The Command System Malfunction of the *Telstar* Satellite

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Loss of the command function of the Telstar satellite first occurred on November 24, 1962. There had been earlier indications of degraded performance. Facts are presented which led to the conclusion that the malfunction of the command system was due to surface damage to certain transistors in the redundant command decoders by the enhanced radiation in the inner Van Allen belt.

Correction steps have included laboratory experiments to gain a better understanding of the cause of failure, the use of continuous normal commands, commands transmitted from Johannesburg, South Africa, and specially modified commands to circumvent failure of the more vulnerable transistors. The operations which aided in the gradual rejuvenation of both command decoders are described. Also covered are the subsequent reappearance of the command system malfunction on February 21, 1963, and its correlation with the variation of the average radiation intensity seen by the satellite.

I. INTRODUCTION

After more than four months of successful performance, difficulties were experienced with the Telstar satellite command system. Early in the week of November 18, 1962, the command system became sluggish — the satellite responded only after a long string of continuous commands had been sent. Normally, a command is carried out as soon as it is received. On November 24, after five days of increasingly sluggish performance, the command system failed to respond.

There had been signs of deterioration earlier, which, however, did not affect command system performance. On August 7, about one month after launch, there was an indication that one of the redundant command decoders may have been operating intermittently. By August 21, failure of one decoder appeared to be complete. However, intermittent operation of that decoder was again possible for a three-day period during October.

A program was initiated to determine the cause of failure and the action to be taken to recover the command function. Several steps were taken as a result of this study and, on December 20, through the use of modified command pulses, certain commands were executed by the satellite. With the command function recovered (in a limited sense), operations were performed on the satellite, and evidence suggests that these operations aided in gradual rejuvenation of both command decoders. On January 3, 1963, with both decoders responding to *normal* commands, the communications-experiment equipment in the satellite was turned on and tests indicated normal performance.

This paper describes the stages of failure and recovery of the command system. An explanation is suggested for both failure and recovery in light of the available evidence.

Complete failure of the command system again occurred on February 22, 1963. The pattern of malfunction in many ways resembled that of late 1962. Detailed treatment is given of only those events which occurred during November, December, and January.

II. COMMAND DECODER

The failure of the command system of the satellite was traced to the command decoders through the examination of telemetry data. Hence, a brief discussion of the command decoders, which are described in detail elsewhere in this issue,[1] is in order here.

There are two virtually identical command decoders in the command system. Each is driven by one of the two command receivers and each drives a command switch unit, as shown in Fig. 1. Each command relay is normally driven by both command switch units in parallel; the design is such that a pulse from either or both command switch units is sufficient to operate a relay. Thus, redundancy exists between the input to the command receivers and the output of the command switch units.

Several checks are available on the health of the redundant command circuits: The AGC and output voltages of the command receivers are telemetered. Also, two commands are used to disable the decoders. T-1 command disables decoder 2 for 15 seconds and permits testing of decoder 1; T-2 command disables decoder 1 for the same length of time and permits testing of decoder 2. These and the 13 other commands are described in Table I of Ref. 1. Information is telemetered, telling whether or not T-1 or T-2 commands have been executed, as well as indicating the state of the relays in the command switch.

III. MALFUNCTION OF THE COMMAND SYSTEM

3.1 *Failure to Respond to T-2 Command*

The first indication of trouble in the command system of the satellite came on pass 260 on August 7 when there was no response to the T-2 command. On the next visible pass that same day, T-2 command was carried out in a normal manner. Table I shows the erratic response to the T-2 command between August 7 and October 21, when the T-2 command function had apparently failed completely. Note that there is a gap of approximately two months during which no acknowledgement of T-2 command was received.

Failure to respond to the T-2 command is not conclusive evidence that decoder 2 has failed. The same symptom could result from failure of command receiver 2, T-2 relay, or T-2 relay-state telemetry channel

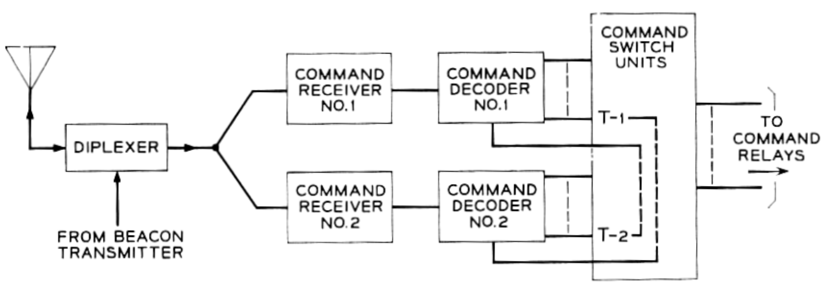

Fig. 1 — Block diagram of command system.

TABLE I — FAILURE OF DECODER 2

Date	Pass	Observation
Aug. 7, 1962	260	No response to T-2 command
	261	Normal operation
Aug. 8	268,9	No response to T-2 command
	270	Intermittent T-2 command response
	271	Normal operation
Aug. 9–20		Intermittent T-2 command response
Aug. 21		Decoder 2 apparently completely failed
Oct. 17–20		Intermittent T-2 command response
Oct. 21		Decoder 2 apparently completely failed

or of the circuits in the command decoders and switch unit associated with T-2 command.

3.2 *Gradual Failure of Command System*

Except for the difficulty described in the previous section, the command function was satisfactory until November 18; the response to commands from the ground appeared to be instantaneous. On November 18, however, it took 8 minutes before the satellite responded to a command. Delay between command and response became gradually greater and, on November 23, complete failure of the command system occurred.

The chronology of events of the week of November 18 is given in Table II. During this week, one important consistency was apparent: After the first command was executed on a pass, other commands were carried out immediately in a normal way, even if the first command took several minutes to go through. One can see from Table II that three different commands were used to bring about recovery (for at least one pass). The duration of continuous pulsing to bring about recovery gen-

TABLE II—THE WEEK OF NOVEMBER 18

Date	Pass	Duration of Commands Before Recovery	Command at Recovery	Successful Commands After Recovery	Final Command of Pass
Nov. 18	1203	8 min	T-1	DD, D, T-1	T-1
	04	0	—	A, AA, B, C, CC	AA
	05	0	—	A, AA, B, C, CC	AA
	06	0	—	T-1	T-1
19	1212	0	—	A, AA, B, C, CC	AA
	13	0	—	A, AA, B, C, CC	AA
	14	0	—	A, AA, B, C, CC	AA
	15	No commands sent	—	—	—
20	1221	No recovery	—	—	T-1
	22	2 min	A	A, AA, B, T-1	T-1
	23	20 sec	T-1	F, FF, T-1	T-1
	24	0	—	F, FF, T-1	T-1
21	1230	No recovery	—	—	T-1
	31	3 min	C	C, CC, F, FF, T-1	C
	32	15 sec	T-1	C, CC, F, FF, T-1	T-1
	33	0	—	C, CC, F, FF, T-1	T-1
22	1239	No recovery	—	—	T-1
	40	No recovery	—	—	C
	41	11 min	T-1	C, CC, F, FF, T-1	F
	42	3 min	T-1	C, CC, F, FF, T-1	T-2
23	1247	No recovery	—	—	—

erally decreased for succeeding passes on a given day. Increased degradation was apparent from day to day. Also, during a period when commands were not executed, several different commands were sent with no response; the failure appeared to be in the part of the decoder which is common to all command channels.

