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GENERAL ELECTRIC

INTEGRAL SENSOR TELEMETRY
PHASE A REPORT

Contract NAS 8-11715

Apollo Support Department
General Electric Company
Daytona Beach, Florida

ABSTRACT

19762

This report covers the effort on Phase A, Part I of Contract NAS 8-11715, Integral Sensor Telemetry.

The purpose of Phase A is to study the application of integral sensor transmitters to factory checkout. Included in this effort are:

a. Definition of the system requirements and the generation of an equipment specification for five sensor transmitters to be used in the ATCOMED facility of the Quality and Reliability Assurance laboratory at MSFC.
b. Evaluation of presently available sensor transmitters with respect to the specification.
c. Definition of system requirements for an ultimate integral sensor system for factory vehicle checkout. As a part of this requirement, the following areas of particular interest are reported in detail:
    (1) Propagation of sensor signals.
    (2) Electrically small antennas.
    (3) Transmitter power supplies.
    (4) Radiated RF energy as a power source.
    (5) Remote control of transmitter radiation.

As a result of the studies conducted in Phase A, it was concluded that the presently available transmitters would meet the specifications for the five transmitters for the ATCOMED facility, and a set of requirements were defined for the ultimate system. Since some question of explicit requirements for the ultimate system still exist, particularly in the area of signal propagation, a follow-on program for an intermediate system, beyond Phase B of this contract, is recommended. This system is to be a multichannel system for use on board as S-IC vehicle. A recommended specification for this system is included in this report as Section 5.

Author

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

SECTION 4 - PHASE A, PART 2

TABLE OF CONTENTS (Cont.)

SECTION 5 - SYSTEM PERFORMANCE SPECIFICATION

TABLE OF CONTENTS (Cont.)

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION 1

PURPOSE AND SUMMARY

The purpose of this program is to investigate the feasibility of applying the integral sensor concept to factory stage checkout of a Saturn type vehicle. In its ultimate form, an integral sensor telemetry system would consist of a miniature transmitter, with a sensor that is integral with the transmitter, transmitting the sensed data by radio frequency propagation to a central receiving facility. A system of this type would eliminate the hard wire, its connector, and attendant problems between the sensor and the point where the data is utilized. The integral sensor system also offers the ultimate in instrumentation flexibility. With this system, sensors can be moved as required without the chore of rerouting cabling with its associated probability of damaging other vehicle equipment. Where no physical tie-in to the vehicle systems is required, such as zone temperature measurements, changing the data point is accomplished simply by moving the sensor/transmitter package to the desired location. A system of this type would greatly facilitate the factory checkout of large space vehicles, offering a reduction in checkout time and providing test data from the most desirable points of the vehicle systems.

SECTION 2

SCOPE

Under the present contract, NAS 8-11715, Part I, the total program is divided into two major parts designated Phase A and Phase B. Phase A is the requirements study and Phase B is the application and evaluation phase. This report documents the results of Phase A.

Phase A is further subdivided into two parts. Part I is devoted to the study of the application of engineering model transmitters to subsystem module test in the ATCOMED facility of the Quality and Reliability Assurance laboratory at MSFC. The results of this study is a specification for five miniature telemetry transmitters to be delivered in Phase B of the contract.

Part II of Phase A is an application study to define the characteristics of an ultimate miniature telemetry system (transmitters and receivers), suitable as carry-on checkout telemetry equipment. This system would be used to replace the present hardwire system that is normally added to each vehicle during factory checkout. This study effort resulted in a definition of requirements for a system to perform this function.

SECTION 3

PHASE A, PART 1

3.1 DISCUSSION

This part of Phase A is devoted to defining the requirements and the generation of a specification for the five miniature telemetry transmitters. These transmitters are to be used, with receivers loaned by the General Electric Company, to demonstrate the advantages of the integral sensor approach to factory checkout. The transmitters are to be used with the module carts of the ATCOMED facility. The transmitters will be mounted on the module carts, modulated by the data from conventional sensors on the module carts, and resultant data transmitted to a central receiver facility.

The best information available to date indicates that the sensors to be used on the module carts are as listed in Table 3-1.

Table 3-1
Available Sensors for Use on Module Carts

Module Cart	Sensor	Manufacturer	Part Number
Control System	Pressure	Edcliff	2-8-6 (0-3000 psi)
	Pressure	Edcliff	2-8-6 (0-750 psi)
Fuel System	Pressure Switch	Frebank	4188-1
LOX System	Pressure Switch	Frebank	4184-1
	Pressure Switch	Frebank	4184-2

No information on the sensors for the engine and guidance modules has been made available. The pressure transducers are potentiometer types with a nominal resistance of 2 kilohms. The pressure switch output will be a contact open or closed.

The receivers to be furnished to test the transmitters will be modified commercial receivers. The data output from these receivers will be in analog form, 0 to 5 volts.

The system will therefore consist of the transmitters mounted on the module carts which will be somewhere in the ATCOMED facility, transmitting pressure data to a central receiver location where the data is presented as an analog signal of 0-5 volts. This system will not be representative of an actual vehicle checkout telemetry system, but it will serve to demonstrate the flexibility and convenience of the integral sensor approach to checkout.

3.2 TRANSMITTER REQUIREMENTS

The basic requirements for the transmitters for this application are as follows:

a. The transmitters must be capable of operating in the working environment of the hangar area of building 4708 at MSFC.

b. The transmitters must be capable of sufficient accuracy to provide useful data from the module carts.

c. The transmitters must be compatible with either the sensors specified for the module carts or with a substitute transducer complying with the requirements of the Quality and Reliability Assurance Laboratory.

d. The transmitters must have a self-contained power supply with sufficient capacity to operate the transmitters for a reasonable length of time.

e. Physical characteristics, such as size, weight, and dimensions, are not particularly critical in this application but size should be held to a minimum. The size of the transmitter antenna should also be as small as possible, consistent with adequate performance.

In consultation with Quality and Reliability Assurance laboratory personnel, these general requirements were further definitized.

The working environment of the hangar area of building 4708 was defined as having an ambient temperature range of from 40°F to 140° F and a background RF noise level in the vicinity of the ATCOMED facility of 30 db above 1 microvolt/Mc as measured with an NF 105. It was also concluded that the shock and vibration conditions would be no greater than those experienced in normal laboratory handling.

To provide useful evaluation data, the system accuracy, from transmitter input to receiver output, the random error must be no more than 5 percent of full scale when measured under steady state conditions. An accuracy of 3 percent of full scale was considered to be highly desirable.

The input to the transmitters from the module cart sensors was defined as being the standard telemetry modulation level (0 to +5 volts). The sensors and their output impedance characteristics have been discussed previously.

The primary power for the transmitters is to be supplied by a self-contained battery. Since the useful life of the battery and its physical size are directly interrelated, a compromise must be reached. It was felt that changing batteries once a week would not be unreasonable; therefore, a useful battery life of 100 hours was agreed upon. This would allow twelve, 8-hour shifts of continuous operation. When the transmitters are not used continuously, the time between battery changes would of course be extended.

These requirements have been incorporated into the specification for the transmitters to be delivered in Phase B of the contract.

3.3 TRANSMITTER SPECIFICATION

The following specification defines the characteristics of the five miniature telemetry transmitters to be delivered in Phase B of this contract, NAS 8-11715, Part I.

3.3.1 OPERATIONAL SPECIFICATIONS

3.3.1.1 Frequency of Operation

The transmitters for this application will operate on the frequencies listed in Table 3-2.

Table 3-2
Transmitter Frequencies

Channel	Frequency in Mc
1	27.650
2	27.700
3	27.750
4	27.800
5	27.850

These frequencies were chosen since they are within the operating range of presently available equipment and are also within a frequency band assigned for Government use.

3.3.1.2 Accuracy

The over-all system accuracy from transmitter input to receiver output shall be 5 percent of full scale or better. Three percent of full scale is to be a system goal. These error figures are for a steady-state measurement exclusive of any timing or phase errors. To maintain this accuracy, end-point calibration will be required no more often than every 24 hours.

3.3.1.3 Transmission Range

The transmitter-receiver system shall be capable of useful operation over a range of up to 300 feet between transmitting and receiving antennas. This range of operation is for a 12-inch monopole transmitting antenna, an ambient RF noise level of 30 db above 1 microvolt/Mc, and a free-space transmission medium. The receiver is assumed to be external noise limited.

3.3.1.4 Data Bandwidth

The system will be capable of transmitting data frequencies of from 0 to 80 cps at the specified accuracy.

3.3.1.5 Modulation Input

The transmitters to be supplied will accept a modulation input of from 0 to +5 volts with a transmitter input impedance greater than 40,000 ohms.

3.3.1.6 Calibration

Calibration will be accomplished by insertion of a calibration probe with "zero and full scale" switch.

3.3.1.7 Mode of Operation

The transmitter will be equipped with a manual on-off switch.

3.3.1.8 Power Supply

The transmitter will be supplied with self-contained batteries with sufficient capacity to operate the transmitter for a minimum period of 100 hours.

3.3.2 ENVIRONMENTAL SPECIFICATIONS

3.3.2.1 Temperature

The transmitter will be capable of operation at the specified accuracy over the temperature limits of 40°F to 140°F. Receiver will operate over a temperature range of 50°F to 130°F.

3.3.2.2 Shock and Vibration

The transmitters will be constructed to conform to good commercial practice and will be sufficiently rugged for normal laboratory handling.

3.3.3 MECHANICAL SPECIFICATIONS

3.3.3.1 Size

The transmitter, exclusive of antenna, will be no larger than 4 inches by 3 inches by 1 inch (see outline drawing, Figure 3-1).

3.3.3.2 Weight

The transmitter package will not exceed 10 ounces in weight.

3.3.3.3 Antenna

The transmitting antenna will be a monopole antenna not exceeding 12 inches in physical length.

3.3.3.4 Mounting

The transmitter package will incorporate suitable mounting hardware to effect convenient and secure mounting of the transmitters to the module carts.

3.4 EQUIPMENT EVALUATION

A presently available sensor transmitter was tested to the specification of the five channel system to be delivered in Phase B of this contract. The results of these tests are described in following paragraphs.

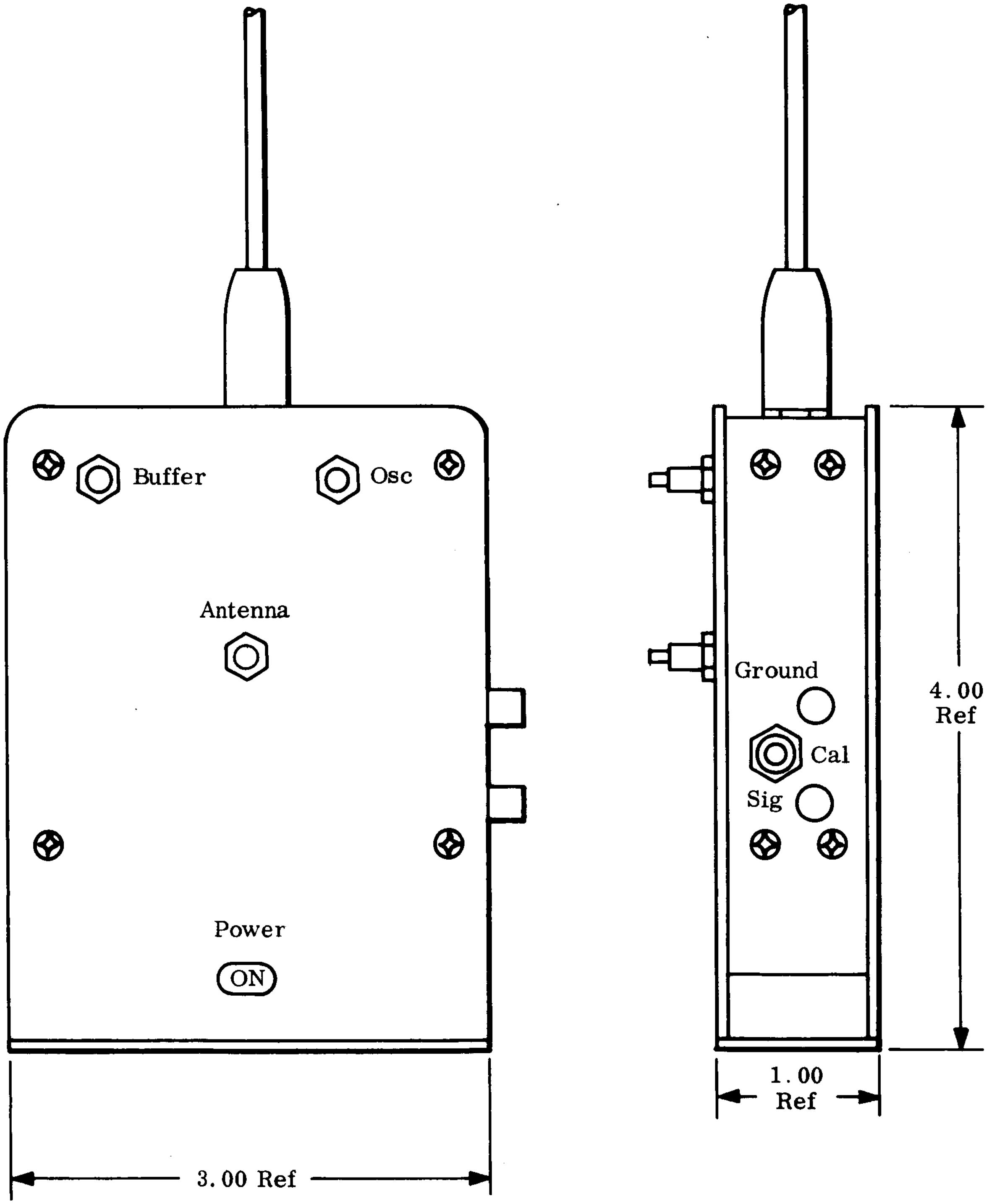

Figure 3-1. Sensor Transmitter

3.4.1 ACCURACY

Total system bias errors over a 24-hour period and a temperature range of 40°F to 140°F did not exceed 2 percent. This error is from the following sources.

Source	Error (percent)
Transmitter-Voltage Control Oscillator Frequency Shift 40°F to 140°F	1
Receiver Data Recovery Unit 40°F to 140°F	0.21
Transmitter-Voltage Control Oscillator Frequency Shift over 24 hours (measured at room temperature)	0.12
Receiver Conversion Error	1.5

An additional error of up to 2 percent may be incountered as a result of loading of the sensor by the transmitter, but this can be reduced by proper choice of sensor impedance.

The random error component of system accuracy is primarily a function of the signal-to-noise ratio at the receiver, with the noise level being a function of the environment. The receiver for this system was simulated using the GEESE analog computer facility to evaluate the effects of signal-to-noise ratios*. The results of this simulation indicate the following accuracy can be obtained for the indicated signal-to-noise ratios (see Table 3-3).

Table 3-3

Receiver Signal-to-Noise Ratio as Simulated on GEESE Computer

S/N in db	Error (percent)
+10	4.02
+16	1.91
+19	1.23
+22	0.90

---

*See Appendix B.

The transmitter tested produced a signal level of 43.2 db above 1 microvolt/meter at a range of 300 feet. For an assumed background noise level of 30 db above 1 microvolt/megacycle or 8 db above 1 microvolt/meter in a 10 kc bandwidth this results in a signal-to-noise ratio of 35.2 db. The random error component in the 5-channel system should therefore be much less than 1 percent. The total system error then should fall within the 3 percent to 5 percent specified.

3.4.2 TRANSMISSION RANGE

As discussed above, the transmitter is easily capable of useful operations at a distance of 300 feet under the assumed conditions.

3.4.3 DATA BANDWIDTH

The accuracy discussed above is for a data bandwidth of 100 cps. Operation with data at 0-80 cps is encompassed.

3.4.4 MODULATION INPUT

The transmitter was designed to accept 0 to +5 volt modulation input and an input impendance in excess of 40,000 ohms.

3.4.5 POWER SUPPLY

The tested transmitter is capable of about 80 hours of continuous operation with the battery size consistent with the package size specified. Improvements in transmitter efficiency is expected to increase battery life.

3.4.6 ENVIRONMENTAL SPECIFICATIONS

As indicated under the accuracy discussion, the system will perform satisfactorily over the specified temperature range.

3.4.7 MECHANICAL SPECIFICATIONS

Packaging is within the specified size and weight limits.

The transmitter is packaged in a 1/16-inch thick aluminum case and exceeds normal good commercial practice.

SECTION 4

PHASE A, PART 2

4.1 DISCUSSION

This part of Phase A is a study effort to examine the characteristics and define the requirements for an ultimate integral sensor carry-on checkout telemetry system for factory checkout of large space vehicles.

The philosophy of factory checkout of a space vehicle differs from that of preflight checkout, and for this reason the instrumentation requirements are different. In factory checkout, all systems are assumed to be untested and performance of all systems must be proved, while preflight checkout assumes that all systems have been previously tested, and is concerned with flight readiness and flight performance. In the flight instrumentation system, the number and location of sensors are normally quite different from that required for factory checkout. As a result, a number of extra sensors are normally added to the vehicle during the factory checkout cycle and then removed prior to shipment of the vehicle. The addition of these sensors using conventional hardwire techniques is time consuming, and the installation and removal of the wiring can lead to damage of other vehicle systems. To use conventional sensors, in many cases, also requires signal conditioning with its attendant problem of frequent calibration.

The integral sensor approach offers the possibility of overcoming the problems of the conventional sensor-hardwire method of adding sensors to the vehicle. The true integral sensor is one in which the sensor and RF transmitter are contained in the same package and where the sensed quantity has a direct effect on some characteristic of the transmitted signal. An example would be where some component of the transmitter is made deliberately temperature-sensitive such that the frequency is shifted in a direct relationship to the temperature to be measured. This type of arrangement is ideal since no tie-in to the vehicle system is required and the integral sensor transmitter can be placed in any desired location and moved at will.

Since the sensing element is designed as part of the transmitter itself, no signal-conditioning or dc amplification is required. Other sensing elements could also be incorporated in a similar manner. As an example, a tunnel diode will change its characteristics as a function of pressure. In the case of pressure sensors and others where a line must be broken or some other connection must be made to the vehicle system under test, an integral sensor probably has little advantage over a conventional sensor used with a miniature transmitter which is designed to operate with that particular sensor. In other cases, the integral sensor would not be practical at all. In the case of very high temperatures, for example, the environment for the transmitter itself would be much too severe; thus, a sensor remote from the transmitter would be indicated.

