal battery only. Prior to each exposure the unit was activated 3 minutes before burst time. Telemetry EM radiation was detectable, with no apparent change in radiated power level, from 2 minutes before to 2 minutes after burst time. After twenty-four consecutive operations (without detectable malfunction) the particular package under test accumulated a sufficient dose to constitute a radiation hazard. The same unit, however, eventually was used successfully in a field operation.

System performance and conclusions. Prior to each operation the payloads were assembled, checked out, and calibrated. After assembly to the rocket motors on the launcher, they were again checked out by means of an internal calibrate pulse. The RF probe coupled to the horn antenna provided sufficient signal to the receiver for calibration.

The telemetry systems were turned on by signals through the umbilical cable. Calibrate signals were received and recorded prior to launch. The receiving antennas were then prepositioned to the launch angle and calibrate pulses again were received at payload separation. The calibrate pulses were turned off prior to burst time by an internal timer used also to separate the payload from the booster. The calibrate off command was interlocked with the sensor windscreen to confirm explosive separation of this unit in some instances. A total of ten payloads was launched (see Fig. 5). The telemetry transmitters operated satisfactorily on seven of these. Of the three failures, two were caused by mechanical failures of the rocket system and one by probable mechanical failure.

An additional problem developed in the form of "roll coupling" which caused the payloads to precess. The precession caused amplitude modulation of the received signal by the transmitter antenna pattern. This resulted in loss of data in one case.

In conclusion, it can be stated that the feasibility of conducting high-resolution diagnostic measurements from a rocket in a space environment through ionized media was demonstrated conclusively under actual flight conditions. Useful data were telemetered and recorded.

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Fig. 1 HRT Nike-Apache diagnostic rocket on launcher.

Fig. 2 Major components of telemetry package.

Fig. 3 HRT receiving station block diagram.

Fig. 4 HRT telemetry package and SPRF arrangement
for radiation environmental studies.

Fig. 5 Nike-Apache night launch.