When it was apparent that the command system was deteriorating, care was taken to hold the satellite in the condition which would be most useful in the event of failure of the command function. The communications experiment could not be left on because, under that condition, energy would have been drained from the storage cells faster than it would have been replenished by the solar plant. The resultant dropping battery voltage would have automatically tripped the low-voltage trigger circuit which disconnects the storage cells from the power supply circuit* and turns off all circuits except the switching regulator in the power supply, the command receivers, the command decoders, and the two-year timer. Power restoration to all other circuits can only be accomplished through use of the command system. Incidentally, the action of the low-voltage trigger circuit is the same as that accomplished by sending the SS command; knowledge of the function of this command is essential to the understanding of Section V. The low-voltage trigger circuit and the SS command control the same S relay.

Hence, during the week of November 18, care was taken to assure that the satellite was left with the VHF beacon, radiation experiment and telemetry circuits powered; the command system is permanently connected to the switching regulator and always receives power except when the S relay is open and the satellite is in darkness. Thus, even without an operative command system, valuable information was relayed from the Telstar satellite; radiation field mapping data, battery charging rate (from which solar cell quality could be ascertained), solar aspect data, temperatures throughout the satellite, pressures and the performance of the command receivers were among the useful pieces of information received.

The failure of the command system which began on November 18 suggests that the T-2 command difficulty was indeed a failure of a circuit common to all commands in decoder 2. The later pinpointing of the exact failure in decoder 2 further supports this idea. Hence, most of the time since launch, command signals were probably being interpreted only by decoder 1.

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* There is an exception; the storage cells can be charged by the solar plant through a diode.

IV. FAILURE MECHANISM

4.1 *Possible Causes of Failure*

The earth satellite environment creates a number of effects which should be suspected as possible causes of failure. The pertinent effects are enumerated and discussed in this section.

4.1.1 *Temperature Variation*

Because of the thermal design of the satellite, the assemblies within the electronics canister are subjected to relatively small temperature excursions. In particular, the temperature of the decoders has been between 22 and 37 degrees C since launch. During a given pass, the temperature of the decoders will vary by only one degree and may go up or down depending on the state of circuits in the satellite, solar aspect and the time of occurrence of an eclipse. The range of temperature is small and is well within the design limits of the decoders. There appears to be no correlation between temperature and the recovery of the command function during a pass.

One can hypothesize the following: The decoder circuit has failed because a component has deteriorated badly but can be made "good enough" if warmed slightly. Further, assume that one can heat the faulty component by means of the application of command signals to the decoder. In practice, the amount by which the temperature of a device can be changed by this method is only a few degrees. If one assumes, however, that the component in question is cool enough at the beginning of a pass so that the circuit has failed, then behavior of the sort listed in Table II might be explained. Final collapse of the command function could be attributed to further deterioration of the component. However, the data show that the deterioration is slow and that it does not correlate with decoder ambient temperature. Hence, one might suppose that the recovery is caused by a temperature variation which has been brought about by application of command signals, but that the damage itself results from some other effect. It is shown below that there is a much more probable cause of recovery.

4.1.2 *Eclipse*

Whether the satellite is in sunlight or the shadow of the earth greatly affects the temperature on the outer surfaces of the satellite. However, the electronics canister is hardly affected by a single eclipse.* Study of the data has indicated that there is no correlation between the occurrence of an eclipse and the failure of the command system.

4.1.3 *Magnetic Field Variations*

The command switch unit drives nine magnetic latching relays. Satisfactory operation is achieved in the leakage field of the traveling-wave tube, which is as large as 10 gauss at some of the relays. The external magnetic flux density never exceeds 0.44 gauss. No evidence supports magnetic effects as the cause of decoder failure, especially since it would take a very strong magnetic bias to render *all* relays inoperative.

4.1.4 *Noise*

Galactic noise was considered as a possible cause of failure, but was ruled out because there were no indications of a noisy signal entering the decoder. Commanding under extremely noisy conditions usually results in the execution of incorrect commands, but there were no errors during the week of November 18. No unusual noise conditions were detected at the ground station during the period the command system was inoperative. Telemetry signals indicated that normal signals were entering the two decoders and that the command receiver AGC voltage was consistent with the range and aspect of the satellite.

4.1.5 *Aging*

Another possible cause of failure would be aging failure of a component. Even though very reliable components were used, the large numbers in this experimental model do raise the question of the statistical probability of such a failure. On the basis of estimated random failure rates under operating conditions of one in 10^9 component hours for passive components (largely resistors and capacitors), and 10 in 10^9 for semiconductor components, there results a 9 per cent probability of one component failure in the entire system or a 1 per cent probability of failure in each decoder in a four-month life. This is not consistent with the occurrence of two failures, one at even a shorter time, each occurring in the same portion of the system. Furthermore, the failure of the command system was gradual rather than catastrophic. Gradual failure would be expected if one component were undergoing a gradual

* Unless, of course, S relay is in the SS state. For this case, eclipse will turn off all circuits, including the command system.

change in characteristics and thus causing a circuit to become marginal. Since the components used were carefully screened under power aging conditions to eliminate those with drifting characteristics, only a catastrophic equipment failure is reasonable by residual random failure mechanisms. The absence of catastrophic failure points to the presence of a wear-out mechanism distinct from power aging.

4.1.6 *Radiation Damage*

Bulk damage to semiconductor materials by energetic particles, i.e., protons and electrons, is a well known phenomenon which leads primarily to degradation of minority carrier lifetime. This degradation is the failure mechanism for solar cells and must be considered for wide-base, low-frequency transistors. The effect is negligible for the diodes and narrow-base transistors used in the decoder. Therefore, this mechanism can be ruled out as an explanation for the failure.

4.1.7 *Ionization Damage*

Exposure of certain types of transistors to ionizing radiation can cause failure at radiation doses appreciably lower than those necessary to cause bulk damage.[2] Parameters which are dependent on the semiconductor surfaces, such as the collector reverse current or the transistor gain, will degrade gradually under radiation (with considerable variation in degradation rates among different transistors), and will typically recover temporarily to some degree when removed from exposure or when exposed with a reduced (or zero) collector-to-emitter voltage. Issuance of a command to the satellite turns some "off" (V_{CE} high, I_C low) transistors "on" (V_{CE} low, I_C high), and hence could cause recovery of those transistors. Recovery is not instantaneous with either voltage reduction or removal from exposure. Therefore, ionization damage could explain why (*i*) during the failure of decoder 1 during the week of November 18, delayed response to commands was observed, but once commands were obeyed, the command function was operative during at least that pass, and (*ii*) the temporary recovery of decoder 2 in October occurred during an experiment which involved continuous transmission of commands.