Another class of measurements are those of electrical quantities, voltage, current, etc. For these measurements, a sensor as such is not normally required and thus an integral sensor as such does not exist for this type of measurement.

An ultimate system then would consist of a mix of integral sensors and miniature sensor transmitters designed to operate with conventional or other external sensors. The sensor transmitters should be designed to accept the sensor input directly without signal conditioning. Another desirable feature is to have the separate sensor derive its excitation from the transmitter power supply or require no excitation at all. This would eliminate one more wiring connection.

The use of an RF link for data transmission obviously requires a receiver to accept and recover the data signal. The present receiver system for the integral sensor consists of one receiver for each data channel. This approach is convenient for a system with a relatively small number of channels, but for a system of perhaps 50 or more channels this technique becomes less and less practical. For an ultimate system, some combination of time and frequency multiplexing would be required.

The output of the receiver system should be compatible with the checkout ground station and would also be capable of providing an input to the vehicle onboard telemetry system. This would provide a system capable of supplying data directly to the ground station when propagation conditions permit. When the area under test is completely enclosed, or nearly so, by the vehicle skin then an output from the receiver to a channel of the onboard telemetry system would provide a practical method of transmitting the data to the ground station. The receiver output could also be transmitted by cable to the ground station if desired. This onboard use of the receiver system implies that the receiver package must be miniaturized to an extent where it would be easily portable.

The onboard application of this system introduces a number of problem areas not encountered with the system for the ATCOMED facility. Perhaps the most critical area is that of propagation. With the five-channel system, the propagation medium is nearly that of free space. The onboard system, however, must be capable of operating in an enclosed conducting cylinder. Considerable effort was devoted to a study of the propagation problem in this part of the program. The results of this study are documented in detail in paragraph 4.3.1.2 of this report. In this study, some consideration was given to propagation mediums other than air, such as the vehicle skin and a common carrier cable. This was limited primarily to experimental investigation, but the techniques look promising for difficult situations. The final proof of these techniques would, however, have to be in an actual application.

Transmitting antennas are also more critical in a vehicle application. A thin monopole antenna sufficiently rugged to withstand the accidental abuse of personnel working around it is likely to become a safety hazard to these personnel. In light of this problem, a study effort (originally scheduled later in the program) was undertaken under the General Electric CIRP Program to investigate other types of electrically and physically small antennas. This effort was followed as a part of the contract and the results of this study effort are included as a part of this report in paragraph 4.3.1.

The problem of supplying primary power to the transmitter was investigated in two study efforts. One deals with a study of self-contained power supplies and the other with an investigation of the feasibility of supplying power by means of radiated RF energy from a central transmitter. The results of these studies are included in paragraphs 4.3.3 and 4.3.4, respectively. It seems clear from the results of the radiated RF study that such a technique, while possible, is impractical because of the very high transmitter power required.

To reduce the RFI problem created by a large number of sensor transmitters, the transmitters must be turned off except for periods when data is being taken. To manually turn each transmitter on and off when there are a large number or when their positions are relatively inaccessible is undesirable. A study to investigate the feasibility of providing turn-on/turn-off capability from a remote location was undertaken. Such a capability would also serve to increase the useful life of the transmitter batteries and could provide the basis for a time multiplexing technique for the system and a remote calibration procedure. The latter two areas are beyond the scope of this contract but are being considered as part of the CIRP Program. The results of this study area are presented in paragraph 4.3.5.

To summarize briefly, the ultimate system would consist of a number of miniature sensor transmitters, some with integral sensors, transmitting checkout data to a central receiver. The receiver would be capable of being used on board the vehicle and operating into the conventional onboard telemetry system or cable for transmission to the ground station, and it would be adaptable to operating directly into the checkout ground station. The system requirements for this telemetry system are defined in paragraph 4.2.

4.2 REQUIREMENTS

An ultimate integral sensor telemetry system should meet the following basic system requirements:

a. The system must function satisfactorily in the working environment of a vehicle factory assembly area and aboard a large space vehicle during factory checkout.

b. The system must be capable of providing data of sufficient accuracy to accomplish the checkout function.

c. Maximum use should be made of integral sensors where practical, but transmitters capable of accepting inputs from a number of conventional sensor and electrical inputs are also required.

d. The transmitters must have a remote turn-on/turn-off capability, and automatic or remote calibration.

e. The receiver output must be compatible with the onboard telemetry system and capable of driving cable and compatible with the checkout ground station.

f. The transmitting antenna, due to personnel safety and reliability consideration, should be physically small and compact.

g. The power supply for the transmitter should be self-contained and should have sufficient capacity to last for the factory checkout test cycle of approximately 4 months.

h. Physical size of the transmitter package is not extremely critical but should be as small as practicable. The size of the receiver package is limited by the requirement that it be portable and capable of being installed in the vehicle.

The temperature limit for the transmitter has been chosen at 0°F to 140°F which is the temperature limits of the best available batteries suitable for this application. This limit would seem to be more than adequate for any application within a factory checkout area or on a vehicle during factory checkout. The receiver limit must be the same for this application since the receiver may also be placed aboard the vehicle.

The question of accuracy for the system is a complex one depending to a large extent on what factors are important in the particular application. In most cases the reproduction of the amplitude of signals in a given bandwidth is the only item of interest. In this case, only the random error and the system bias error are of consequence. Another case to consider is the after-the-fact deduction of the cause of a malfunction where a number of measurements are involved. In this case, the question of the order in which events occurred may be of primary importance. Here the timing or phase errors of the system becomes a factor in setting the system accuracy. In yet another case, it may be that the exact reproduction of a complex waveform is required. This would be a very difficult task since it would require that the entire system have linear phase characteristics. For a factory checkout operation the reproduction of the amplitude of simple signals is in general the only case of interest. A further discussion of timing error is presented in Appendix A.

The system accuracy for this application should be equivalent to that obtainable from a conventional telemetry system using the same modulation technique. According to data released by Astrionics Laboratory, MSFC, the accuracy possible with a typical well-calibrated FM/FM system is 1.0 percent. Since the integral sensor system is an FM/FM system, a random error component of 1.0 percent of full scale or better will be required.

The types of sensors to be used for factory checkout would in general be the same types as used for the flight system. A review of the flight system transducers for SA-5 shows the classes of sensors and their output characteristics (see Table 4-1).

Since this is an in-hangar checkout operation, some of these sensor types would not be required. The vehicle is not moving; therefore, there would very likely be no need for accelerometers or rate gyros. The level probes also should not be required since the vehicle is not fueled during hangar checkout. The high-intensity microphone should not be required in a hangar environment. This leaves, for primary consideration, the pressure gages, strain gages, tachometers, and temperature gages. The sensor transmitters should be capable of operation with these types of sensors. To achieve the maximum advantage from this type of system, the sensor transmitter should be adapted to the particular sensor to be used. As an example, the sensor transmitter can be designed to operate directly from a change in resistance which would eliminate

Table 4-1

Flight System Transducers and Their Output Characteristics

Type Accelerometers	Sensors Output Characteristics
Piezoelectric Type	50 kilohms to 100 megohms minimum load (5 to 20 Mv/g usually used with ac amplifier)
Electromechanical servo	0-5 vdc
Pendulum	5 kilohms output impedance 2.5 v/g
Level Probes	
Optical type	On-Off
Capacitance	Continuous - low impedance - 0-5 v output
Microphones	
Piezoelectric Type	1.5 Mv at 120 db
Pressure Gages	
Resistive (pot)	2 kilohms to 10 kilohms
Vibrating wire	0.7 v to 1.0 v 50 kilohms load
Variable reluctance	5 kilohms - 0 to 5 vdc
Resistive strain gage	350 ohms, reading from +15 to -15 mv
Rate Gyros	
Angular velocity	Electrical output
Strain Gage	120 ohms, 240 ohms, 350 ohms
Tachometers	
Inductance type	25 cps to 167 cps, 5 volts
Temperature Gages	
Thermoresistive	100 ohms to 2 kilohms
Thermistor	2 kilohms to 10 kilohms
Thermocouple	Mv output - very low impedance depending on length and wire size.
Calorimeter	Similar to above

the need for excitation for the potentiometer-type pressure transducers. This would eliminate the need for tying into a regulated supply voltage for the transducer. This limits the number of different sensors a given transmitter can utilize but, for this application, this limitation should not be objectionable since the same sensors are used with a number of vehicles.

It is also recognized that special sensors will probably be used during factory checkout and, here again, the best approach is to adapt a transmitter to match the characteristics of the sensor. In this way, the system can be optimized for the task at hand.

The desirability of having remote turn-on and turn-off capability has already been discussed and the results of the study effort in this area are included in this report. Calibration is a similar problem in that manual calibration of each individual transmitter at frequent intervals is undesirable. One approach is to increase the stability of the system to a point where calibration is not required except over very long periods. This approach is not very practical since to implement it would probably be beyond the state of the art in component stability. A more desirable approach is the addition of calibration on remote command or to have calibration accomplished automatically. One of these approaches would be recommended for an ultimate system.

To summarize briefly, this ultimate system would have the following characteristics:

a. The system would be capable of operation with specified accuracy over the temperature range of from 0°F to 140°F.
b. The system would have a random error of 1 percent of full scale or better, exclusive of phase or timing error.
c. A mix of integral sensor transmitters and sensor transmitters for use with conventional sensors would be available.
d. Remote turn-on and turn-off, along with a remote or automatic calibration technique, would be provided.
e. The receiver would be capable of being used aboard a space vehicle with an output compatible with the onboard telemetry system, capable of driving a cable from the vehicle to the ground station and capable of providing an output to the ground station directly for use where a line-of-sight transmission path exist.
f. Evaluation of compact antennas to determine their applicability would best be performed during an actual onboard test of the transmitters.
g. The transmitter power supply would have sufficient capabity to last for four months of intermittent operation of approximately two hours per day.

h. In the ultimate system, maximum use would be made of microcircuit techniques to achieve small physical size for the transmitters and receivers.

Other desirable system characteristics would no doubt be defined in an actual onboard system application. To this end a follow-on program for an onboard system is recommended as a next step in the application of the integral sensor system to stage checkout. The description of this program and a system specification is detailed in Section 5.

4.3 SUPPORTING STUDIES

The study described in the following paragraphs was undertaken to investigate areas of special interest to the application of integral sensor and sensor transmitters to factory stage checkout. The studies are listed below:

a. Propagation of sensor signals.
b. Electrically small antennas.
c. Transmitter power supplies.
d. Radiated RF energy as a power source.
e. Remote control of transmitter radiation.

4.3.1 PROPAGATION OF SENSOR SIGNALS

The problems likely to be encountered in transmitting the sensor signals were studied in two parts. The first part was a study of the characteristics of free space transmission in the frequency range from 10 megacycles to 1 gigacycle. This part of the study primarily described transmission losses under the most ideal propagation conditions that might ever be expected. Free space propagation tests using 27 Mc sensor transmitters were also performed.

The second part of the study was an investigation of signal attenuation under what might be considered worst case conditions; that is, transmission within small conductive enclosures. Tests were conducted, using 27 Mc sensor transmitters and receivers, for comparison with theoretical data.

Neither free-space nor enclosed-space studies were limited solely to the investigation of signal attenuation. Problems of antenna size and matching were also reviewed.

4.3.1.1 Transmission Loss in Free Space

The basic transmission loss, L_{bf}, for isotropic antennas in free space is:

$$\underset{db}{L_{bf}} = 10 \log \frac{P_r}{P_a} = 10 \log \frac{(4\pi d)^2}{\lambda^2} = 36.58 + 20 \log d + 20 \log F_{Mc} \qquad (4\text{-}1)$$

The above considers an idealized isotropic antenna in free space radiating a power P_r. Such an antenna produces a field intensity of $P_r/4\pi d^2$, watts per unit area, at a distance d provided that $d \gg \lambda$. Since the absorbing area of a perfectly conducting isotropic receiving antenna in free space is $\lambda^2/4\pi$, the power available, P_a, from such an antenna is $P_r\ (\lambda/4\pi d)^2$. Figure 4-1 shows this basic transmission loss as a function of frequency. It should be pointed out that as a result of direct coupling between the transmitting and receiving antennas via their induction and electrostatic fields, the relationship illustrated by equation 4-1 is true only for basic transmission losses greater than 30 db or for distances greater than 90 feet at 27 Mc.

In an actual transmission system, there will always be some antenna gain above that of an isotropic antenna. For example, with two non-directional infinitisimal dipole antennas on the same plane and separated by a distance greater than a wavelength, the total antenna gain will be 3.5 db. The transmission loss for such a system is 3.5 db less than the basic transmission loss shown in Figure 4-1. From equation 4-1 it can be seen that the transmission loss increases with frequency because of the decreasing absorbing area $(\lambda^2/4\pi)$ of the receiving antenna. Thus, it is usually desirable to use the lowest frequencies available providing that antenna coupling losses are not considerable. If antenna gain is considered with equation 4-1, the system transmission loss L_F can be expressed as:

$$L_F = 36.58 + 20 \log d + 20 \log f_{Mc} - G_r - G_t. \qquad (4\text{-}2)$$

where G_t and G_r are transmitter and receiver antenna gains.

Continuing further with the example, consider one of the antennas to be replaced with a highly directional antenna having a gain:

$$G_{db} = 10 \log A_e + 20 \log F_{Mc} - 38.54. \qquad (4\text{-}2a)$$

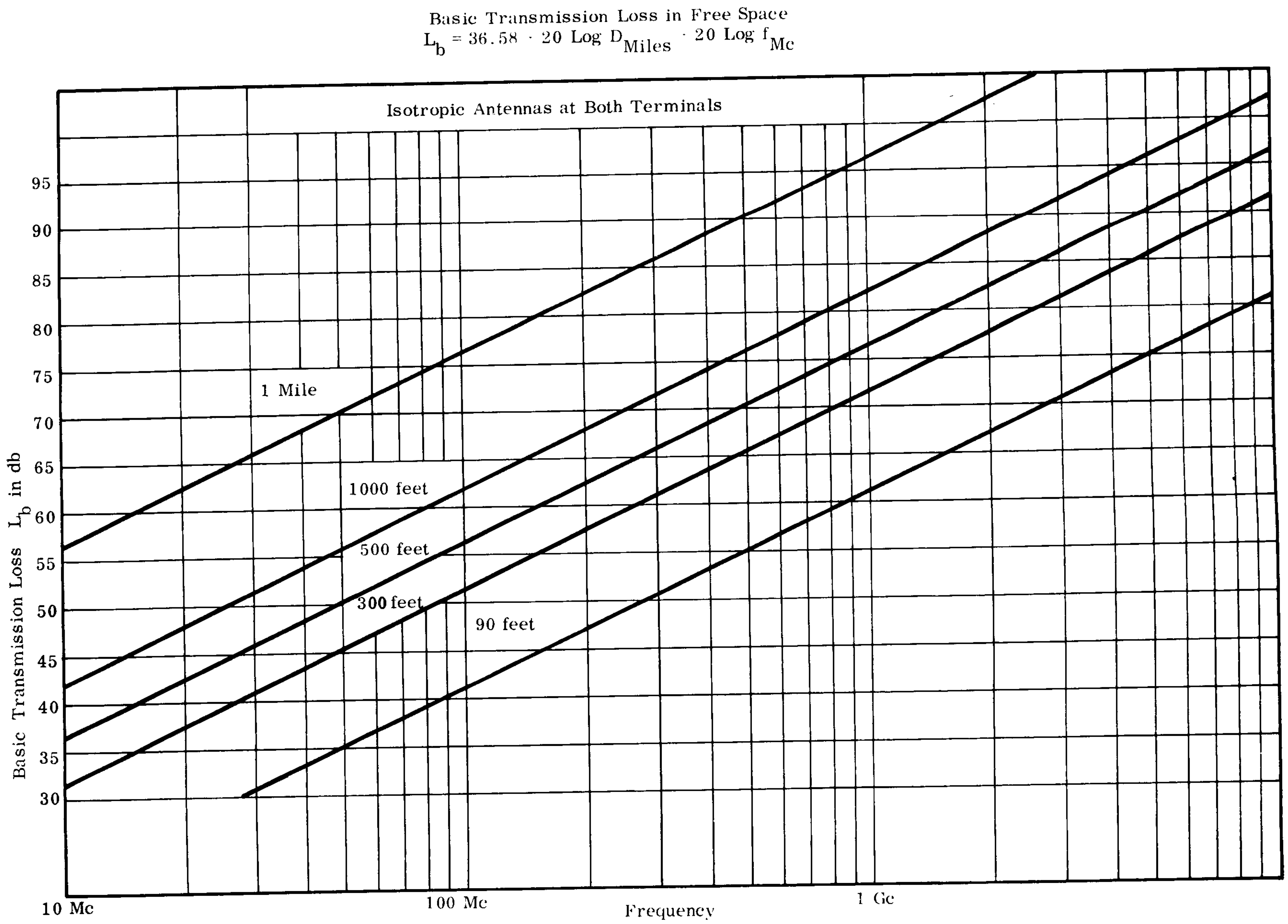

Figure 4-1. Basic Transmission Loss as a Function of Frequency

where $F_{Mc} > 100/(A_e)^{\frac{1}{2}}$, and A_e is the effective absorbing area of the directional antenna, or about 50 to 70 percent of the actual antenna area of a large parabolic type antenna. In this case, the system transmission loss can be expressed using equations 4-2 and 4-2a as:

$$L_f = 75.12 + 20 \log d - 10 \log A_e - G_t \,. \qquad (4\text{-}3)$$

It can be seen that the 20 log F_{Mc} terms in equations 4-2 and 4-2a cancel and the system loss as defined by equation 4-3 appears to be independent of frequency and is a function of distance and antenna size only.

Carrying the example still further, if directional antennas are used at each terminal, the free-space transmission loss is:

$$L_f = 113.67 + 20 \log d - 20 \log F_{Mc} - 20 \log A_e . \qquad (4\text{-}4)$$

It can be seen in this case that the free-space transmission loss now decreases as frequency increases.