Since many transistors in the command decoder are of a type sensitive to ionizing radiation such as that encountered in the Telstar satellite orbit, it is reasonable to consider this phenomenon as a plausible cause of failure. In fact, since the other possible causes of failure do not satisfactorily account for the deterioration observed, ionization damage is thought to be the most probable cause. The next section describes the evidence which supports this contention.

4.2 *Radiation Effects*

4.2.1 *Ionization Damage to Transistors*

The effect of ionizing radiation on transistors has been described in considerable detail.[2] It appears to result from the interaction of semiconductor surface contaminants with gaseous ions produced in the transistor enclosure by radiation, and with electrical bias applied to the transistor. A few of the features of this effect, pertinent to the immediate consideration, are:

(a) Transistors encapsulated in a gaseous atmosphere are generally most susceptible to surface radiation damage.

(b) Parameters sensitive to surface states are affected; these parameters include I_{CBO} , h_{FE} and noise figure at low frequencies.

(c) Transistors removed from radiation will typically recover usable characteristics.

(d) A degraded transistor will tend to recover when the collector voltage is removed, or even reduced, while either in radiation or out of radiation. This recovery may be quite appreciable even within the first few seconds.

(e) Collector junction degradation rate is dependent upon the magnitude of reverse collector voltage, so that a marginal transistor may be more or less degraded, depending upon its voltage condition.

These effects were recognized while the Telstar circuits were being assembled. Where possible, units of the sensitive types were irradiated and the most resistant ones selected for use. Screening experiments indicated that pre-irradiation up to one tenth of the expected orbital dose could reasonably predict the behavior in orbit. However, test results had also indicated that the reliability of screening predictions decreases with increasing ratio between the actual and screened radiation levels. Because the average dose rate encountered in the Telstar orbit was found to be approximately two orders of magnitude greater than expected at the time of launch (see Section 4.2.2), and because only a part of the transistors in the command decoder were screened, ionization damage remains the prime suspect as the cause of circuit malfunction.

4.2.2 *Radiation Intensity Seen by Telstar Command Circuits in Orbit*

The radiation effects on the devices in the Telstar satellite are produced by the Van Allen belt, which is composed of energetic electrons and protons trapped in the earth's magnetic field. The surface effects depend only on the ionization caused by these particles inside a transistor's encapsulation. Protons and electrons which actually penetrate the transistor's container contribute directly. In addition, there may be a contribution from the bremsstrahlung, X-rays, created in stopping energetic electrons. It is convenient to express the integrated radiation dose in rads, a unit of energy deposited by the ionizing particle flux per unit mass of material.* In principle, the dose is calculable for any location in the satellite from a knowledge of the energy distribution of the particle flux at the surface of the satellite and the shielding provided by the satellite skin and frame, the wall of the canister housing the electronic circuits, other components, etc. Only approximate calculations are feasible in view of the complex geometry of the shielding in the satellite and the incomplete information concerning the electron energy distribution.

The highest intensity in the inner Van Allen belt is around the magnetic equator of the earth and extends between about 1200 and 2500 statute miles above the earth's surface at the equator. The Telstar satellite's orbit is in the region about 20 per cent of the time. Because the earth's magnetic field which controls the motion of the trapped particles is misaligned with respect to the earth's geographic axis, the particle flux incident on the satellite varies from orbit to orbit. The daily average also varies as the apogee of the orbit precesses between its extremes at 45° north and south latitudes with a period of 181 days. In addition, of course, there are time variations of the radiation belt.

The estimated upper limit of the radiation dose contributed by energetic protons in the region of highest intensity is illustrated in Fig. 2 as a function of aluminum absorber thickness. The radiation dose rate is shown under the assumption of uniform shielding and exposure to a uniform omnidirectional proton flux. For the decoders which are very close to the surface of the electronics canister, the minimum shield thickness is only about 0.1 inch of aluminum, but the solid angle for acceptance of particles through this thickness is between $\frac{1}{4}$ and $\frac{1}{2}$ of the total 4π solid angle. The curve applied to this case gives an orbital average of between 5 and 10 rads per hour. The proton exposure of the satellite has been quite close to the pre-flight estimate.

Trapped electrons can also contribute directly to ionization. For an electron to reach the average component in the canister, it must have an energy of more than 5 Mev, and for a circuit shielded by 0.1 inch of aluminum, such as the decoder, the electron energy must exceed

* One rad equals 100 ergs of absorbed energy per gram of material.

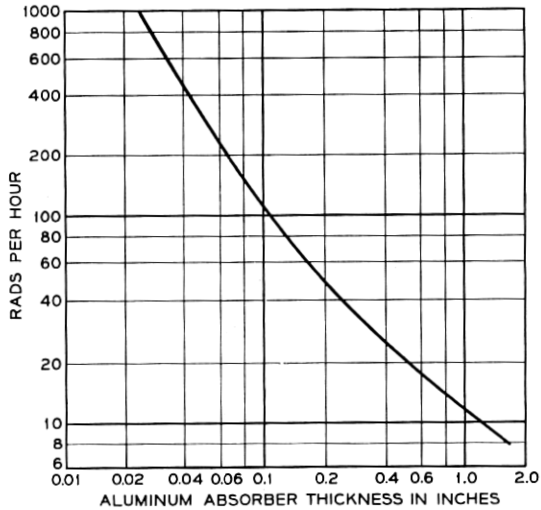

Fig. 2 — The radiation due to high-energy protons in the peak of the inner Van Allen belt.

about 1.5 Mev. It was believed before launch that there were very few electrons with energies this high in the inner Van Allen Belt, and thus it was concluded that direct electrons were of no importance. Consequently, with the expected orbital average flux less than 10 rads/hour, which implied a total dose of 1.8×10^5 rads over the two-year expected useful life of the satellite, the screening dose for sensitive transistors was held to 1.4×10^4 rads.

From measurements by the Telstar and Explorer XV satellites, it has been concluded that a very substantial fraction of the electrons in the inner Van Allen Belt have energies above 1.5 Mev. In parts of the inner belt region, the energy distribution can be reasonably represented by an expression of the form exp $- E/E_0$ where $E_0 = 1.2$ Mev. A large part of these high-energy electrons are believed to have been introduced by the high-altitude nuclear explosion of July 9, 1962.

The omnidirectional electron flux averaged over the first four months of the Telstar satellite's orbit is about 10^8 electrons/cm² sec. The radiation dose rate for electrons with this flux and the above spectrum is shown as a function of shield thickness in Fig. 3. The curve represents the radiation in the Telstar canister for shielding thicknesses small compared to that in the middle of the canister.* For transistors in the

* The curve includes the influence of the solar cells and the canister itself in reducing the effective solid angle for incident electrons. It also contains the effect of nonnormal incidence on the effective shielding.

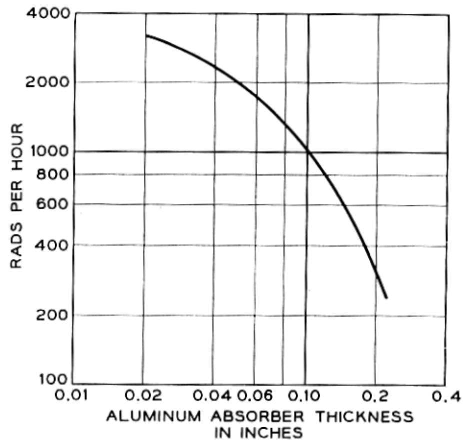

Fig. 3 — The average radiation due to high-energy electrons in the Telstar orbit.

decoder the dose rate due to electrons is approximately 10^3 rads/hour. The estimated dose rate due to protons is only 5 to 10 rads/hour. Hence the components in the Telstar command decoder have been exposed to approximately 100 times the anticipated radiation intensity, and the major contribution is not from protons but from high-energy electrons. It is believed that the peak radiation intensity could be as high as 10^4 rads/hour. The bremsstrahlung is insignificant in comparison with the direct electron effects.

4.2.3 *Transistor Ionization Damage Experiments**

Two kinds of experiments were conducted to evaluate the hypothesis that radiation was the cause of command decoder malfunction and to pinpoint the problem areas in the circuit with the ultimate hope that some corrective action could be taken. Transistors of the same code as those used in the decoders were cycled in a radiation field (gamma rays from a cobalt 60 source) with a period about the same as the Telstar satellite orbital period. Also, complete command decoder circuits were subjected to gamma irradiation. These experiments confirmed what was already known about surface ionization damage, summarized in Section

* The experiments described in this section are a direct extension and application of experience gained in work on surface effects of radiation in semiconductor devices, a part of which was performed under contract with Electron Technological Laboratories, Aeronautical Systems Division of the United States Air Force Systems Command.

4.2.1, but the data obtained were more directly applicable to the Telstar command problem.

Since there is a very large variation in radiation damage for different transistors of the same code and because the experiments did not duplicate the environment of the transistors in orbit,* the conclusions are qualitative or, at most, quasi-quantitative. The following statements can be made regarding the radiation-sensitive transistor type used in the command decoder, which is a nitrogen-filled diffused silicon npn unit.

(*i*) Those units which were heavily degraded in the high-intensity field partially recovered in the low-intensity field. The time constant for I_{CBO} and h_{FE} degradation ranged from 1 to 20 minutes; recovery has logarithmic time dependence. Typical cycles are shown in Fig. 4 for a transistor which had been pre-irradiated to degrade I_{CBO} from a few nanoamperes to several microamperes.

(*ii*) Short-term reciprocity does not hold; i.e., during cycling tests it was apparent that a given total dose applied at a fast rate caused more degradation than the same dose applied at a slower rate. Note from Fig. 5 that 3.6 hours at 4.5 kilorads per hour induce less effect than 1 hour at 16 kilorads per hour, although the total dose is the same for both cases.

(*iii*) Removal of power from the device during cycling resulted in temporary improvement, and the improvement was generally greater if power was removed during the high-intensity interval. The degree of memory of this improvement varied widely from one transistor to another.

Although irradiation tests on an actual command decoder are less useful from a statistical point of view than the experiments conducted with individual devices, they offer the possibility of focusing attention on vulnerable areas in the circuit and can possibly bring to light certain subtleties which might be overlooked in a perusal of circuit diagrams. Two command decoders (referred to here as decoder A and decoder B) were irradiated, both at high intensities (0.68 and 0.34 megarad per hour) to cause early failure; then decoder A was disassembled to study the failed component, and decoder B was placed in a low-intensity field (500 rads per hour) to study various recovery techniques. A summary of the results of these tests follows:

(*i*) Decoder A failed at a total dose of 2.3 megarads. (If reciprocity were to hold between time and dose rates, then this total dose would

* In most of the experiments the units were cycled between a level of 10 kilorads per hour for one hour and 30 rads per hour for one and one-half hours. This high average dose rate (5 kilorads per hour) was used to accelerate deterioration.

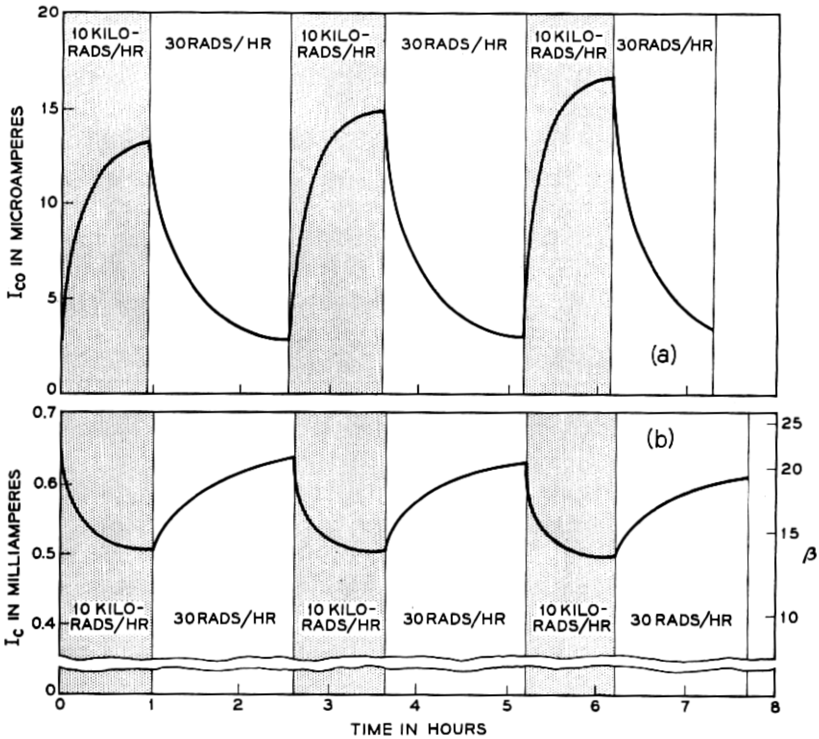

Fig. 4 — Leakage current and gain of a transistor cycled between high and low radiation field intensities.

correspond to 26.5 years at 10 rads per hour or 3.2 months at 1 kilorad per hour.) Up to this dose level, continuous commands had been sent to the decoder and some degradation (but not failure) had been observed. Failure occurred immediately after the continuous commands ceased, which indicates that the commanding had retarded failure.

When the circuit was removed from radiation, it recovered and operated satisfactorily.

The failure was traced to low h_{FE} in the "zero" digit gate transistor, which, because of its load configuration, had a turn-on time which was too slow to advance the digit counter.[1] Measurements on the device confirmed the diagnosis.