The above examples illustrate that in free-space transmission the type of antennas used in a system can determine the variation of the transmission loss with frequency.

Another important variable that must be considered in determining total system losses is the antenna-coupling loss. At lower frequencies this loss will be most significant. This loss is discussed in detail in paragraph 4.3.4 of this report. Briefly, this loss is a function of how closely the low radiation resistance of a physically small antenna can be matched to the transmitter output or to the receiver input.

The total sensor transmission system losses, including the antenna coupling loss, as a function of frequency, are shown in Table 4-2. In the example considered in this table, it is assumed that the transmitting antenna will be limited in size. This table was compiled using equations 4-2 and 4-2a and by evaluating coupling loss, A_{db} from:*

$$A_{db} = 10 \log \frac{R_a}{R_a + R_L} \qquad (4\text{-}5)$$

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*L. C. Humphrey, Efficiency of Small Antennas, General Electric Company, TIS R64ELC54, December 1964.

where R_a is the antenna radiation resistance and R_L is the output resistance of the sensor transmitter or the input resistance of the sensor receiver. R_L is assumed to be 20 ohms.

Table 4-2

Summary of Sensor Transmission Losses in Free Space
(Transmitting Antenna Restricted in Size)

Frequency (Mc)	Range (feet)	Basic Transmission Loss	Antenna Gain		Antenna Coupling Loss		Total System Loss
		$L_b f$ db	$G_t{}^1$ db	$G_r{}^2$ db	$A_t{}^1$ db	$A_r{}^2$ db	L_f db
10	300	31.58	1.76	1.76	24	3	55.1
20	300	37	1.76	1.76	18.3	3	54.8
27	300	40.5	1.76	1.76	14.5	3	54.5
50	300	45.7	1.76	2.15	10.5	3	55.3
100	300	51.6	1.76	2.15	5	3	55.7
200	300	57.6	1.76	7.5	3	3	54.3
500	300	65.6	2.15	15.5	3	3	54
1000	300	71.6	2.15	21.5	3	3	54

Notes:

1. Transmitter antenna is assumed to be a 12-inch monopole antenna on a good ground plane.
2. Receiver antenna is assumed to be a half-wave dipole from 10 Mc to 100 Mc and a parabolic dish with an effective area of one square meter, from 200 Mc to 1 Gc.

It can be seen from Table 4-2 that although the basic transmission loss increased with frequency, these losses were offset by the higher antenna coupling losses at lower frequencies and the additional gain available if a dish is used as a receiving antenna at higher frequencies. As a result, the total system losses are almost independent of frequency. This, of course, is only true for free-space transmission and for the range and system configuration assumed in this example.

The total sensor transmission system losses are shown in Table 4-3 as a function of frequency with both the transmitting and receiving antennas limited in size to 12 inches.

Table 4-3

Summary of Sensor Transmission Losses in Free Space
(Transmitting and Receiving Antennas Restricted in Size)

Frequency (Mc)	Range (feet)	Basic Transmission Loss L_{bf}	Antenna Gain*		Antenna Coupling Loss*		Total System Loss
			G_t db	G_r db	A_t db	A_r db	L_f db
10	300	31.58	1.76	1.76	24	24	76.1
20	300	37	1.76	1.76	18.3	18.3	70.1
27	300	40.5	1.76	1.76	14.5	14.5	66
50	300	45.7	1.76	1.76	10.5	10.5	63.2
100	300	51.6	1.76	1.76	5	5	53.1
200	300	57.6	1.76	1.76	3	3	60.1
500	300	65.6	2.15	2.15	3	3	69.3
1000	300	71.6	2.15	2.15	3	3	73.3

*Both transmitter and receiver antennas are assumed to be 12-inch monopole antennas on a good ground plane.

It can be seen from Table 4-3 that the total system losses are very much dependent upon the transmission frequency. This was not true in Table 4-2. In the example described in Table 4-3, the size of the transmitting and receiving antennas have been limited, and it appears that an optimum operating frequency exists at around the 100 Mc range.

A free-space propagation test was made using one of the early model 27 Mc sensor transmitters and a Empire Device field intensity receiver T-1/NF 105 with a LP 105 loop antenna. The results of the test are plotted in Figure 4-2. The field strengths measured were 5 to 8 db less than what might be calculated from equation 4-2 with an estimated radiated power of 9.2 microwatts.

Recently, a later model of the sensor transmitter was tested and field strengths approximately 6 db higher than those shown in Figure 4-2 were measured.

4.3.1.2 Transmission Loss in Enclosed Space

If the sensor transmitter is completely enclosed by conducting surfaces, there will be practically no radiated RF energy to the outside. Good conductors are effective RF

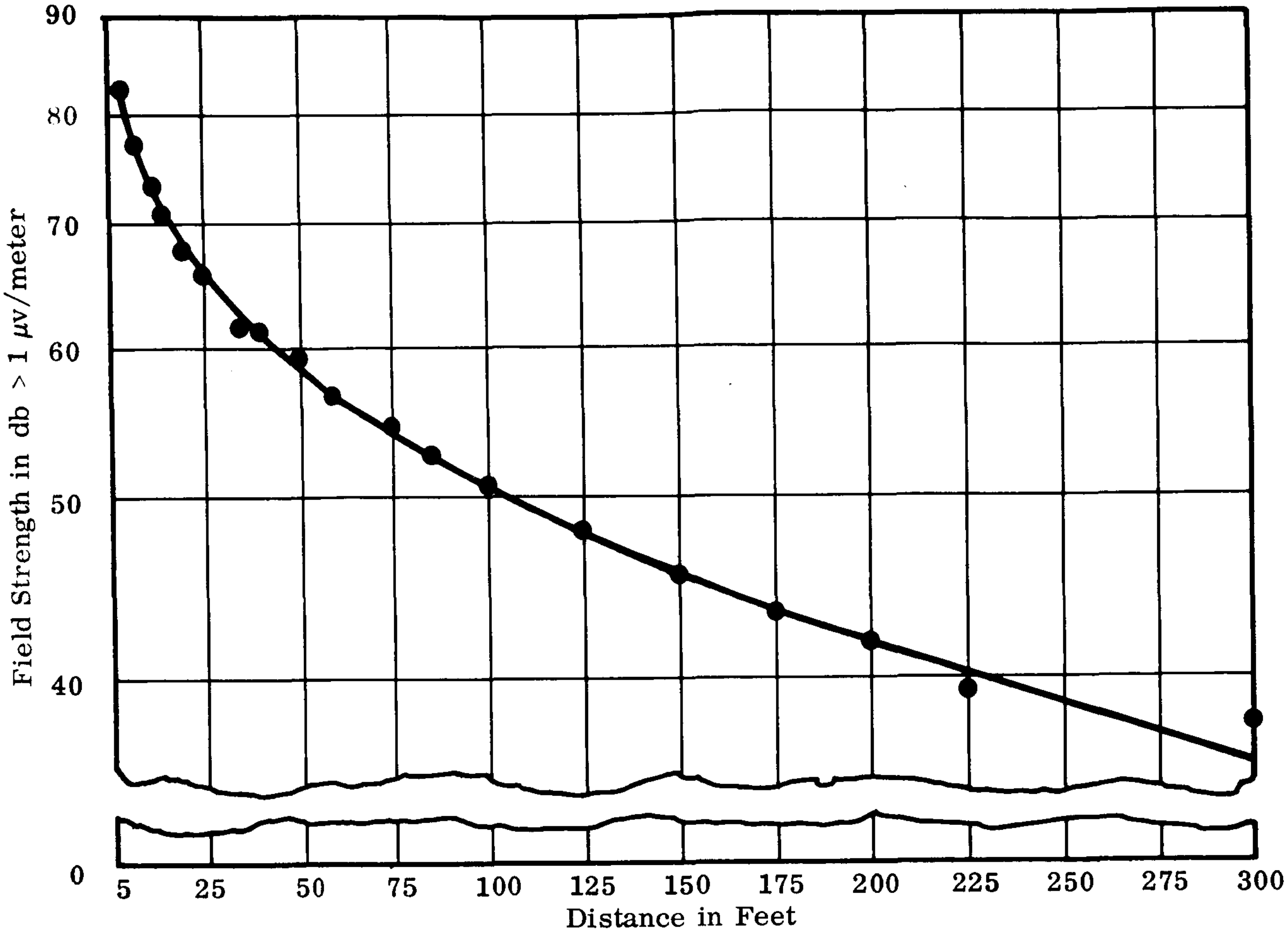

Figure 4-2. Sensor Transmitter Free-Space Propagation Tests

shields and any field set up inside the enclosure by a sensor transmitter will be greatly attenuated by the skin of the vehicle, leaving the outside of the vehicle free of radiated fields. Also, transmission by simple conduction from within the enclosure will not be practical, since the skin depth at the frequencies of interest will be only 10^{-3} to 10^{-4} inch.

If the sensors are being used inside a launch vehicle, the skin of the vehicle or metal equipment inside sections of the vehicle will act as effective RF shields. When this condition exists, it will be necessary to relay the signals from the sensor transmitters within the vehicle to receivers on the outside. Prior to the assembly of the entire vehicle, some partial openings will of course exist on the vehicle. These openings can be used for relaying of signals.

This section of the propagation study will examine the problem of transmitting signals within a relatively small and simple conductive enclosure. Transmission losses within such an enclosure will be highly dependent upon the size and shape of the enclosure as well as on the location of conducting metals and dielectrics within the enclosure. The physical size of the enclosure is particularly significant because if the critical dimensions of an enclosure are less than the cutoff wavelength of the enclosure, substantially higher than free space signal attenuation will result.

In order to understand this cutoff attenuation more clearly, consider Figure 4-3.

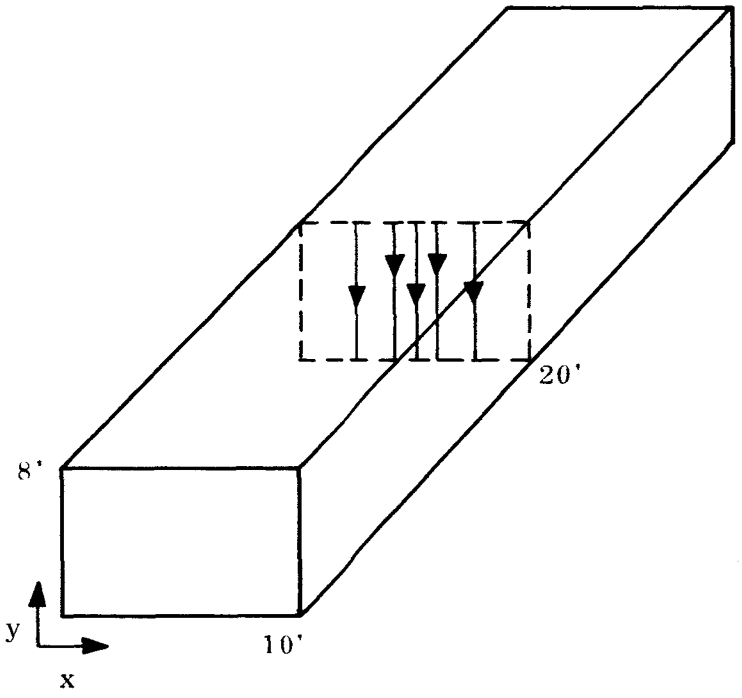

Figure 4-3. The Rectangular Conductive Enclosure Used in the Example. The Dominant TE_{10} Mode is Indicated in the X-Y Plane Only.

Figure 4-3 can be considered to be a section of a rectangular conductive enclosure having a width of 10 feet and a height of 8 feet. Since the length of enclosure is greater than the cutoff wavelength at 27 Mc, the illustration can be considered to be a section of rectangular waveguide and not a cavity. In any waveguide, the mode of transmission that has the lowest cutoff frequency is called the dominant mode. The dominant mode in a rectangular waveguide is the TE_{10} mode indicating that the wave is of the transverse electric type; that is, there is a single half-wave variation of transverse field along the width dimension and no variation of transverse field along the height dimension. The typical field distribution of the dominant TE_{10} mode is shown in Figure 4-3. Considering the TE_{10} mode to be dominant, the cutoff wavelength of the guide can be calculated from*:

$$\lambda_c = 2a \qquad (4\text{-}6)$$

where a is the width or critical dimension of the guide for the TE_{10} mode.

λ_c in the example is 20 feet. Thus the cutoff frequency for this guide is 49.2 Mc. The TE_{10} field strength in the guide as a function of distance, d, along the length of the guide from the point of excitation is:

$$E = E_o e^{-\alpha d} \qquad (4\text{-}7)$$

E_o is the initial amplitude of the field at the excitation point and α is the attenuation. The attenuation, α, below cutoff, can be expressed as**:

$$\alpha = 8.69 \left[\frac{(2\pi)^2}{\lambda_c^{\,2}} - e \frac{(2\pi)^2}{\lambda^2} \right]^{1/2} \quad \text{db/feet} \qquad (4\text{-}8)$$

where λ is the wavelength of the excitation frequency and e is the dielectric constant of the medium in the guide. For the example, at a 27 Mc excitation frequency, the attenuation is 2.3 db/foot. If a circular section of waveguide with a diameter of 10 feet was used in the example, the attenuation would be approximately 2.8 db/foot.

At this point, it would be of interest to discuss the shielded room tests made using a 27 Mc sensor transmitter and a NF 105 receiver with a loop antenna. The shielded room used in the test had the same dimensions as the example. The receiver was located about 5 feet from the back and side wall of the room and the sensor transmitter was moved along the length of the room on the centerline. The results of this test are shown in Figure 4-4. The variation of the signal strength with distance, or attenuation rate, was 2.6 db/foot. This value is only 0.3 db less than the value calculated in the previous example.

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* S. Ramo and J. R. Whennery, Fields and Waves in Modern Radio, p367, Wiley & Son, 1953.

**T. Moreno, Microwave Transmission Design Data, Dover 1948.

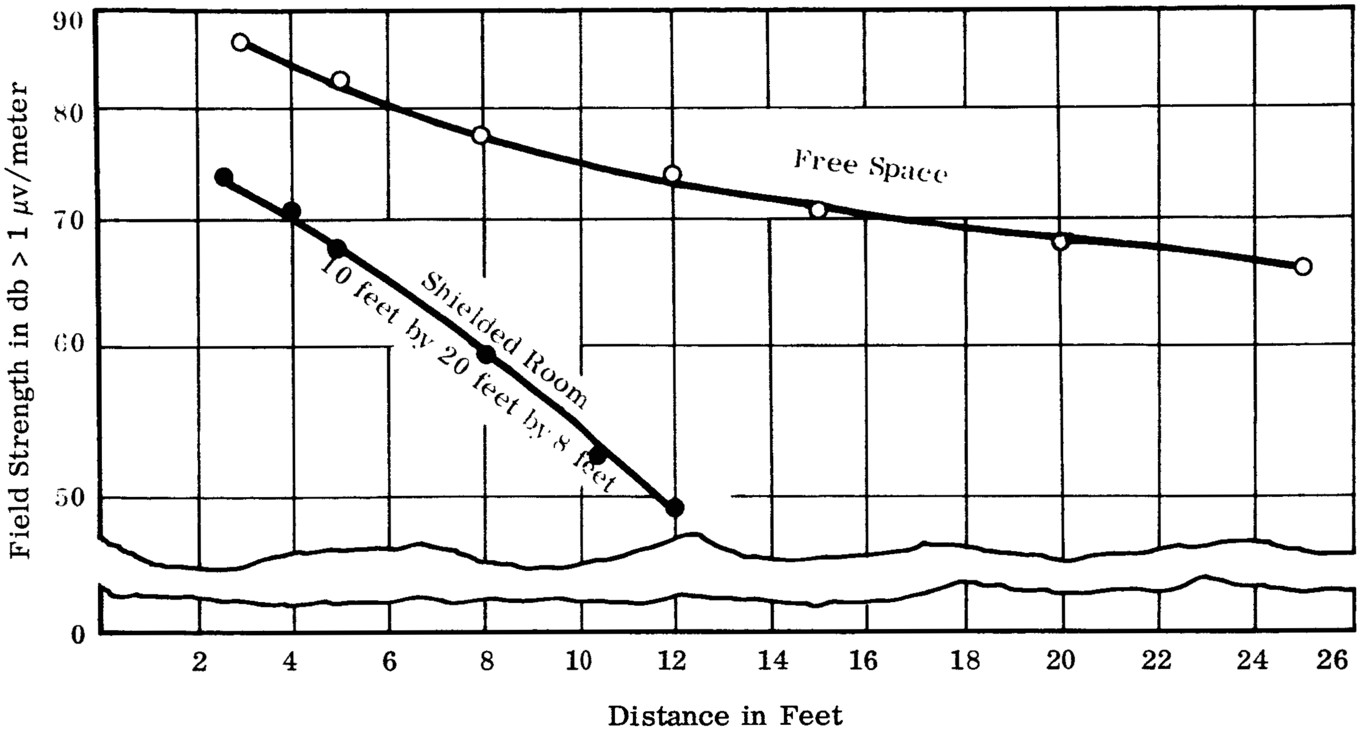
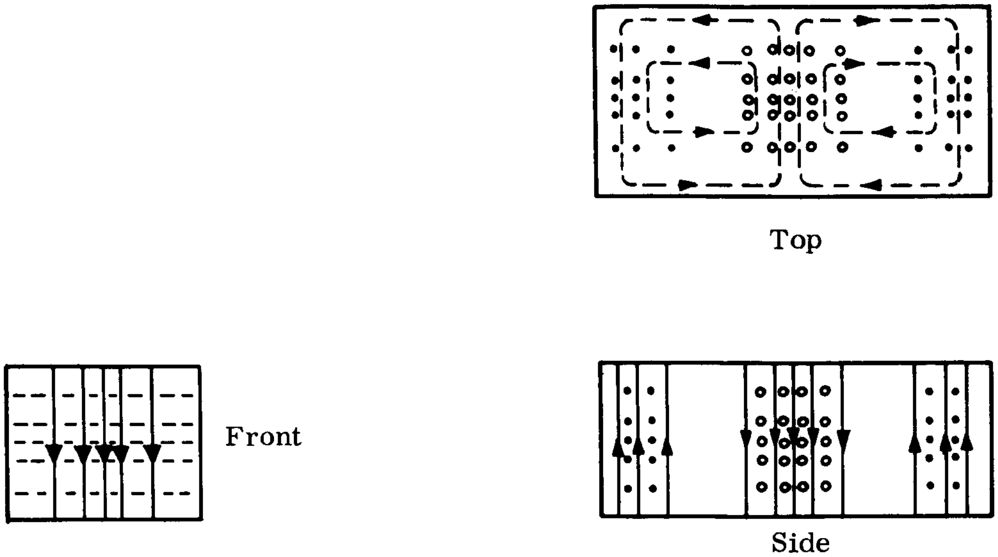


Figure 4-4. Sensor Transmitter Propagation Tests Using T-1/NF 105 Receiver with LP 105 Loop Antenna

Figure 4-4 is a composite plot including Figure 4-2. It shows the substantial difference between free space and enclosed space attenuation rates below cutoff.