(*ii*) For tests on decoder B, commands were sent only intermittently until failure had occurred. The failure occurred at a total dose of 0.62 megarad (7 years at 10 rads per hour; 25 days at 1 kilorad per hour). The decoder did not respond to the first of a continuous train of com-

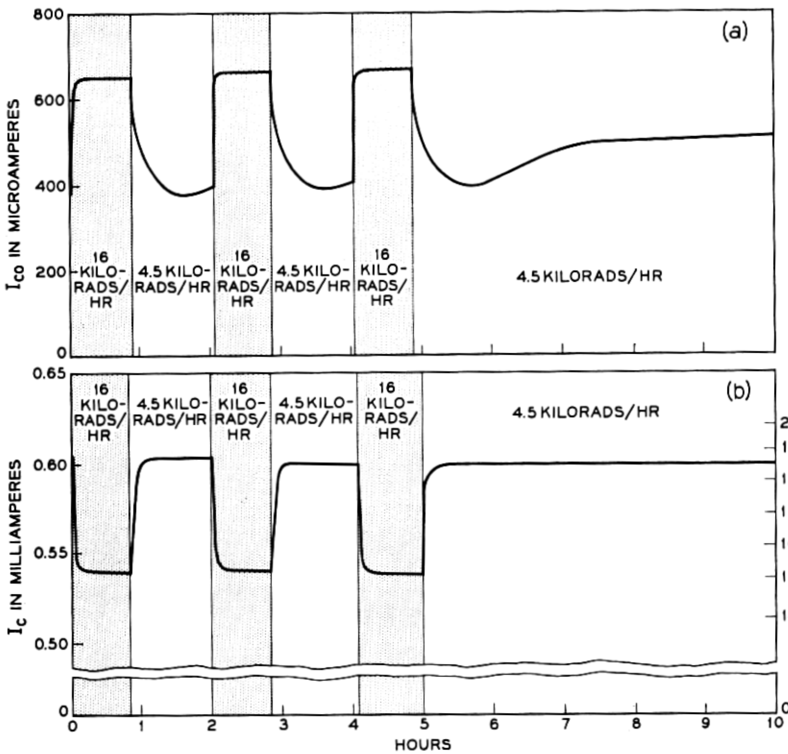

Fig. 5 — Leakage current and gain of a transistor cycled between two high radiation field intensities.

mands, but did react properly to all succeeding commands. (Each command lasts about 0.1 second.)

Deterioration was gradual: Continuous commands caused recovery in 2 seconds at a total dose of 2.4 megarads and in 14 seconds at a total dose of 4.0 megarads.

Even after the command decoder had received a total dosage of 10 megarads, recovery occurred when it was removed from the radiation field.

The failure occurred in the shaping network which controls the pulse generator.[1] The pulse generator, a gated astable circuit, is held off most of the time by the shaping network, but due to increased I_{CBO} of either the first or the second stage of that circuit,* the astable circuit became free-running, independent of the decoder input signal.

* See Appendix Sections A.2 and A.3.

(*iii*) After a total dose of 10 megarads at the high dose rate, decoder B was placed in the low-intensity field (500 rads per hour). Failure again occurred, but the malfunction was not in the shaping network. The trouble, which occurred at an additional exposure of about 0.3 megarad, was traced to the one digit gate, which has several output functions. One of these, which is the resetting of the timer circuit, was not being performed by the digit gate.[1]

Eventually the shaping network did fail in the low-intensity radiation field. However, since the total exposure to cause this failure was much greater for the low-intensity field than for the high one, it is suggested that either an out-of-radiation recovery mechanism exists or that deterioration is rate-sensitive for some transistors.

Continuous commands, power removal or extraction of the circuit from the radiation field could bring about recovery of the circuit.

4.2.4 *Ionization Damage as the Cause of Failure*

Two significant facts which pertain to the failure are apparent from the previous three sections: (*i*) High radiation dose rates were encountered by the satellite prior to the failure of the command system, and (*ii*) the gradual failure with temporary recovery after a successful command is consistent with the kind of failure observed in the laboratory when transistors were irradiated.

In addition to their usefulness in pinning down the cause of failure, the data described above also helped lead to the recovery of the command function. The action which was taken to this end is described in the next section.

V. RECOVERY OF THE COMMAND SYSTEM

5.1 *Corrective Measures*

Since previous tests had provided evidence that either reduced radiation field or voltage removal from certain transistor stages might lead to recovery of the command function, certain corrective steps were taken.

5.1.1 *Turning "Off" Transistors "On"*

The command decoder is basically a digital logic circuit and, as such, contains mostly transistor and diode stages which are normally in either a "conducting" or "nonconducting" state. When a command pulse train is being interpreted by the decoder, its stages alternate one or several times between these states, and the majority of them end up in a particular state at the end of each command pulse train. There are, however, several circuits whose resting state is a function of the last received command signal. Out of the 34 transistors of the radiation-sensitive type in each decoder, 24 can be controlled to be "off" (high V_{CE}, low I_C) or "on" (low V_{CE}, high I_C). Any of the 24 transistors could have been triggered into the more desirable "on" state (from the standpoint of radiation damage), and, of course, if it had been known that a particular one of these devices was the cause of malfunction, such action would have been taken. Even though response to commands would not be expected initially, the healing effect of reduced V_{CE} might have led ultimately to recovery. Unfortunately, no device could be "tagged" as the most probably faulty one,* and further, acquisition of the more desirable state by one device usually resulted in forcing an adjacent device into the "off" state. Several experiments, which were designed to control the states of the various stages, were carried on over a period of three weeks, but to no avail.

5.1.2 *Continuous Commands*

Although the command function was inoperative, it was felt that some benefit could be gained from sending continuous commands from the ground terminals whenever the satellite was in view.† The probability was high that such action would reduce the average V_{CE} applied to the damaged transistors. Command signals were designed to benefit particular transistors; e.g., a train of signals consisting of "ones" only was sent to exercise optimally the one digit gate. A number of such commands were tried, all with no success, in attempts to "heal" the satellite after the command failure.

5.1.3 *Commands from Johannesburg*

The normal operating procedure called for issuance of commands from Cape Canaveral, Florida, or Andover, Maine. However, at the time of the failure of the command system, the apogee of the orbit, at which the radiation field is at a minimum value, was in the southern hemisphere and was not visible to either normal command station. The NASA command and telemetry station at Johannesburg, South Africa, was selected as a third Telstar satellite command terminal. In addition

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* Examination of the data taken during the week of November 18 was carried out to see if any correlation between the last command sent and depth of recovery existed. No conclusive correlation was apparent.

† That recovery can be brought about with continuous commands had been demonstrated in the laboratory. See Section 4.2.3.

to the advantage of apogee visibility, it also had sight of the satellite as it passed through the region where radiation was thought to be a minimum because of the anomalies in the earth's magnetic field.

The tests were begun on December 6. On at least one pass each day, conditions were thought to be favorable from the standpoint of passage through the radiation belt. As many commands as possible were sent during each visible pass on the assumption that the cumulative effect of a large number of commands would increase the probability of response in the reduced radiation field. All results were negative, although telemetry indicated a normal signal at the output of the command receiver. These tests were terminated on December 17.

5.1.4 *Modified Commands*

By far the most fruitful approach to the recovery of the command function was the use of command signals which were designed to circumvent some assumed failed circuit. Such a procedure, if successful, would lead to full use of the satellite for communications experiments and would also locate the exact area of the decoder circuit in which the failure had occurred.

The first procedure was a process of elimination to focus attention on those stages for which the probability of failure was highest. The considerations which greatly reduced the number of suspects are listed below:

1. Only those circuits which had a function common to all command channels were considered, since failure existed for all commands. Also, during the week of November 18, when the circuit recovered, all commands which were issued were carried out.

2. Only stages containing the device-type known to be radiation sensitive were examined in detail.

3. Stages which were normally in the "on" state except during a command pulse train were excluded.

4. First priority in the investigation was given to those devices with especially high V_{CE} and in circuit positions known to have stringent leakage current and gain requirements.

The results of this study suggested that six transistors were most vulnerable. For only one of these, the reset digit gate transistor,[1] was it not possible to design a satisfactory modified command. However, this device could be set into the "on" state by means of the transmission of a start pulse (normally at the beginning of each command) as the last pulse of a pass. This procedure was carried out as soon as its importance was realized. The other five transistors were the first two stages of the pulse shaping network, the normally "off" transistor of the astable pulse generator, and the zero and one digit gate transistors.[1]

The modified commands were designed either to permit satisfactory circuit operation without the use of the stage under study or to enable circuit operation to occur even after the normal operating margin had been reduced to zero. Refer to the Appendix for a description of each of the modified command procedures.

Prior to use of the modified commands on the orbiting satellite, a laboratory test was carried out on a decoder which had a condition simulating the probable failure. In this way, the reliability of the procedure was evaluated.

An interesting aspect of use of modified commands involved the experiments on irradiated decoders which were described in Section 4.2.3. The failures observed in those experiments were all in regions which were thought to be most vulnerable to radiation damage and which were arrived at through the process of elimination described earlier. Furthermore, in each instance, it was demonstrated that modified commands could restore the command function. This fact is indeed a fortunate coincidence, for one could point to other stages, which are thought to be less vulnerable to radiation damage, where increased leakage or reduced gain would lead to a failure about which nothing could be done.

5.2 *Return to Normal Operation*

On December 19, two different test signals were transmitted to the satellite. They were designed to override high leakage in the first and second stages of the shaping network. Neither test was successful. A third test, which was established to circumvent failure of the zero digit gate, was successfully tried on December 20. The C command was carried out on pass 1492, and during the next pass CC command was properly executed.*

Following the success of the test on December 20, on December 21 it was decided that commands C, CC, T-1 and T-2 would be tried. The C, CC and T-2 commands were successful; T-1 command was not successful but, because of the nature of that command, one could not definitely say that decoder 1 was not functioning (see the Appendix).

* The C command, which normally turns on the traveling-wave tube anode voltage, is not executed unless A and B commands are sent first and, since a telemetry channel indicates the state of the C relay, C and CC commands provide a convenient means for checking the command system.

The significance of execution of the T-2 command was substantial for it meant that the zero digit gate failure was in decoder 2. This decoder was the first to exhibit command system difficulties (one month after launch).

With the failure pinpointed in one decoder, the plan was to increase the size of the list of commands which would be obeyed. For operating convenience, magnetic tape recordings were made of the modified command signals. As outlined in the Appendix, application of the modified command which circumvents the zero digit gate failure is somewhat difficult because of the bandwidth limitations of the satellite command receiver system. Through a gradual increase in confidence in operation of the command system, it was expected that all features of the satellite repeater would be recovered. On December 27, on pass 1555, after a successful C command, CC command was interpreted as an SS command and the S relay opened; this removed the connection between the nickel-cadmium battery and the solar plant and left the command system powered by only the solar plant. This occurrence, which has since been duplicated in the laboratory, was unexpected since it meant that the CC command had been converted into its complement. Within one minute the S relay opened, closed and opened again, and it was left in this state as the satellite disappeared over the horizon.

While out of view of Cape Canaveral and Andover, the satellite went into eclipse for a period of 25 minutes. Thus power was removed from the ailing decoders for that length of time On the next pass the satellite first became visible to Cape Canaveral, which had not yet been equipped to send the modified command signals. With the hope that power removal might have caused enough recovery of the damaged transistors, a continuous normal S command was transmitted from Cape Canaveral for 12 minutes; however, the satellite did not respond. When the satellite came in view of Andover, a modified S command was sent and properly executed. Telemetry, which is automatically turned off through the interpretation of an SS command, was turned on again with a modified D command.

On December 28 and 29, continuous normal command signals were transmitted to the satellite and, during pass 1574, a repetitive *normal* C command was executed after 37 minutes. The time to execute repetitive normal C, CC and T-2 commands gradually decreased, and, during pass 1602 on January 1, 1963, the first nonrepetitive command (C) was executed. Up until that date, there had been no response to T-1; all successful commands had been decoded by decoder 2. On that day, however, T-1 command was also properly interpreted, and it was clear that both decoders were responding to normal commands, although some sluggishness was still apparent.

On the last visible pass of January 1, the SS command was executed erroneously by the satellite during a sequence of normal T-2 commands. The S relay was not closed and the decoders were left powered by only the solar plant; the satellite went through five 20-minute eclipses during which power was removed from the command equipment. On the next visible pass (1609) the following day, normal operation was observed for decoder 1; response to T-2 command was less sluggish. The S relay was deliberately left open on the last pass of January 2 (1613), and on January 3 complete recovery of both decoders had taken place.

The traveling-wave tube was turned on, for the first time since November, on January 3, and normal operation of all systems was reported. Since that time, commands have been successfully carried out through the use of both normal and modified commands. The latter commands do not use the zero digit gates of either decoder. On only four different occasions have the modified commands been misinterpreted by the satellite.

Since January 2, the SS command has been sent intentionally whenever it was operationally convenient to do so to retard radiation damage and hopefully to increase the circuit operating margins. The length of an eclipse varies with time, however, and dropped to zero from January 6 to February 4.[3] Hence, power was applied continuously to both decoders during that period. Nevertheless, normal commands gave satisfactory performance throughout that interval.

5.3 *Cause of Recovery*

There is no conclusive evidence that there is any one cause of recovery of the normal command function. Laboratory experiments have shown that reduction of V_{CE} and/or reduction of the radiation field intensity can bring about recovery, although the degree of improvement varies greatly among devices. The facts related in the previous section show that there is a definite correlation between recovery and V_{CE} reduction through the use of continuous commands and the occurrence of eclipse with the S relay open. However, simultaneous with the efforts to regain the command function, there was a reduction in the radiation flux seen by the Telstar satellite due to decay of the particle density in space and the oscillatory change in the orbital average as the line of apsides of the orbit precessed. On January 1, 1963, the average flux had dropped to less than 20 per cent of the value it had on November 15, and to less than 10 per cent of that measured during the month of July.* The re-

* The temporary recovery of the T-2 command on October 17 occurred at the time of a minimum in the radiation intensity with apogee of the satellite's orbit at the equator.

covery was probably due to a complex combination of the effects described above.