Figure 4-5 is a sketch of the electric and magnetic fields of dominant TE_{10} mode in a rectangular waveguide or in the conductive enclosure shown in Figure 4-3.

The conduction current in the enclosure is confined to the inner surface of the "guide," the depth of penetration being determined by skin depth considerations. The direction of the current flow is orthogonal to the direction of magnetic field at the inner surface of the enclosures. The lines of current flow for the dominant mode are shown in Figure 4-6.



Top

Front

Side

Figure 4-5. Electric and Magnetic Fields of the Dominant TE_{10} Mode in a Rectangular Waveguide. Solid Lines Indicate Electric Field, and Broken Lines Indicate Magnetic Field.

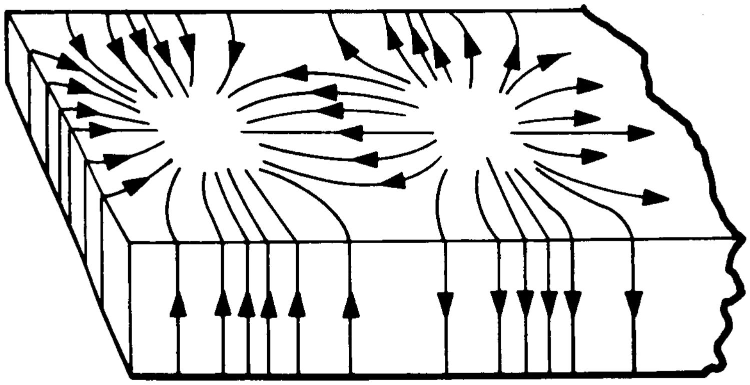


Figure 4-6. Current Flow in the Walls of a Rectangular Waveguide Propagating the TE_{10} Mode

Another series of tests were conducted in the 8 foot by 10 foot by 20 foot shielded room to investigate the feasibility of utilizing these conduction currents to transmit sensor data. A sensor transmitter with a 12-inch whip antenna was placed in various locations within the room. In one receiver arrangement, the tip of the conventional 24-inch whip antenna of a sensor receiver was grounded to the wall of the room, and the chassis was grounded to the floor; thus, directly coupling to the conduction current. In another receiver arrangement, the antenna was replaced with a ten-foot length of insulated hookup wire that was run along the walls of the enclosure.

The received signal was measured at the output of the IF section of the receiver and in each case the receiver antenna input circuit was returned for maximum received signal. When the results of the tests were compared to previous radiated tests made in the shielded room, it was found that the conductive tests with the insulated wire resulted in received signals approximately 15 db higher. Lower received signals were measured with the tip of the 24-inch antenna grounded; however, these signals were still 6 db higher than signals received by radiation over similar distances. When using the grounded 24-inch receiving antenna it was confirmed that the conduction currents were not uniformily distributed on the inside of the enclosure. In fact, a pattern not unlike that shown in Figure 4-5 may have been present.

In summary, it can be concluded that when a conductive enclosure has critical dimensions less than its cutoff wavelength, signals radiated in that enclosure will suffer substantially greater than free-space attenuation. This high loss may be circumvented by propagating signals conductively on the inner surface of the enclosure. However, the relative position of the transmitter and receiver is sometimes more significant than is the range in determining the maximum received signal. For this reason, the feasibility of propagating signals conductively can only be conclusively demonstrated by actual tests on the launch vehicle.

4.3.1.3 Determination of Transmitter Power Required

The power output required from the sensor transmitter at a given frequency will not only be dependent upon system transmission loss already discussed elsewhere in this report, but it will also be dependent upon the accuracy and rate at which the information must be transferred. C. E. Shannon expressed this relationship in a form similar to:

$$C = B \log_2\left(\frac{1 + S_v}{N_v}\right), \text{ bit/second} \qquad (4\text{-}9)$$

where C is information rate, B is the system bandwidth, and S_v/N_v is the signal voltage-noise voltage ratio. This expression, although formulated for an ideal and not yet very practical communication system, can be used to point out the various system tradeoffs that can be made in a practical communication system design. For example, one can trade bandwidth for signal-to-noise ratio, realizing of course, that limits exist because noise itself increases with bandwidth and that a minimum signal-to-noise voltage may exist for a particular type of modulation, and for a given probability of error or accuracy in transmission.

In the case of the sensor transmitter system, the information rate has been fixed by operational requirements at about 100 cycles per second. It was estimated in the analog simulation study, that for 1 percent accuracy, an approximately 22-db signal-to-noise ratio would be required at the output of the receiver IF strip. Also, it was determined that a 10-kc receiver bandwidth would be adequate to allow for a 100-cycle information rate and for the carrier frequency shift over the wide operating temperature range.

Considering all of the above, the transmitter power can be estimated by first determining the environmental noise in a 10-kc bandwidth. Then the required received signal level can be determined based on the 22-db signal-to-noise ratio necessary for the required accuracy. Finally, the required transmitter power can be estimated.

A recently completed MSFC survey of electromagnetic interference in the vicinity of the IU checkout area in building 4708 indicates that interfering signal levels of 60 db greater than one microvolt per megacycle bandwidth might be expected in the 27 Mc region. If it is necessary that the sensor transmitter provide a signal at the receiver 22 db higher than these RFI signals, then the transmitter (10 kc bandwidth) will be required to produce a signal 60 db greater than one microvolt per meter, or about 1000 microvolts/meter in a 10 kc bandwidth at 300 feet.

This substantial signal level would require modification of the presently developed sensor transmitters to increase the power output. It is more realistic to assume that each transmission frequency in the 27 Mc region will be so chosen that it will not fall within the bandwidth of these interfering signals. In this case, if a background noise level of 30 db greater than one microvolt per megacycle is assumed, then a signal level of 30 db greater than one microvolt per meter will be required for a signal-to-noise ratio of 22 db. The present sensor transmitter can provide a signal level of 43.2 db greater than one microvolt per meter at this distance.

4.3.2 ELECTRICALLY SMALL ANTENNAS

General Electric has a continuing company sponsored effort to design compact antennas compatible in size with the sensor transmitters and receivers. Some of the results of this investigation pertinent to this MSFC application will be discussed below.

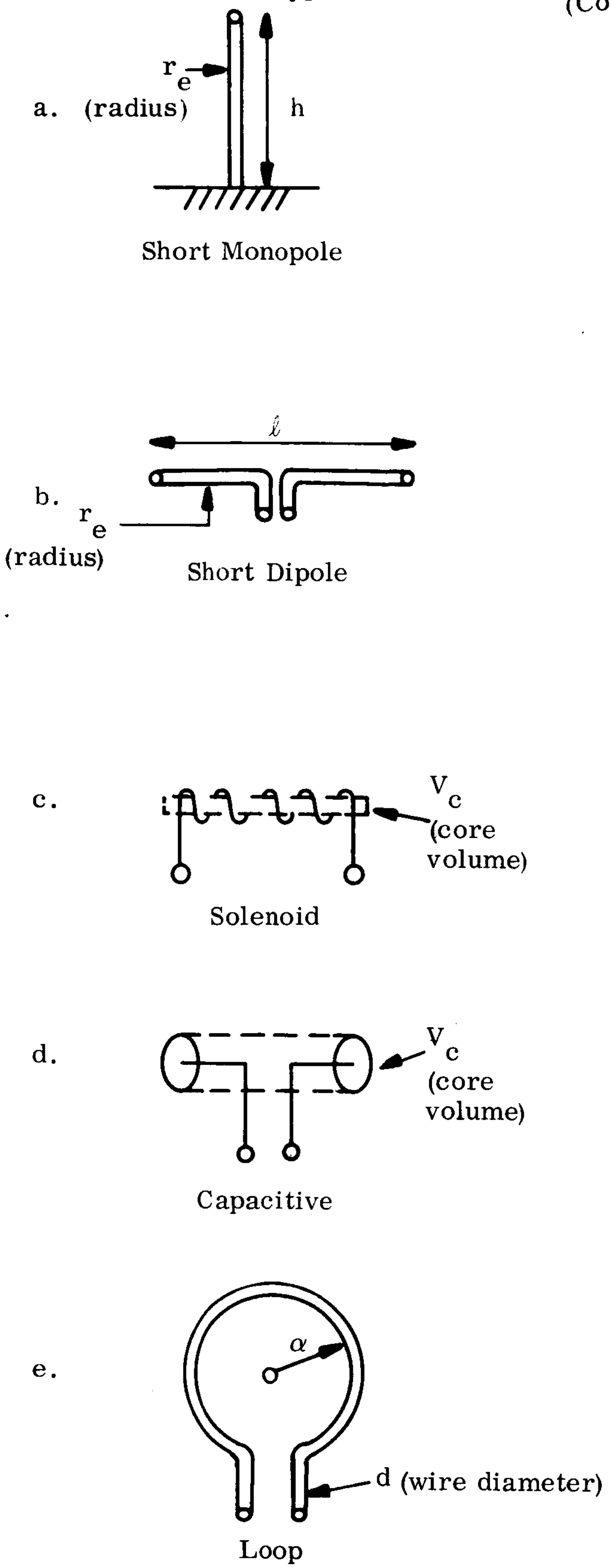
In general, at the relatively low frequencies of interest, any compact antenna will be an electrically short antenna. An electrically short antenna is not an efficient antenna because its input impedance cannot be matched for maximum power transfer. The input impedance of a typical electrically short antenna is made up of a radiation resistance often much less than one ohm, and of an input reactance often capacitive and usually greater than 100 ohms. In fact, it is not unusual that the resistance loss in the required matching circuits alone are much greater than the radiation resistance of the antenna, thus making an efficient match impossible. The design of an optimum antenna is therefore a compromise, where an attempt is made to achieve efficiency for a given antenna size in spite of the fact that this maximum efficiency can never be quite high. Most often, this compromise is carried out by changing the antenna configuration to modify the antenna input impedance for maximum power transfer, while maintaining a constant desirable antenna volume.

Some of the antenna types studied for use with the sensors are shown in Figure 4-7. Table 4-4 defines the terms used in Figure 4-7 to describe the relative efficiency of each antenna.

Figure 4-8 is a plot of the variation of efficiency of each of the antennas as the configuration of the antenna is changed. An unloaded Q of 200 was assumed for these curves.

It can be seen from Figure 4-8 that a fat monopole antenna is the most efficient antenna type considered. For example, at 27 Mc, consider a monopole with a radius of 5.5 mm. It can be seen from Figure 4-8 that for a relative efficiency of 0.04 with this fat monopole, a $(h/\lambda)^3$ ratio of 14×10^{-6} is required. An $(h/\lambda)^3$ ratio of 14×10^{-6} results in a monopole height of 265 mm.

The physical volume of such a monopole just described is 25×10^{-6} cubic meters. If the same efficiency is required of a capacitor or solenoid antenna, an antenna volume of 18.3×10^{-3} cubic meters is necessary. Or looking at it another way, if the capacitor or solenoid antenna volume is made equal to the physical volume of the monopole, the relative efficiency would be only 0.05×10^{-3}. Thus, the monopole antenna for a



Antenna Type	Relative Antenna Efficiency (Compared to a Perfect Dipole)
a. Short Monopole	$\eta = BQ\left(\frac{h}{\lambda}\right)^3$
b. Short Dipole	$\eta = \frac{BQ}{8}\left(\frac{\ell}{\lambda}\right)^3$
c. Solenoid	$\eta = 13.3\,\frac{\mu_{eff}Q}{\lambda^3}$
d. Capacitive	$\eta = 13.3\,\frac{V_cQ}{\epsilon_{eff}\lambda^3}$
e. Loop	$\eta = GQ\left(\frac{\alpha}{\lambda}\right)^3$

Figure 4-7. Antenna Configurations and Efficiencies

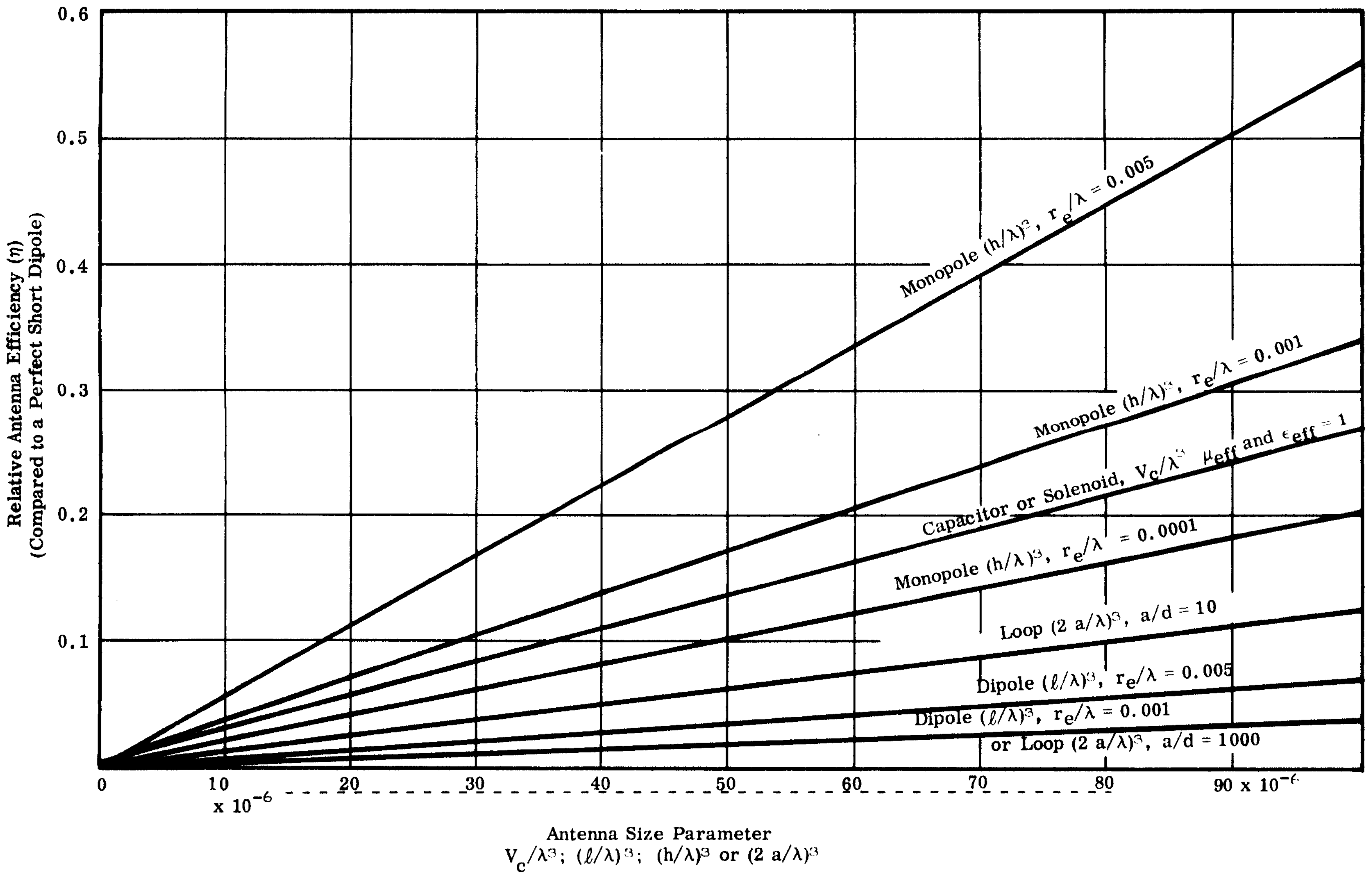


Figure 4-8. Relative Antenna Efficiency versus Antenna Size Parameters (Q = 200)

given volume is far more efficient than the capacitor or solenoid antennas. This same method of comparison can be used for a small dipole antenna or a loop antenna.

Table 4-4
Definition of Terms Used in Figure 4-7

η, relative antenna efficiency (compared to a perfect short dipole).

r_e, radius of antenna element.

λ, wavelength in free space.

B, reactance variation factor, a function of r_e/λ, where:

r_e/λ	B
0.005	28
0.0025	25
0.001	17
0.0005	12
0.0001	10

ϵ_{eff}, effective dielectric constant.

μ_{eff}, effective relative permeability.

V_c, volume enclosed by solenoid or between capacitor plates.

Q, unloaded Q of antenna.

G, loop configuration factor, a function of loop diameter, α, and wire diameter d where:

a/d	G Single Turn	G Multiturn
10	43.6	41.6
100	24.3	23.3
1000	17.4	16.8

Relative efficiency and small size are not the only considerations to be made in antenna selection. Antenna directivity and the influence of nearby conductive surfaces on a particular type of antenna are also important. For example, a loop antenna, although relively less efficient, may be a better choice for a particular sensor transmitter because it is less effected by nearby structures. In many applications, the transmitter may have to be located very close to large metal surfaces.

The permeability of ferrite material is very temperature dependent. If ferrite cores were used, the antenna Q would have to be artificially dropped to broaden the antenna enough to cover the possible drift of the tuned antenna circuit. For this reason, ferrite core antennas are not considered feasible for operation throughout a wide temperature range.

From the antenna work done so far, it is apparent that although the monopole antenna is the most efficient antenna for a given volume, a single type of compact sensor antenna will not be optimum for all conditions of environment and geometry under which the units will be operated. For this reason, Company-sponsored experiments are now underway to develop several specific antenna types considered to be optimum for particular propagation conditions.

4.3.3 TRANSMITTER POWER SUPPLY

To obtain the utmost flexibility from the integral/sensor transmitter device, the power supply should be self-contained in the transmitter package. There may be occasions in specific applications of the device where the power may be available from the equipment being measured or from other nearby equipment. This, however, is a special case and would not in general apply.

Self-contained power immediately brings to mind batteries; but there are other devices which should be considered. These devices derive energy from some external source such as light, heat, or magnetic fields. Examples of these devices would be solar cells, thermo-electric generation, and Hall effect generators. These devices then convert some external form of energy into electrical energy and are, therefore, dependent on the availability of the external energy source. One can visualize a specific application where one of these methods of supplying power could be advantagous. There are also large numbers of applications where none of these sources exist, at least for realistic amounts of power. If we then confine attention to a generally applicable power supply, the obvious choice is a battery.

Batteries come in numerous types and thus arises the problem of choosing the right battery for the job. Batteries are basically divided into two groups. Primary batteries and secondary or rechargeable batteries. Primary batteries are irreversible in in that the materials of the battery are used up; an example of a primary battery is a flashlight battery. Secondary batteries, on the other hand, make use of chemical reactions that can be reversed by supplying electrical energy to a cell that is recharging.

In this application, the battery needs to be capable of supplying power for long periods of unattended operation. This implies that the battery must have a large capacity or be recharged in place. To recharge the battery, energy must be supplied to the battery by some means other than wire to be useful. No matter what the source, more energy must be supplied to the cell than was removed during discharge. The charging rate is limited by the cell construction to the same as the 10-hour discharge current and it normally requires 14 to 16 hours to charge a battery that has been discharged to its normal cutoff voltage of 0.9-volt per cell. If it is assumed that the battery would be recharged overnight, this would be 14 to 16 hours recharging time for every 8 to 10 hours of use. On the basis of power, it would be more logical to supply the transmitter directly from the external source. In the case of a larger capacity battery, longer operating times could be obtained with the same 14 to 16 hours recharging time, but the power that must be supplied during recharging becomes prohibitively large to be supplied from an external source. From a study on supplying the transmitter directly by radiated RF (see paragraph 4.3.4), a transmitted power of about 1 kw would be required to supply 1.3 Mw of power over a range of 300 feet in free space. Assuming the same technique for battery charging and assuming a distance of about 30 feet and 50 Mc-frequency, the losses would be as follows:

Transmission loss	19.0 db
Receiver coupling loss	10.5 db
RF/dc conversion loss	3.5 db
Transmitter coupling loss	3.0 db
	36.0 db - total

$$\frac{\text{Power transmitted}}{\text{Power received}} = \frac{P_t}{P_r} = 36 \text{ db} = 3980$$

for 1×10^{-3} watts at the receiver

$$P_t = 1 \times 10^{-3} \times 3980 = 3.98 \text{ watts}$$

If it is assumed that the transmitter requires approximately 20 milliwatts of input power and the battery is to last for 100 hours, then the charging rate for the standard recharging time would be 200 milliwatts. Under these conditions, the required transmitter power would be

$$P_t = 3.98 \times 200 = 796 \text{ watts.}$$

The numbers used are only approximate but they do point out the magnitude of the power required. On this basis, recharging batteries by radiated RF does not appear practical, and since RF is the only source of external energy that could be made generally available, it can then be assumed that recharging of batteries with the transmitter battery in place is impractical.

The preceding assumption leaves for consideration the primary batteries. The four basic types of primary batteries are:

a. Carbon-zinc (standard dry cell).
b. Alkaline manganese.
c. Mercury.
d. Silver-oxide.

In this application, emphasis is on small battery size and long life. The battery should also have a discharge characteristic that is relatively flat with time. The requirement for small size and long life dictates a battery with high energy density. Comparing the batteries on this basis yields the following information:

Type	Energy Density in Watt-hrs/in^3
a. Carbon-zinc	4.3
b. Alkaline-manganese	4.9
c. Mercury	7.5
d. Silver-oxide	8.3

On the basis of this data, the mercury and silver-oxide batteries are considerably better than the other type types. The mercury and silver oxide-types also have a flat discharge characteristic which the other types do not have. In this light, the choice of battery for this application is limited to the mercury and silver-oxide types. Actually, the difference between the two batteries in energy density is about the difference in terminal voltage, being 1.4 volts for the mercury cell and 1.5 volts for the silver oxide. Batteries of equal size will deliver very close to the same ampere-hours of life.

Examining the other characteristics of the two battery types, we find that the ordinary mercury battery exhibits very good high-temperature performance up of to about 130°F with operation possible up to about 200°F. However, severe loss of cell capacity results at temperatures below about 40°F. At 40°F the capacity is about 95 percent of the 70°F value but drops to about 6 percent at 28°F. Recent improvements have been made in the low-temperature performance by changing the anode structure (wound anode) of the cell. These new cells have about 94 percent of rated capacity at 32°F, 45 percent at 15°F, and about 9.6 percent at -4°F. The high-temperature performance is unaffected by this change in structure. This improvement makes the cell very attractive for use between 32°F and 130°F with full capacity and useful for short periods at the extreme of 0°F to 200°F. Even where the capacity is reduced by low temperatures, the cell voltage is not materially affected and the low in capacity is not permanent unless the cell is exhausted. That is, when warmed from the low temperature the higher capacity is again available.

The silver-oxide cell exhibits a low-temperature performance that is significantly better than the wound anode mercury cell. At 40°F, the capacity is about 80 percent of the 70°F value, 60 percent at 28°F, and 40 percent at -4°F.

In the mercury and silver-oxide cells, the capacity is a fixed number of ampere hours that does not depend on the discharge schedule. That is to say, within limits the ampere hour capacity of the cells remains the same whether the cell is discharged at high or low currents, or whether the cell is operated continuously or intermittently.

A factor to be considered when selecting between mercury and silver-oxide cells is the milliampere/hour capacity required. At the present time, silver-oxide batteries are manufactured in 100 to 165 milliampere hour sizes, and the improved wound anode mercury cell in 360 to 13000 milliampere hour sizes. There is apparently no technical reason to limit the sizes, but special cells would be considerably more expensive than the present cells.

While not a battery in the sense that has been considered previously, the nuclear battery is potentially useful as a power source. As presently constructed, the device produces a high voltage, about 10 kilovolts, and very low current, about 0.1 microamperes, or about 1 milliwatt of power. If this can be efficiently converted to a low voltage and higher current, the device could be very attractive. A battery having the above parameters would be about 1 inch in diameter and about 0.125 inch thick, and would supply power for up to 30 years. A novel technique for converting to a low-voltage device is being investigated on the CIRP program.

Another device which shows promise as a power supply is the thermo-electric generator which is basically an array of thermocouples. Each thermocouple produces an output of about 400 microvolts per degree of temperature differential and these can be arranged in series and parallel configurations to supply the required power. This device, of course, operates on a difference in temperature between two junctions and to be practical the temperature difference must be available from the equipment measured. Presently, differences as small as 25°F have been used successfully. To achieve reasonable power levels, large numbers of junctions are required and with presently available junctions the size of the package becomes large. To be useful, then, a reduction in size of the individual junctions is required, and this is the area receiving special attention at this time. The device is not generally applicable but it could be useful in a number of applications where temperature differentials normally exist such as between the LOX tank and ambient, or between ambient and an electronic package with vacuum tubes.

As a practical power supply for the sensor transmitters, either the mercury cell or the silver-oxide cell would appear to be the logical choice. The major deciding factor between the two is the availability of a cell with the appropriate milliampere capacity.

4.3.4 RADIATED RF ENERGY AS A POWER SOURCE

The objective of this study is to determine the feasibility of using radiated RF energy as a power source in the "integral" sensor program.

The procedure will be to briefly synthesize a hypothetical system model as shown in Figure 4-9 and then to briefly analyze each loss separately. Finally, all significant losses will be summarized.

The following shall be considered specifications for the hypothetical system:

<u>Minimum dc Power Required</u>: 2.7 milliwatts.

<u>Antenna Types</u>: Simple dipole, 12-inch total length for receiver; half-wave dipole, 10 Mcs to 100 Mc; and parabolic dish, 200 Mc to 1 Gc for transmitter.

<u>Frequency Range</u>: 10 Mc to 1 Gc.

<u>Transmission Range</u>: 300 feet.

Propagation Medium: Free space.

Input Resistance of Detector: 20 ohms.

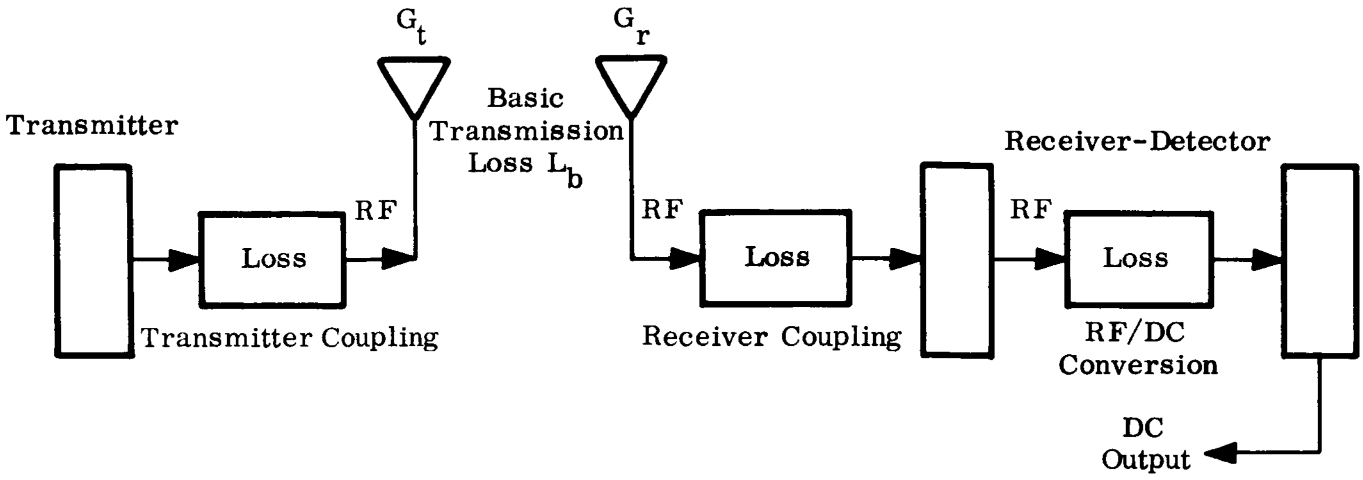


Figure 4-9. Definition of Losses in RF/dc Power Conversion

The system losses that will be evaluated will include:

a. The basic transmission loss and antenna gains.

b. Transmitter and receiver coupling losses.

c. Detector RF/dc conversion losses.

Each of these system losses will be analyzed assuming likely transmission ranges and equipment characteristics. Feasibility will be determined on the basis of transmission power requirements to produce approximately the amount of power required by a typical sensor transmitter.

4.3.4.1 Transmission Loss and Antenna Gain

Actual transmission loss, L, is defined as the basic transmission loss, L_b plus the path gain, G_p.

$$L = L_b + G_p.$$

Path gain, in free space, can be assumed to be equal to the sum of transmitting and receiving antenna gains.

$$G_p = G_t + G_r.$$

Therefore, with the assumption of free-space transmission, the actual transmission loss will be:

$$L = L_b + G_t + G_r.$$

The basic transmission loss L_b versus frequency is shown in Figure 4-10. G_t and G_r are listed as follows for several antenna types:

Antenna Type	Gain Above Isotropic Radiator
Isotropic	0
Infinitestimal dipole	1.76 db
Half-wave dipole	2.15 db
Parabolic dish, effective area of 1 square meter	$G_{db} = 20 \log f_{mc} - 38.5$

It should be noted that no polarization loss is assumed in this study.

4.3.4.2 The Receiver Coupling Losses

The following equivalent circuit, Figure 4-11, represents the RF receiving portion of the system.

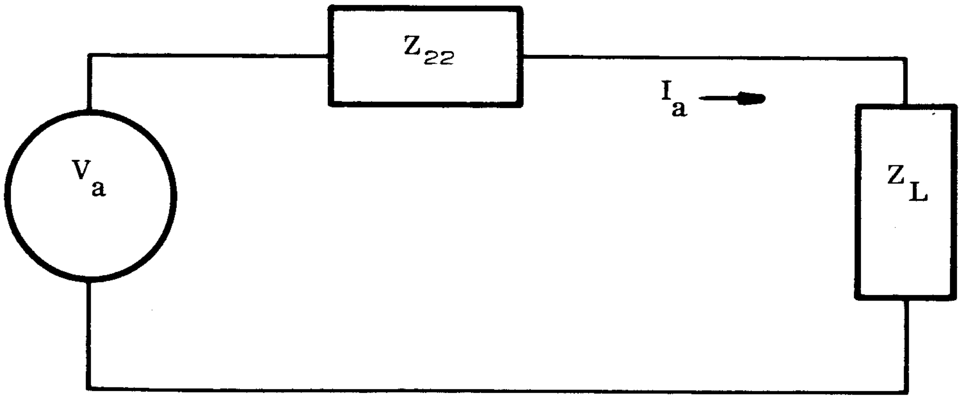


Figure 4-11. Equivalent Circuit Used in Estimating Receiver Coupling Loss

where:

V_a is the induced open circuit voltage in the antenna.

Z_{22} is the receiving antenna circuit impedance. This impedance includes the antenna input resistance and reactance along with all other resistive losses in the antenna circuit not considered part of Z_L.

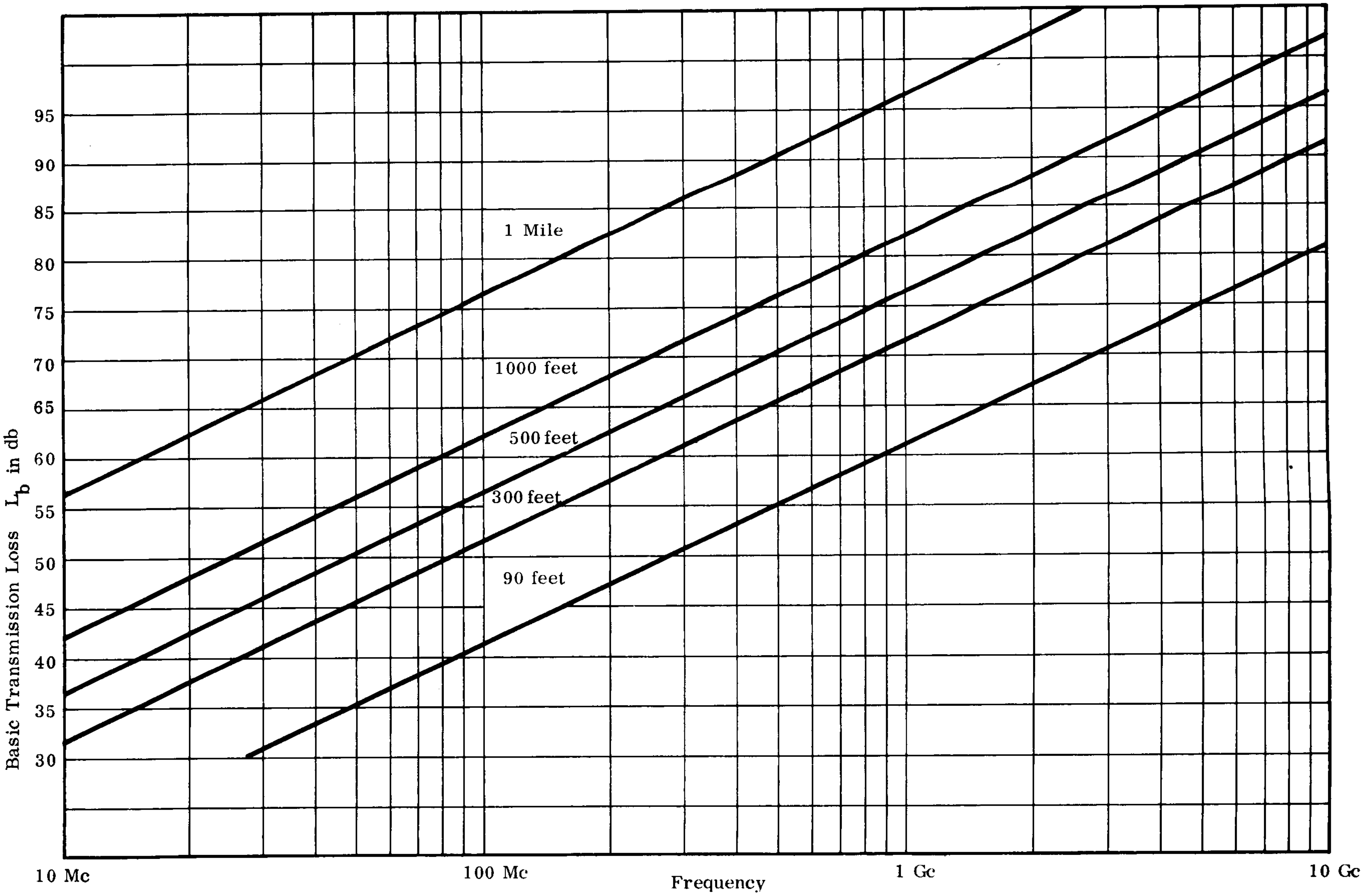


Figure 4-10. Basic Transmission Loss in Free Space $L_b = 36.58 + 20 \text{ Log } D_{mi} + 20 \text{ Log } f_{me}$

Z_L is the antenna load impedance or input impedance of the receiver or RF detector circuits.

If Z_L is finite; then:

$$V_a = Z_{22} I_a + Z_L I_z \qquad (4\text{-}10)$$

If the antenna ohmic resistance* due to skin effect, the resistance due to the dielectric loss from any capacitance coupling, and any other resistance in the antenna circuit are much less than the antenna radiation resistance, the receiving antenna circuit impedance Z_{22} will be equal to the antenna input impedance Z_a.

$$V_a = Z_a I_a + Z_L I_a \qquad (4\text{-}11)$$

In order to obtain maximum power transfer, in the receiving antenna circuit, the load impedance Z_L should be the conjugate of Z_a

where:

$$Z_L{}^* = Z_a = R_a + X_a$$

and (4-12)

$$X_L{}^* = X_a, \; R_L = R_a$$

where

R_a is the antenna radiation resistance.