5.4 *Reappearance of Command System Malfunction*

Throughout the month of January, the command system responded normally. On February 5, however, the malfunction of the zero gate in decoder 2 again appeared, and it was necessary to command through that decoder with the use of the modified command signals described in Section A.4. Decoder 1 continued to function normally until February 14, and, to assure reliable operation, taped modified commands were used almost exclusively for commanding the satellite through decoder 2. On February 21, however, the command system apparently misinterpreted a modified T-2 command and the S relay was opened. Thus the storage batteries were disconnected from the solar plant and power was supplied to only the command system. The satellite has failed to respond to further command attempts.

The cyclic behavior of the average radiation intensity to which the Telstar satellite is exposed has a period of approximately three months. It is significant that the February malfunction, like that of November, occurred near the peak of the cycle.

The phenomenon of the conversion of a modified command to the SS command has been demonstrated in the laboratory. It occurs when I_{CBO} of the reset digit gate transistor attains a critical value. Circumstances indicate, therefore, that the problem in decoder 2 might be failure of both the one and reset digit gates.

VI. CONCLUSION

The facts have been presented which led to the conclusion that the malfunction of the command system was due to surface damage to certain transistors by enhanced radiation in the inner Van Allen belt. Correction steps have included laboratory experiments to gain a better understanding of the cause of failure, the use of continuous normal commands, commands transmitted from Johannesburg, South Africa, and specially modified commands to circumvent failure of the more vulnerable transistors.

VII. ACKNOWLEDGMENTS

Other members of the technical staff of Bell Telephone Laboratories were instrumental in planning and conducting the experiments and tests which led to the diagnosis and cure of the command system mal-

function. Contributions were made by R. H. Shennum, R. C. Chapman, H. H. Henning, D. B. Cuttriss, W. Rosenzweig, J. D. Gabbe, E. R. Schmid, and W. Gianopulos.

APPENDIX

Modified Command Signals

A.1 *General*

The five most vulnerable transistor stages, selected in the manner described in Section 5.1.4, require the use of different modified command signal structures to accomplish proper decoding in failed units. The relative location of each of these stages can be determined from the block diagram of the command decoder shown in Fig. 6. A detailed description of the operation of the decoder circuit is given in Ref. 1.

A.2 *First Stage of the Pulse Shaping Network*

This circuit is an emitter follower with a high V_{CE} ; high I_{CBO} (>25 microamperes) will force the base voltage of this stage above a threshold level and will consequently cause the pulse generator to free-run. The input of the emitter follower is coupled to the output of the command

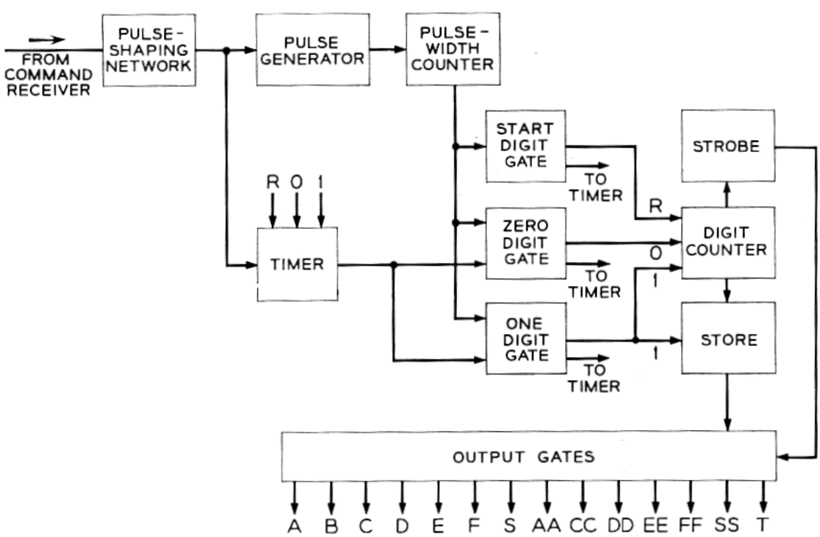

Fig. 6 — Command decoder block diagram.

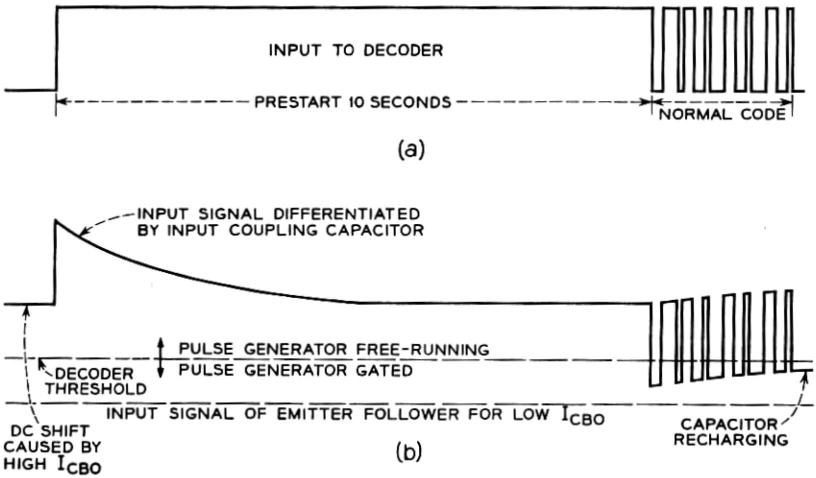

Fig. 7 — Modified command for high I_{CBO} in pulse shaping network first stage.

receiver through a capacitor. By preceding a normal command signal by a long pulse, as shown in Fig. 7(a), the input capacitor is charged to the full pulse amplitude level. When the pulse is removed, the charged capacitor will serve to pull the base of the emitter follower below the threshold level so that a command may be transmitted during the interval that the capacitor is being discharged by the leakage current (see Fig. 7b).

A.3 *Second Stage of the Pulse Shaping Network*

If the leakage current of this stage is above 150 microamperes, the pulse generator will free-run. Leakage currents in excess of 300 microamperes will cause the digit gates to be held off; consequently, the modified command signal described here will be effective only for a leakage current below 300 microamperes. Normally, the pulse generator, a gated astable circuit, is allowed to free-run only when an input pulse is present, as shown in Fig. 8(a). The modified command consists of a near-standard command set up on a shorter time interval basis, so that the input pulses are occasionally "in phase" with the free-running astable circuit, as shown in Fig. 8(b). With the shortened code it is possible to cause spurious decoder response when proper phasing does not exist. Errors can be avoided if the command pulse sequence is very carefully established.