R_L is the effective load resistance of the input resistance of the detector circuit.

The degree of mismatch in the receiving antenna circuit will then be dependent upon how close the load resistance can be made to match the antenna radiation resistance. This mismatch coupling loss can be estimated by the equation:

$$A = \frac{R_a}{R_a + R_L} \qquad (4\text{-}13)$$

---

*The ohmic resistance due to skin effect at 1 Gc for a simple 12-inch dipole is approximately 0.06 ohms. It will be, of course, less at lower frequencies.

It should be noted once again that equation 4-13 is true only when the antenna radiation resistance and the load resistance are the most significant resistive components in the antenna circuit and that this requires that other antenna losses, such as the ohmic resistance loss and dielectric loss, be much smaller than the antenna radiation resistance.

Equation 4-13 under the preceding conditions can thus be used to evaluate the power loss resultant from the receiver coupling mismatch. The actual power loss will be a direct function of this mismatch.

From equation 4-13 it can be seen that even with maximum power transfer, the match can only be 50 percent efficient.

$$A = \frac{R_a}{2R_a} \qquad (R_a = R_L) \qquad (4\text{-}14)$$

Or since R_a and R_L are made equal and the current is same in each one half of the received power is dissipated in the antenna circuit and one half is given over to the receiver.

If the receiving antenna is assumed to be a dipole approximately 12 inches long the radiation resistance R_a, will vary with frequency as shown in Table 4-5.

Table 4-5

Radiation Resistance vs Frequency for a 12-Inch Single Dipole Antenna

f Mc	R_a ohms
10	0.08
20	0.32
27	0.7
50	2
100	9
200	41
500	73
1000	-

In the receiving circuit, the load impedance, Z_L, will be the effective input resistance of the receiver RF detector circuit. The value of R_L will be dependent upon the input resistance of the detector circuit. Since no specific type of RF detection circuit has yet been proposed, it will be assumed that a type of RF crystal detector circuit as shown in Figure 4-12 might be used for RF/dc conversion.

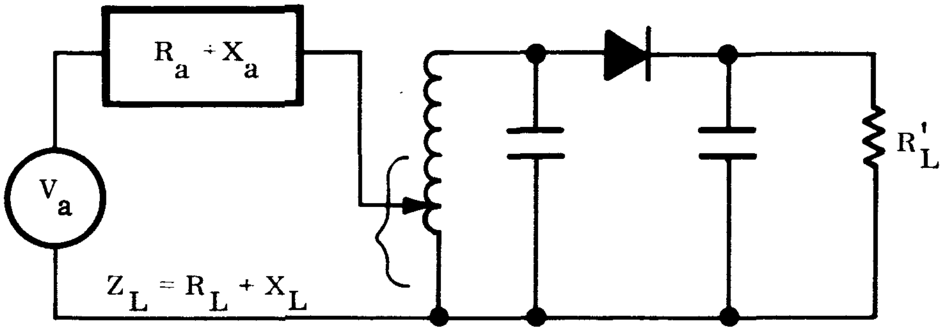


Figure 4-12. A Receiver-RF Detector Circuit for RF/DC Conversion

With this type of circuit a minimum effective input resistance of about 20 ohms might be possible. This relatively low value of input resistance might be accomplished as shown in Figure 4-12 by a step-down resistance transfer of the forward diode conduction resistance and power supply load resistance R_L. Naturally, the resistive losses in the matching inductor must be kept low.

Thus, if a minimum value of effective input resistance of 20 ohms is assumed, the total receiver coupling loss versus frequency can be estimated from equation 4-13 and Table 4-6.

4.3.4.3 Transmitter Coupling Loss

Since the transmitter antenna will not be limited in size, the coupling loss from equation 4-14 is estimated to be optimum or 3 db.

4.3.4.4 Detector RF/DC Conversion Loss

If it is assumed that a practical diode detection circuit can be fabricated to convert the RF power to dc power, the rectification efficiency is assumed to be about 45 percent for about a 3.5 db loss factor.

4.3.4.5 Total System Losses

Table 4-7 is a summary of the system losses over the frequency range of interest. It is interesting to note that although the basic transmission loss increases with frequency, this variation is offset by the high receiving antenna coupling loss at lower frequencies and the increased gain available from the dish transmitting antenna at the higher frequencies. The over-all effect is to make the total system loss vary less than 2 db over the entire range of interest.

Table 4-8 lists the amount of transmitter power required to supply 2.7 milliwatts of dc power. The transmitter power required at any frequency is considerably greater than 1 kw - the maximum uppper limit set on the transmitter. From this, the system as described should be considered to be not feasible. However, it should be pointed out that if receiver antenna coupling losses could be reduced by decreasing the input resistance of the RF detector circuit in the receiver to 2 ohms, then the system losses in the range of 50 Mc might be reduced by approximately 7 db. In this case, only 400 watts of power would be required.

Table 4-6

Receiver Coupling Loss vs Frequency

fmc	$\frac{R_a}{R_a + R_L}$	$\frac{R_a}{R_a + R_L}$, db
10	0.4×10^{-2}	-24 db
20	0.015	-18.3 db
27	0.035	-14.5 db
50	0.09	-10.5 db
100	0.31	-5 db
200	0.5	-3 db*
500	0.5	-3 db*
1000	0.5	-3 db*

*Optimum Coupling is Assumed

Table 4-7

A Summary of Losses vs Frequency

Frequency and Range		Basic Transmission Loss, L_b	Antenna Gain		Antenna Coupling Loss		RF/DC Conv Loss	Total System Loss
(Mc)	(feet)	(db)	G_r (db)	G_t (db)	A_r (db)	A_t (db)	(db)	(db)
10	300	31.6	1.76	1.76	24	3	3.5	58.6
20	300	37	1.76	1.76	18.3	3	3.5	58.3
27	300	40.5	1.76	1.76	14.5	3	3.5	58
50	300	45.7	1.76	2.15	10.5	3	3.5	58.8
100	300	51.6	1.76	2.15	5	3	3.5	59.2
200	300	57.6	2.15	7.5	3	3	3.5	57.4
500	300	65.6	2.15	15.5	3	3	3.5	57.5
1000	300	71.6	2.15	21.5	3	3	3.5	57.5

Table 4-8

Transmitter Power Required

Frequency (Mc)	Range (feet)	DC Power Required (dbw)	Transmitter Power Necessary for 2.7 mw DC Power	
			(dbw)	(watts)
10	300	-25.7	32.9	1950
20	300	-25.7	32.6	1820
27	300	-25.7	32.3	1698
50	300	-25.7	33.1	2042
100	300	-25.7	33.5	2239
200	300	-25.7	31.7	1479
500	300	-25.7	31.8	1514
1000	300	-25.7	31.8	1514

4.3.5 REMOTE CONTROL OF TRANSMITTER RADIATION

The following is a study of the apparatus and the transmission media applicable to the development of a remotely operated switch to be used as an integral part of a small, battery-powered sensor transmitter.

The purpose of this switch is to remove primary power from the transmitter during nonoperating periods, thus conserving energy and extending useful battery life.

It is the intent of this study to investigate system concepts as related to each of the transmission techniques, light, sound, and RF, based on the idea of free-space transmission. Further discussion of the actual operating environment, as presently conceived, will be presented. Finally, a system configuration in the light of the actual operating environment will be suggested. It should be pointed out that the discussion of component devices contains those items uncovered in literature searches which are examples of the present state of the art and a more exhaustive search might well prove profitable should actual development work be performed.

4.3.5.1 Discussion

A general description of the switch cannot be given without first stating some basic ground rules. The following statements will serve as a guide throughout this report toward determining the practicality of a particular method or operating medium:

a. The switch must be capable of actuation from distances up to 100 meters.
b. The switch must respond to a turn-on signal and a turnoff signal so that continuous excitation of the switch will not be required. This requirement implies a separate signal for each function.
c. Power drain of the switching system must not exceed 10 percent of that used by the transmitter (0.1 times 21.6 milliwatts or 2.16 milliwatts).
d. Environmentally, the switch will be exposed to hangar testing where ambient temperatures may drop to zero degrees Fahrenheit.
e. The physical size of the switch should be commensurate with that of the transmitter. A design goal of one cubic inch is, therefore, specified.

With these ground rules as a guide, the basic configuration of a remotely operated switch, hereinafter called TOTO (turn-on/turnoff) shall be considered.

4.3.5.2 TOTO Configuration

In its most basic form, the device consists of the following functional parts:

a. A signal receiver.
b. A signal discriminator.
c. A switch.

Figure 4-13, The Basic Remote Turn-on/Turnoff Configuration, depicts the relationship among the three components comprising TOTO and the battery-transmitter unit. In operation, a signal input to the receiver is transmitted via one of three media to be considered:

a. Light.
b. Sound.
c. Radio frequencies.

The signal is detected by the receiver and is then passed along to two decision circuits. Discrimination as to the function to be performed takes place in the decision circuits, one of which is energized, thereby actuating the switch. The switch may be viewed as an electromechanical single-pole, single-throw device which either applies or removes dc power to the transmitter.

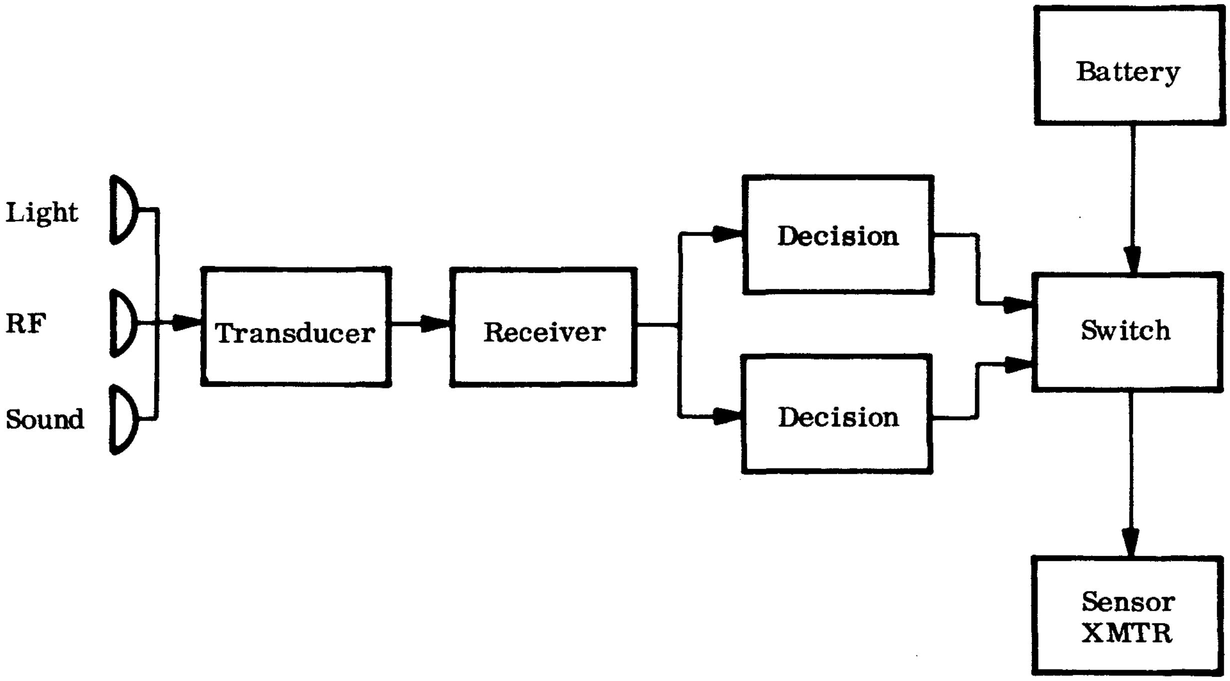


Figure 4-13. The Basic Remote Turn-on/Turnoff Configuration

The receiver for TOTO consists of a sound or light transducer or, in the case of RF, an antenna followed by stages of amplification and/or detection required to convert the signal energy in a useful level for discrimination. Discrimination and switching circuits will probably be the same regardless of the nature of the receiver. With this assumption, the transmission media can be compared on the basis of relative efficiency of the receiver in free space.

4.3.5.3 Transmitting Media

The comparison of the three transmission media will be based on free-space propagation conditions since the parameters of the actual vehicle environment cannot be well defined. These parameters include the reflection and absorption characteristics of the vehicle structure and the existence of line-of-sight paths between the transmitter and the receiver.

4.3.5.4 Sound

Transmission of signal information by means of sound energy implies a simple system consisting of a sound source, receiver, discriminating circuits, and switch. Since signal frequencies are transmitted directly, there is no need for a modulated carrier or demodulating circuits in the receiver. Directivity may be obtained to a degree by use of horn radiators or optical focusing (parabolic reflectors).

On the other hand, radiator efficiencies are low (approximately 3 or 4 percent) and sound transducers inefficient (1 percent or less). Sound waves are subject to dispersion as a result of wind, atmospheric turbulence, and temperature gradients, although in a hangar environment dispersion due to these factors may be small. Path attenuation is caused by molecular absorption and viscosity and heat in the medium, but again the magnitude of attenuation due to these causes is very small at lower frequencies (1 kc) and short range (100 meters), amounting to approximately 0.1 db at 25° F and 50 percent relative humidity.

Transducer efficiency appears to be the deciding factor in the consideration of sound as a transmitting medium.

4.3.5.5 Radio Frequency

The use of RF as a medium required transmission of a carrier frequency modulated in some manner by the signal information to achieve multiple switching operations. Unlike the simple audio amplifier for received sound energy, the receiver for RF waves must demodulate or detect prior to amplification.

At a carrier frequency of 30 Mc, the wavelength is very nearly equivalent to that of a 300-cycle sound wave, and concentration of energy (directivity) assumes the same basic difficulties. Thus, the primary transmission losses at short range are a result of spatial distribution of energy rather than atmospheric attenuation.

The poor directivity at longer wavelengths is compensated to a large extent by the phenomenon of electromagnetic induction in the receiving antenna insofar as the area of the antenna is directly proportional to the square of the operating wavelength.

Power available from antennas is generally much greater than transducers or sound or light.

4.3.5.6 Light

Light energy is similar in characteristics to electromagnetic radiation at the lower radio frequencies, differing primarily in wavelength and methods of measurements. The concept of a carrier, intensity modulated by signal information, is similar to that of RF. Modulation of the light beam can be performed mechanically either as a chopped waveform or by sinusoidal variation. Demodulation is performed in the receiver by a photocell whose output current (or control of current) varies with signal information. Thus, the receiver assumes the simplicity of its sound counterpart.

Attenuation in the atmosphere is primarily a result of refraction and dispersion. On the other hand, the extremely short wavelengths permit concentration of energy to narrow beams which can then be transmitted over long paths through use of optical measures.

In practice, the small sensitive area of the photocell, coupled with a low conversion efficiency, reduces the relative power gain caused by optical beam-forming. Stray sources of illumination or high ambient conditions can saturate or otherwise degrade circuit performance and control of these factors. Use of optical lenses and masks besides adding bulk to the receiver, complicates the effort to illuminate more than one transducer with a controlled light source.

4.3.5.7 Evaluation of Transducer Types

Neglecting attenuation constants, light, sound, and radio waves may be compared in terms of a point source radiating spatially. The statements on the following page will apply to each medium.

> The power density of the transmitted energy at a distance from the radiating source is inversely proportional to the square of the distance.
>
> The power intercepted by a transducer is directly proportional to the cross-sectional area of the transducer aperature whose plane is normal to the direction of the impinging energy.
>
> The available power from a transducer is directly proportional to its conversion efficiency, area, and to the intensity of the incident energy.

For this evaluation, the transducers to be considered are:

a. The microphone - conversion of sound pressure to electrical energy.

b. The antenna - conversion of the longer wavelengths of electromagnetic radiation to electrical energy.

c. The photo-voltaic cell - conversion of electromagnetic energy at the wavelengths of light to electrical energy.

4.3.5.8 Transducer Area

The area of aperture of sound or light transducers is simply the cross-sectional area of the diaphragm or surface which absorbs the energy. The area of an antenna is a function of the wavelength, however, and is given as

$$\text{Area} = \frac{G\lambda^2}{4\pi}$$

where

G is the gain of the antenna over an isotropic radiator. For this exercise the gain will be considered as unity.

λ is the wavelength in meters. For an operating frequency of 30 Mc, this is 10 meters.

The area of the antenna is computed as

$$\text{Antenna area} = 10^2/12.56 \cong 8 \text{ square meters}$$

The area of a typical microphone with a diaphragm one inch in diameter is

$$\text{Microphone area} = \pi/4 \times 6.45 \cong 5 \text{ square centimeters}$$

The sensitive area of a typical photovoltaic cell, such as the RCA SL 2205, is given as approximately 1.8 square centimeters.

4.3.5.9 Transducer Efficiency

Microphones are generally given a sensitivity rating in terms of open circuit voltage gain relative to a reference level, usually one volt per microbar. The computation of power conversion efficiency requires laboratory measurements. For this exercise, the investigations of F. Massa Journal for the Acoustical Society of America, LL 222-224 (1939) are referred to. Massa estimates the efficiency of microphones for airborne sound at 1 percent.

The RCA SL 2205 photovoltaic cell, for the proper spectral content and illumination intensity (100 mw/sq cm), is given a typical conversion efficiency of 10 percent.

The efficiency of a small monopole antenna whose length is 25 centimeters and whose diameter is 2 millimeters, has been computed from formulas by Humphrey, (GE-TIS R64ELC54) at 1.6×10^{-2} or 1.6 percent.

4.3.5.10 The Effective Area

The effective area of each transducer is the product of the computed area and the efficiency given as follows:

Microphone - $5 \times 0.01 = 0.05$ sq cm or 5×10^{-6} sq meters

Photocell - $1.8 \times 0.1 = 0.18$ sq cm or 1.8×10^{-5} sq meters

Antenna - $8 \times 1.6 \times 10^{-2} = 0.128$ sq meters

4.3.5.11 Power Available

The power available into a matched load for each transducer type is the product of the power density (intensity) and the effective area. Considering the power as unity, the relative response of the transducers is merely the effective area of each. With respect to the antenna, the response of the other transducers is

Photovoltaic cell	-38.5 db
Microphone	-44 db

4.3.5.12 Conclusions

After evaluation of transducer types in terms of relative efficiency there appears to be a decided advantage in the use of electromagnetic radiation in the longer wavelengths of radio frequencies. The flexibility of choice of frequency for a given type of antenna or the selection of an optimum frequency for a particular antenna is available to the designer thereby allowing him a greater degree of freedom in the choice of circuitry.

The effective capture area of the antenna/transducer, as compared with either the microphone or photocell, reduces the power gain required of a receiver.

The argument that at the shorter wavelengths of light, large power gains may be obtained through the use of optical means, whereas the gain of a small monopole or loop antenna is negligible, may be resolved by considering the difficulty of redirecting a narrow beam of high-intensity energy to many positions. On the other hand, the concentration of sound energy at the lower frequencies (for instance 300 cps) becomes impractical inasmuch as the reflector for a 10 db gain at this wavelength approaches a diameter of 11 to 12 feet.

From an environmental standpoint, the antenna as a transducer is less susceptible to the ambient interference of its medium than the light transducer.

4.3.5.13 Switching Devices

Ideally, a switch for this application could be characterized as follows:

a. Small in size.
b. High sensitivity.
c. Passive (i.e., no power consumption) except during actuation.
d. Environmentally stable.

Semiconductor devices were considered for this application, but circuits containing transistor switches, silicon controlled switches, or silicon controlled rectifiers all have excessive power consumption in operation.

The basic parameters of these devices are temperature-dependent and require some form of compensation. From a practical standpoint, the state of the art in switching relays in terms of sensitivity, size, and reliability rule out the use of more exotic devices.

The previously listed characteristics narrow the investigation to an electromechanical switch, or relay, of the polarized type. This is a high-sensitivity, fast-acting relay which employs a permanent magnet as part of the magnetic circuit. This type of relay has the advantage of consuming no power except during the change of state. The direction of armature motion reverses and hence the state of the device for a current reversal in the coil. There is no current flow in the magnetic circuit following actuation; the permanent magnet holds the contact mechanism in the desired position. Dual coil construction permits separate signal inputs to actuate the armature.

State-of-the-art parameters for these relays are as follows:

POLAR RELAY SPECIFICATIONS

Operating Power	1 milliwatt
Operating Time	1.5 milliseconds at 10 milliwatts
Coil Impedance	1.4-2.5 kilohms
Temperature Range	-65 to +85° C
Contact Rating	120 milliamperes at 48 volts dc
Contact Arrangement	SPDT
Weight	10 grams
Size	0.18 cubic inch

4.3.5.14 Decision Techniques and Devices

Figure 4-13 shows the receiver output coupled to two separate circuits, called "Decision Circuits." The purpose of either circuit is to recognize or reject the output signal of the receiver. The decision circuit should be passive until it recognizes the proper input signal at which time it generates sufficient energy to actuate a switching function. Thus, the device must be highly sensitive to a specific audio frequency. For TOTO, such a device should be characterized as follows:

a. Extremely small size.
b. High sensitivity.
c. High selectivity (2-3 percent bandwidth at the audio frequencies of interest).
d. Passive when not interrogated at its resonant frequency.
e. Output capability to energize a switching circuit.

Within the limitations imposed, the resonant reed relay and Bulova Accutron Tuning Fork movement appear to provide the desired characteristics. Both devices are of electromechanical/configuration. Although similar in response to an applied signal, these two units differ considerably in bandwidth, sensitivity, and output capability. Following is a brief description of each device.

4.3.5.14.1 Resonant Reed Relay

A resonant reed relay is an electromechanical device that acts as an audio-frequency detector and amplifier switch. It has one or more steel reeds suspended in a magnetic circuit that consists of a permanent magnet and a field coil. Each reed has relay contacts which close intermittently when the reed vibrates at its resonant frequency.

The permanent magnet provides magnetic bias to establish an operating point on the magnetization curve high enough above zero flux density to minimize hysteresis losses. The field coil receives an ac signal and produces an alternating flux that increases and decreases the magnetic circuit flux density once each cycle. When the excitation frequency is the same as the frequency of the reed, the alternating flux causes the reed to vibrate.

As the reed vibrates, an intermittent contact closure is provided for about 10 to 20 percent of each cycle. The intermittent contact closure will supply low levels of pulsating dc voltage which can be integrated to switch light loads, sensitive relays, or transistor amplifier circuits.

The following characteristics are typical of a commercially available unit.

RESONANT REED RELAY CHARACTERISTICS

Frequency	50 channels in 15 cps spacing in the frequency range of 472.5 to 1207.5 cps
Coil Impedance	280 ohms
Standard Driving Current	2.5 milliamps
Selectivity	Inoperative at a current of less than 7 ma in a frequency range deviating more than ± 15 cps from the nominal frequency f_o
Bandwidth	$f_o \pm 1.5$ cps min at 2.5 ma
Temperature Range	-10 to 50° C
Frequency Drift	± 0.5 cps within temperature range
Contact Ratio	2 percent min at standard driving current

Contact Rating	10 watts max 100 mw continuous
Size	0.08 cubic inches (approx)

4.3.5.14.2 Tuning Fork Movement

The Accutron movement (Figure 4-14) has generated considerable interest as a frequency selective device capable of performing switching functions with extremely small energy input. Although the movement is basically that of a feedback oscillator consisting of a tuning fork, two field coils, transistor, and small battery, the mode of operation is comparable to that of the resonant reed relay and may be explained in terms of the forced vibration of the fork in the influence of an alternating magnetic flux whose period is isochronous to that of the tuning fork. A force acting upon the fork having periods θ, $\theta/2$, $\theta/3$, etc. will cause the fork to vibrate but the amplitudes of vibration at frequencies below resonance are neglible in amplitude whereas at resonance the amplitude is a maximum. Amplitude is of significance in this movement due to the mechanical ratchet arrangement by which translation of the vibration through gears to the moving hands is accomplished. Engineering data on this device has not been forthcoming from the manufacturer but available literature and the results of laboratory tests (see GE CIRP Third Quarterly Report No. DB64J035, July-September 1964, pages 39-43) imply a sensitivity of several microwatts which is 20 to 30 db better than that of the most sensitive resonant reed relay.

In order to use this device in TOTO, further laboratory testing will be required to establish output capability (at present sinusoidal) or mechanical redesign to incorporate switching.

4.3.5.15 Receiver

The receiver for TOTO must accept the input signal from its transducer and amplify the signal to a sufficient level to energize decision circuits. In terms of RF circuitry the requirements are:

a. Amplification of the modulated carrier.
b. Detection of the modulating signal.
c. Amplification of the modulating frequency.

In general, RF receivers may be divided into superheterodynes, tuned RF, regenerative and super-regenerative, and crystal video. In selecting a suitable receiver type

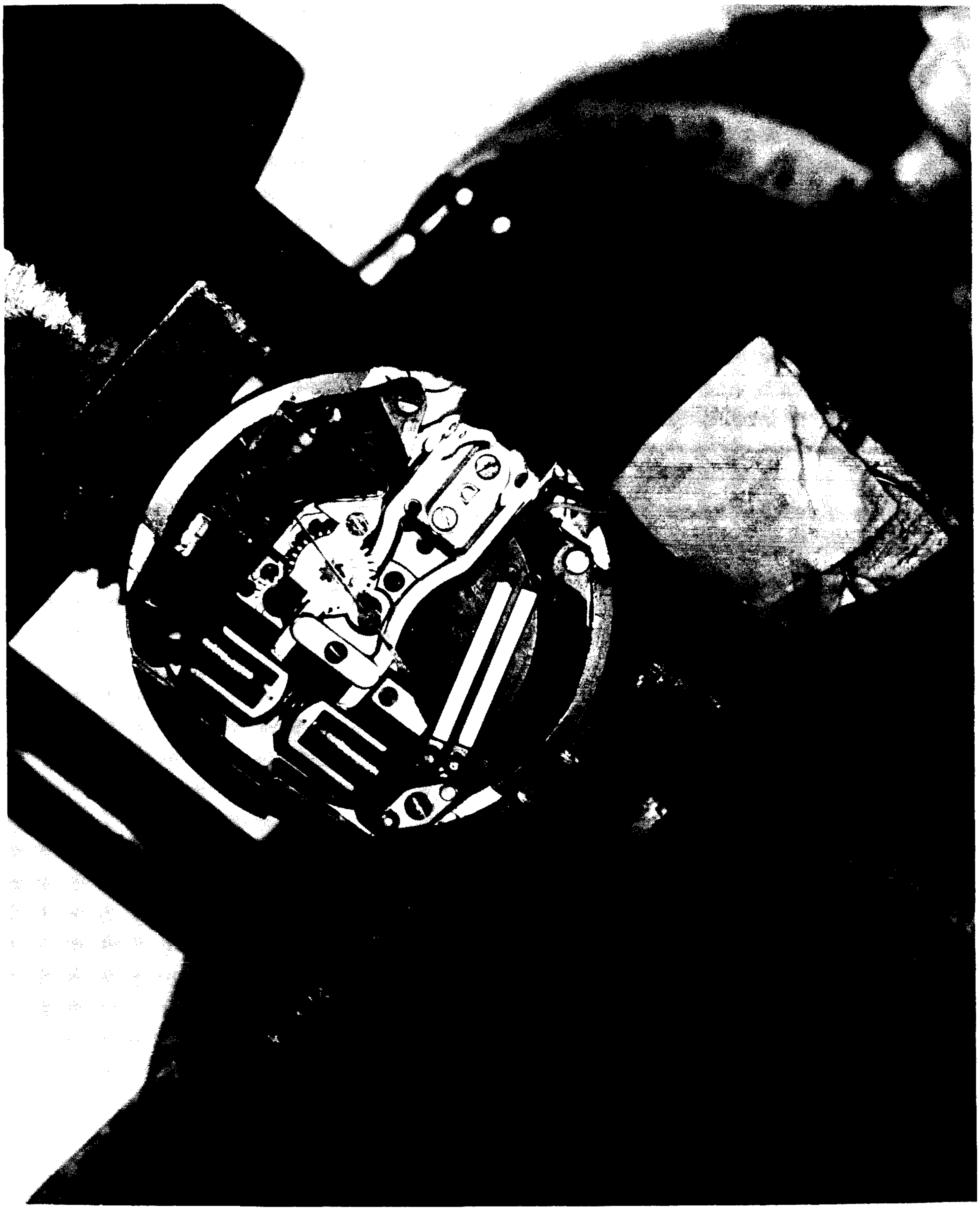


Figure 4-14. Accutron Movement

for TOTO, however, the following facts are to considered:

a. The low available power.
b. TOTO is a single-frequency system.

Superheterodynes are unnecessarily complex for single-frequency operation, the sensitivity and stability of regenerative detectors is marginal, and the crystal receiver is characterized by lack of selectivity and low sensitivity. For the TOTO application, it appears that a simple TRF receiver should satisfy system requirements.

The block diagram of a typical TRF receiver is shown in Figure 4-15. This receiver consists of a single RF stage followed by a detector and one or two stages of audio amplification.

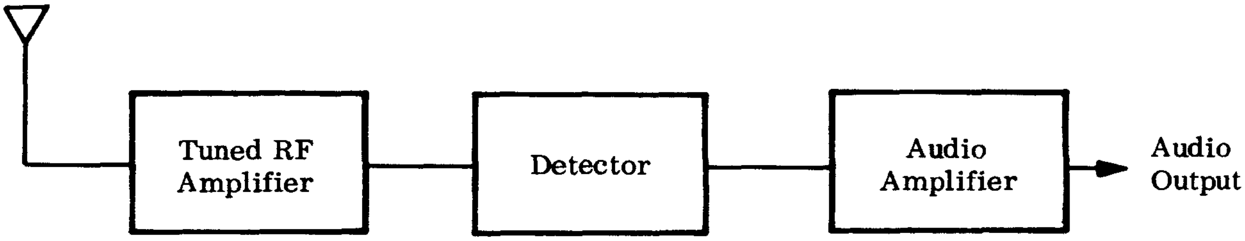


Figure 4-15. Tuned RF Receiver

4.3.5.16 Recommended System Configuration

Figure 4-16 is a block diagram of the recommended developmental approach. The switch is a single-pole, double throw polar relay of dual-coil construction. Each coil is driven by the integrated output of its respective decision circuit which is a resonant reed relay. The resonant reed relays are tuned to separate audio frequencies corresponding to an "on" signal and "off" signal. In size, the three units occupy a volume of approximately 0.4 cubic inch. Each relay is passive in the absence of a signal. The driving power for the resonant reed relays is generated in a tuned RF receiver.

The following tabular material is an analysis of the required signal levels and transmitter power for the TOTO system shown in Figure 4-13. The audio power needed to actuate the resonant reed relay is approximately four milliwatts. With this output level as a starting point, the radiated power (at a frequency of 30 Mc) from a transmitting antenna (half-wave dipole), 100 meters from a TRF receiver equipped with a small monopole antenna, will be developed as follows:

CIRCUIT GAINS			
ANTENNAS:			
Transmitting (Halfwave dipole)	G_T =	+ 2.15 db	
Receiving (short monopole)	G_R =	+ 1.75 db	
Efficiency (0.016)	Eff. =	-18.0 db	
PATH LOSS: (100 meters)	L =	-41.0 db	
Total Gain to Input of RF Amplifier			-55.1 db
ANTICIPATED GAINS			
RF Amplifier		+10.0 db	
Transistor Detector		+10.0 db	
Audio Amplifier (Single-Stage)		+20.0 db	
Total Receiver Gain			+40.0 db
Total System Gain			-15.1 db
Audio Power Required at Decision Circuits			-24.0 dbw

P_T, Total Radiated Power = Audio Power Required - System Gain = - 8.9 dbw.

This corresponds to a radiated power of approximately 130 milliwatts.

4.3.5.17 Signal-to-Noise Ratio

An RF bandwidth of 500 kc seems reasonable with two tuned circuits (including the antenna) prior to detection. The anticipated noise environment for this bandwidth is approximately 60 microvolts-per-meter corresponding to a power density of approximately -110 db.

The signal power at a distance of 100 meters from the radiating antenna ($P_T + G_T + L$) is approximately -47.85 db.

The ratio of signal power to environmental noise power is given as

$$\frac{P_R}{P_N} = \frac{47.85}{110} = 62.15 \text{ db}$$

therefore it appears that environmental noise is not a significant factor.

The tuned RF receiver, therefore appears to be more than adequate as a receiver for the TOTO system.

4.3.5.18 Conclusions

The system configuration as shown in Figure 4-16 will satisfy the requirements of the TOTO system for propagation in free space. For propagation inside a vehicle, refer to paragraph 4.3.1.

The development of a system such as shown in the above mentioned figure can be performed within the ground rules stated at the beginning of this study report.

Although no power consumption was given with regard to the receiver, a conservative estimate would be slightly over one milliwatt. This is the only standby power required by the system.

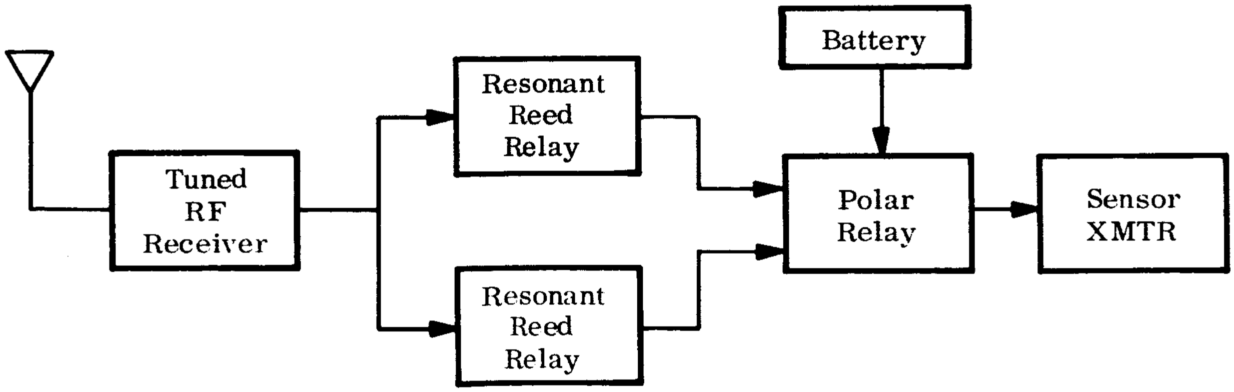


Figure 4-16. Recommended Systems

The high selectivity of this system is achieved by the narrow bandwidth of the frequency selective, resonant reed relays. The bandwidth of a typical resonant reed being ± 1.5 cps at 1 kc.

The system as shown uses a separate antenna for the TOTO function. In the development of an actual system it is probable that a single antenna for TOTO and the sensor transmitter is feasible and should be considered. A further area for additional study would be the use of the Bulova Accutron for the decision circuit. The use of this device would further reduce the power requirements of the receiver.

4.4 CONCLUSIONS

4.4.1 PHASE A, PART 1

The results of Phase A indicate that the use of a sensor transmitter system on the module carts of the ATCOMED facility is entirely feasible. The equipment evaluation of presently available sensor transmitters shows that the transmitter will meet the specifications for the five-channel system, with the exception of the 100-hour battery life. Planned improvements in the transmitter circuitry will improve the transmitter efficiency and extend the battery life beyond the present 80 hours of continuous operation.

4.4.2 PHASE A, PART 2

4.4.2.1 General

The use of an integral sensor system on board a space vehicle during factory checkout can greatly facilitate the gathering of test data from test points other than those of the flight instrumentation system. The use of such a system allows data to be taken with a minimum of setup time and with the least possible hazard to other areas of the vehicle.

The results of this study indicate that the requirements for an integral sensor system to operate on board a vehicle can be met. Those features which are required for a system of this type that are not yet available such as remote turn-on/turn-off have been shown to be feasible and could be incorporated into the integral sensor system. The increased accuracy required for this application will be available using improved system components presently under development on the General Electric Contractors Independent Research and Development Program. One area in which some question exists is the propagation of RF energy inside the enclosed area of the vehicle. This area is discussed in detail in paragraph 4.3.1. Based on experimental results obtained in this program, there should be little difficulty in overcoming the increased attentuation of such an environment. To definitely prove this contention, however, will require a test under actual operating conditions.