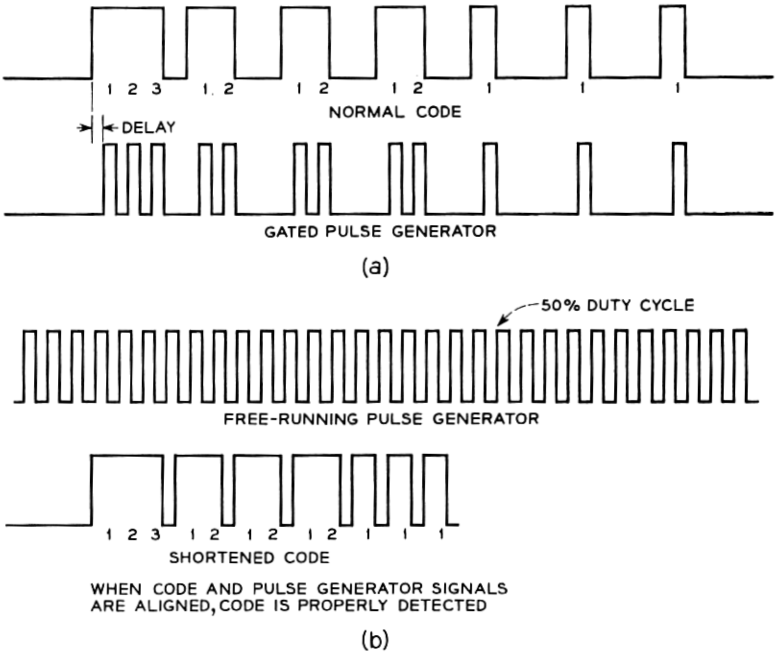

Fig. 8 — Modified command for high I_{CBO} in pulse shaping network second stage.

A.4 *Zero Digit Gate*

If the gain of the zero digit gate transistor becomes sufficiently low in value, that stage will not be capable of driving the digit counter. As one sees from Fig. 6, the zero digit gate drives the digit counter and the timer; the one digit gate drives the digit counter, and, after a small amount of delay, drives the store. The scheme for circumventing the failed zero digit gate is to send in place of a "zero" a modified "one" code in such a way that the one digit gate is turned on and almost immediately turned off again. By use of the notched and shortened pulse in Fig. 9(c), it is possible to advance the digit counter but not to build up sufficient voltage to set a "one" into the store. Thus this notched "one" causes the same response in the digit counter and store as a "zero." Unfortunately, the notched "one" does not fully enable the timer circuit, and it is difficult to handle codes containing three sequential "zeros," unless these "zeros" are at the end of the code.*

* Since the T-1 command contains three "zeros" in sequence, there is uncertainty regarding the reason why a modified T-1 command caused no response on December 21. See Section 5.2.

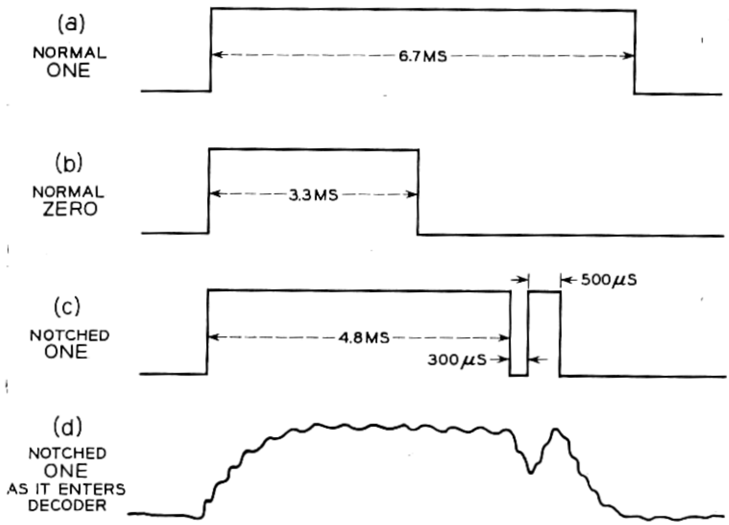

Fig. 9 — Modified "one" to circumvent failed zero digit gate.

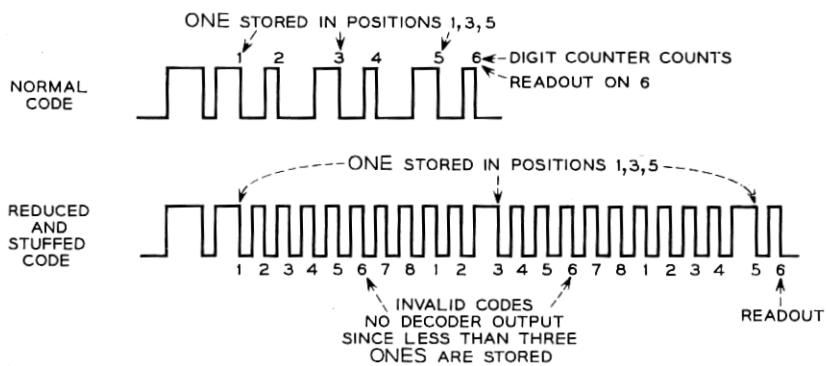

Fig. 10 — Modified command for low gain in one digit gate.

Proper detection of this modified command is difficult (but completely workable) since a code must be transmitted which produces a very marginal "one" out of the one digit gate. The margin involved is of the order of 30 microseconds in a system where the residual ripple from the subcarrier occurs with a period of 100 microseconds. Also, the notch is greatly distorted by the bandwidth limiting which occurs ahead of the decoder (see Fig. 9d). However, through the use of width modulation of the notch, the one digit gate output jitters through the region of uncertainty. As the notch width decreases, the "one" digit notch provides outputs ranging from a "one" to a "zero." One therefore establishes a reliable mode of operation by randomly modulating the notch widths in a manner such that the desired response of the one digit gate to a notched "one" occurs with finite and acceptable probability. The number of commands that must be transmitted to execute a given order is increased. However, since the normal command time is about one-tenth second, an exchange of command time for operating margin is acceptable.

A.5 *One Digit Gate*

There are two ways in which loss of gain in the one digit gate transistor will most probably first show up. Either the gate will fail to advance the digit counter (but still set the store and reset the timer), or it will fail to fully reset the timer (but still set the store and advance the digit counter). Failure to advance the digit counter is easily overcome by preceding each legitimate "one" by a zero. (The zero advances the counter.) Thus 111000 is transmitted as 010101000.

A failure which prevents full resetting of the timer can be combated by sending a code with shortened pulse widths and pulse intervals. If that method is not satisfactory, extra zeros may be inserted in the code (to reset the timer) so that a "one" is stored in the proper slot each cycle of counter operation. See Fig. 10 for an example of this procedure.

A.6 *Normally "Off" Transistor in Pulse Generator*

The effect of excessive leakage or low gain in this stage is to increase the natural frequency of the astable multivibrator, which is the basic pulse generator circuit. To circumvent this problem it is only necessary to set up standard commands on a contracted time scale. This procedure will work up to the point that degradation is so severe that astable operation is no longer possible.

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