To realize maximum value from the integral sensor system it should be considered as a special test system as opposed to a general purpose telemetry system. In this way the sensor and transmitter can be matched to eliminate signal conditioning and, in some cases, the need for excitation voltage for the sensor. This technique will make the placement of sensors even more flexible.

4.4.2.2 Free-Space Propagation, 10 - 1000 Mc

In a free-space sensor transmission system with an inefficient transmitting antenna and a relatively efficient receiving antenna, the system losses are almost independent of frequency.

In a free-space sensor transmission system with both antennas considered to be small and inefficient, the system losses are frequency dependent - being minimum in the frequency range of approximately 75 Mc to 150 Mc.

Free-space propagation tests indicate that at 27 Mc, the present sensor transmitter is capable of producing a field strength of approximately 43 db greater than one microvolt per meter at 300 feet.

4.4.2.3 Enclosed Space Propagation

When a conductive enclosure has critical dimensions less than the cutoff wavelength of the transmission frequency, signals radiated in that enclosure will suffer substantially greater than will free space attenuation. The relative position of the transmitter and receiver in an enclosed space is often more significant than transmission range in determining the level of the received signal. For this reason, transmission tests should be performed on the launch vehicle.

4.4.2.4 Signal-to-Noise and Accuracy Requirements

It was determined by analog simulation of a sensor transmission system that a signal-to-noise ratio of approximately 22 db is required for 1 percent transmission accuracy.

If interferring signals with levels of 60 db greater than one microvolt per megacycle as measured with the NF 105 noise and field intensity meter (38 db greater than one microvolt per meter in a 10 kc bandwidth) are encountered in Building 4708, it will not be practical to operate the sensor system 22 db higher than this level. It is more realistic to assume that sensor channel frequencies will be selected to operate between these high interfering signals.

4.4.2.5 Antennas

Considering the wide range of environment and geometry under which the sensor transmitter and receivers must operate, one antenna type will not be optimum for all conditions. A magnetic antenna (loop or solenoid) will be most feasible when the antenna will be near conducting materials or possibly in a cylindrical cavity. An omnidirectional short monopole will probably be most suitable for large open free space areas. If some directivity is desired, a short dipole antenna can be used under the same conditions. A capacitor antenna might also prove useful in relatively clear areas. In small conductively enclosed spaces it may be more advantageous to couple the receiver to the RF skin currents on the inside of the enclosure or to a common carrier enable.

4.4.2.6 Radiated Power as a Source of Power

For the system assumed, see paragraph 4.3.4. Considerably more than 1 kw of power would have to be radiated to supply 2.7 milliwatts of dc power. This is not considered a reasonable amount of power and the system is not considered to be feasible at this time.

4.4.2.7 Batteries

As a result of the power supply study, batteries appear to be the most practical source of energy for the transmitters. The choice of battery type narrows down to mercury or silver-oxide batteries with the choice being determined by the milliampere-hour capacity required. For low-temperature applications (below about 40° F) the low-temperature, wound-anode mercury cell should be used instead of the standard mercury cell but, in general, physically interchangeable sizes are available.

4.4.2.8 TOTO

The study on remote control of transmitter radiation indicates that supplying remote turn-on/turnoff (TOTO) capability for the sensor transmitter is feasible. A block diagram of a possible TOTO system meeting the requirements for this application is shown in Figure 4-13. With this system the TOTO switch can be actuated from a distance of 300 feet in an unrestricted medium with a transmitter radiated power of 130 milliwatts. A similar system could also be used to supply remote calibration of the sensor transmitter.

4.5 RECOMMENDATIONS

The following actions are recommended:

a. It is recommended that Phase B of this program be continued as a logical step to demonstrate the usefulness of the wireless telemetry approach to factory checkout. In Phase B, five miniature sensor transmitters will be delivered to MSFC for use on the module carts of the ATCOMED facility in the hangar area of Building 4708. This system will provide much useful data on the performance of the sensor transmitter in an operational environment. The results obtained with this system will be used as inputs to the recommended follow-on program.

b. As a second logical step in the evaluation of the integral sensor approach to vehicle checkout it is recommended that a program to provide a multichannel system for use on board an S-IC vehicle be instituted. This system would consist of the necessary transmitters, receivers, and ground station interface equipment to provide a system that will be capable of supplying useful vehicle test data. A system of this type will provide information on operational problems associated with an on-board application. Propagation of the RF signal in a vehicle environment, for example, is a key question in deciding the ultimate usefulness of the integral sensor concept. While tests under simulated conditions indicate that propagation will be possible, the final proof will be in a system operating on board the vehicle. The number of channels in this system should be chosen to fully test the ability of the system to gather data from separate test points in a vehicle section and transmit it to a central receiver.

   The recommended system would also have a system accuracy consistent with the normal checkout data requirements. In this way the system can be used to provide actual test data in comparison with conventional systems. This system should also incorporate as many of the features suggested by the ultimate system requirements as is practical.

   Section 5 describes a 25-channel system that would satisfy the preceding requirements.

SECTION 5

SYSTEM PERFORMANCE SPECIFICATION

5.1 GENERAL

This specification describes the requirements for a 25-channel wireless telemetry system to be used as carry on checkout equipment for large space vehicle factory checkout. The system is to include 25 miniature radio frequency transmitters, 20 of which will be capable of being modulated with a standard telemetry sensor output of 0 to 5 volts, and five which will have integral temperature sensors. A receiver package, capable of receiving the information from the 25 transmitters, will also be provided. The receiver will provide 25 parallel analog outputs.

5.2 OPERATIONAL SPECIFICATIONS

5.2.1 FREQUENCY OF OPERATION

The transmitters for this application will operate on the following frequencies:

Channel	Frequencies in Megacycles
1	27.375
2	27.400
3	27.425
4	27.450
5	27.475
6	27.500
7	27.525
8	27.550
9	27.575
10	27.600
11	27.625
12	27.650
13	27.675
14	27.700
15	27.725
16	27.750
17	27.775

Channel	Frequencies in Megacycles
18	27.800
19	27.825
20	27.850
21	27.875
22	27.900
23	27.925
24	27.950
25	27.975

5.2.2 ACCURACY

The over-all system accuracy from transmitter input (exclusive of the sensor) to receiver output will be as follows:

a. Signals from dc to 0.02 cps:

Bias error	1	%
Random error (no smoothing)	1	%
Timing Error	0	%
Total (no smoothing)	1.4	%
Total (10-point smoothing)	1.05	%

b. Signals from 0.02 cps to 100 cps:

Bias error	1 %
Random error	1 %
Timing error	$0.63 f_s$ %
Total (no smoothing)	$\sqrt{2 + (0.63 f_s)^2}$ %
Total (10-point smoothing)	$\sqrt{1.1 + (0.63 f_s)^2}$ %

where:

f_s = signal frequency

All errors are one sigma errors and are in percent of input full scale, and to maintain the quoted accuracy, end point calibration will be required no more often than every 12 hours.

5.2.3 TRANSMISSION RANGE

The transmitter-receiver system will operate with specified accuracy over a transmission distance of 300 feet in free space or 30 feet inside a conducting enclosure where no major dimension is less than 8 feet. A background noise level no greater than 30 db about 1 microvolt/megacycle is assumed.

5.2.4 DATA BANDWIDTH

The system will be capable of handling data frequencies from 0 to 100 cps at the specified accuracy. Greater bandwidths will be possible at reduced accuracy.

5.2.5 MODULATION INPUT

Twenty transmitters will be supplied to accept modulation inputs of 0 to 5 volts with an input impedance greater than 40,000 ohms. Five transmitters will be supplied with integral temperature sensors to operate in the range of 0° F to 140° F.

5.2.6 ANTENNA

In this application maximum use will be made of antenna types that can be incorporated into the transmitter package.

5.2.7 CALIBRATION

Calibration will be accomplished by insertion of a calibration probe with "zero and full scale" switch located on each transmitter.

5.2.8 MODE OF OPERATION

The transmitter and receiver will be equipped with manual on-off switches.

5.2.9 POWER SUPPLY

The transmitters will be supplied with self-contained batteries with sufficient capacity to operate for a minimum period of 100 hours.

5.3 ENVIRONMENTAL SPECIFICATIONS

5.3.1 TEMPERATURE

The transmitters will have useful operating temperature limits of 0°F to 140°F. Specified accuracy will be maintained over any 70°F range within these limits.

Receivers will operate over a temperature range of 50° F to 130° F with accuracy maintain as discussed in paragraph 5.2.2.

5.3.2 SHOCK AND VIBRATION

The proposed equipment will be constructed to conform to best commercial practice and will be sufficiently rugged for normal laboratory handling.

5.4 APPLICABLE ELECTROMAGNETIC INTERFERENCE SPECIFICATION

MIL-I-6181D will be used as a design goal in the procurement of the proposed equipment.

APPENDIX A

SYSTEM ERROR

A number of factors are involved in specifying a system accuracy and, depending on the application, some factors are important and others are not.

In the case of essentially dc signals, there are two types of errors: envolved, systematic (bias) component, and random (precision) component. In general, in a well designed system these two components will be approximately equal. Figure A-1 shows the difference between the bias (and random error components compared to what might be a true signal. The bias error is due to the accuracy of calibration and the drifts in the system between calibration periods. The random component is a result of the "noise" in the system. The noise is any signal other than the data signal and the true noise such as circuit component noise and atmospheric noise. In a telemetry system, both these components are normally of interest.

When signals other than dc are considered another factor enters the picture. This factor is phase delay in the system. Figure A-2 shows the effects of this delay. We see that the output of the system is delayed in time from the true signal and at any time the output is in error by the amplitude difference caused by this phase delay. For small phase errors $\Delta\phi$, and no other errors

$$e = 100\,\Delta\phi$$

e = error in percent of full scale

$\Delta\phi$ = phase error in radians

if

Δt = equivalent time error in seconds

f_s = signal frequency in cycles per second

then

$$e = 628\, f_s \Delta t\ .$$

If a full scale accuracy of 1 percent of full scale is required, then a signal of 100 cps would require a timing uncertainty of:

$$t = \frac{1}{628 \times 100} = 16 \text{ microseconds.}$$

This timing accuracy would be expensive to implement and would require considerable bandwidth. Where the reproduction of the amplitude of a signal is all that is important, as it is in a number of cases, this timing error is of little consequence. On the other hand, if an after-the-fact deduction of the cause of a failure involves a number of measurements, the order in which the measurements changed can be of considerable importance.

A further consideration in transmitting changing signals is the transmission of complex waveforms. If, for instance, a signal is made up of a fundamental and second harmonic, the relative phase of the two components determine the shape of the waveform. If, during transmission, the relative phase between the components is changed, the waveform is altered as shown in Figure A-3. To overcome this problem a system having linear phase delay would be required, which again would be expensive to implement. Again, application is the important consideration, for in most applications, this relative phase shift is unimportant since the amplitude of the harmonics is preserved and can be recovered by Fouier analysis.

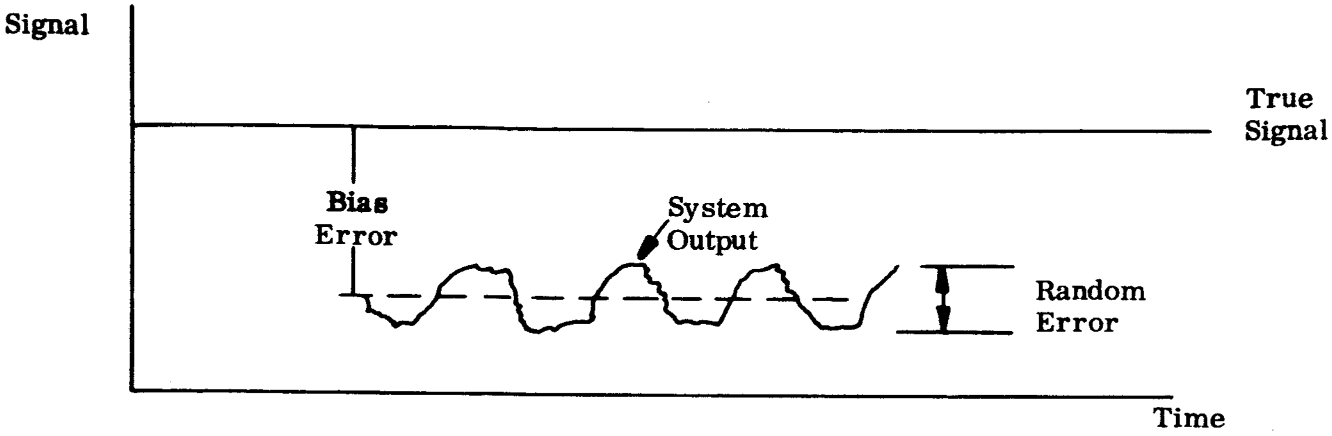


Figure A-1. Difference Between Bias and Random Error Components Compared to a True Signal

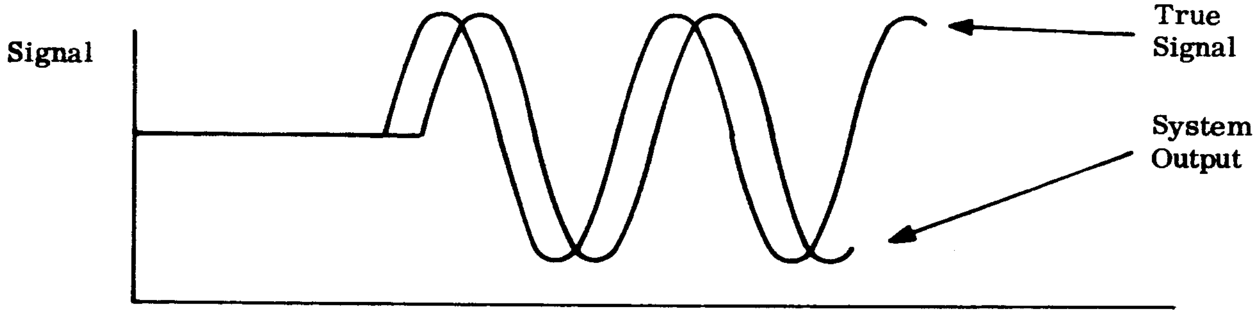


Figure A-2. Effects of Phase Delay

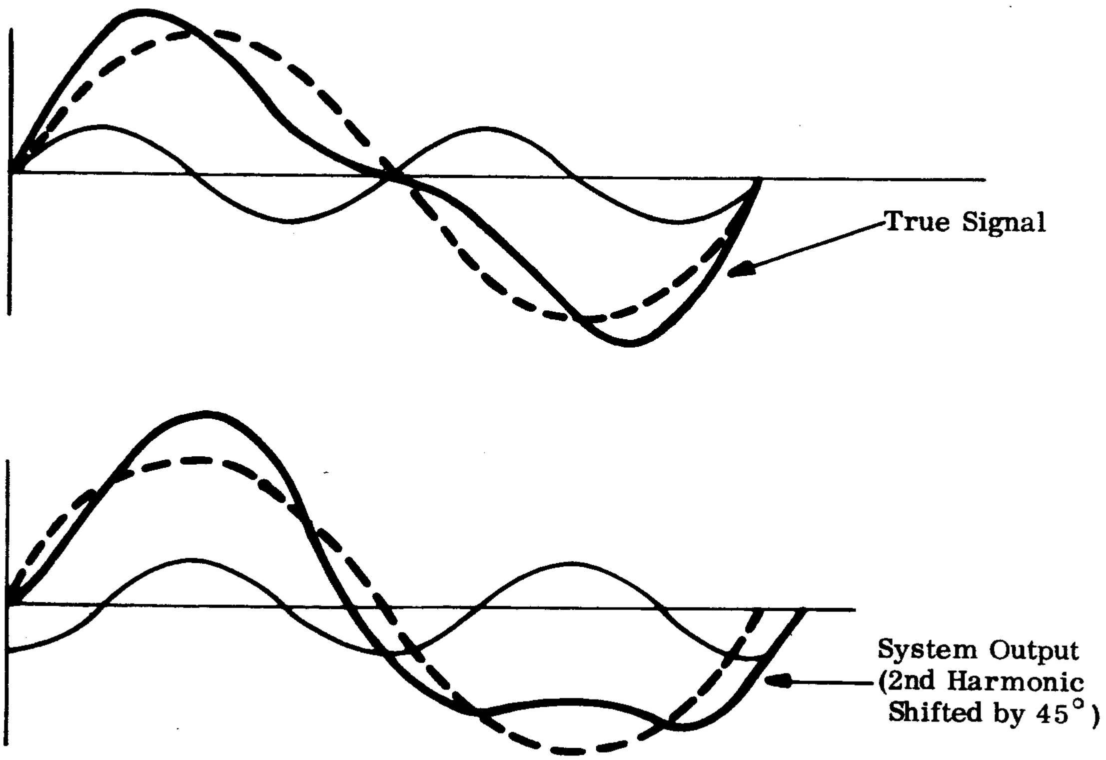


Figure A-3. Change in Waveform as a Result of Change in Relative Phase of Components

APPENDIX B

PERFORMANCE EVALUATION OF AN FM/FM INSTRUMENTATION CHANNEL

An analog computer evaluation was performed on a single-channel sensor transmission system very similar to the present sensor transmitter system. A block diagram of the simulated system is shown in Figure B-1. The evaluation was performed as part of the Contractors Independent Research Program on the GEESE analog computer facility. The objective of the evaluation was to determine the optimum characteristics of the subcarrier filter following the FM discriminator and then to measure the RMS error in the received data as a function of the receiver signal-to-noise ratio.

The evaluation conclusions were:

a. The low-break frequency of the filter is not extremely critical, but the upper-break frequency should be kept as low as possible (while still permitting the subcarrier frequency to pass) with at least a 40 db per decade cutoff at the upper break frequency.

b. The following errors were measured for the indicated signal-to-noise ratios:

S/N in db	Error in Percent
+10	4.02
+16	1.91
+19	1.23
+22	0.90

These results were obtained for a subcarrier filter having a 3 db bandwidth of 0.2 to 3 kc.

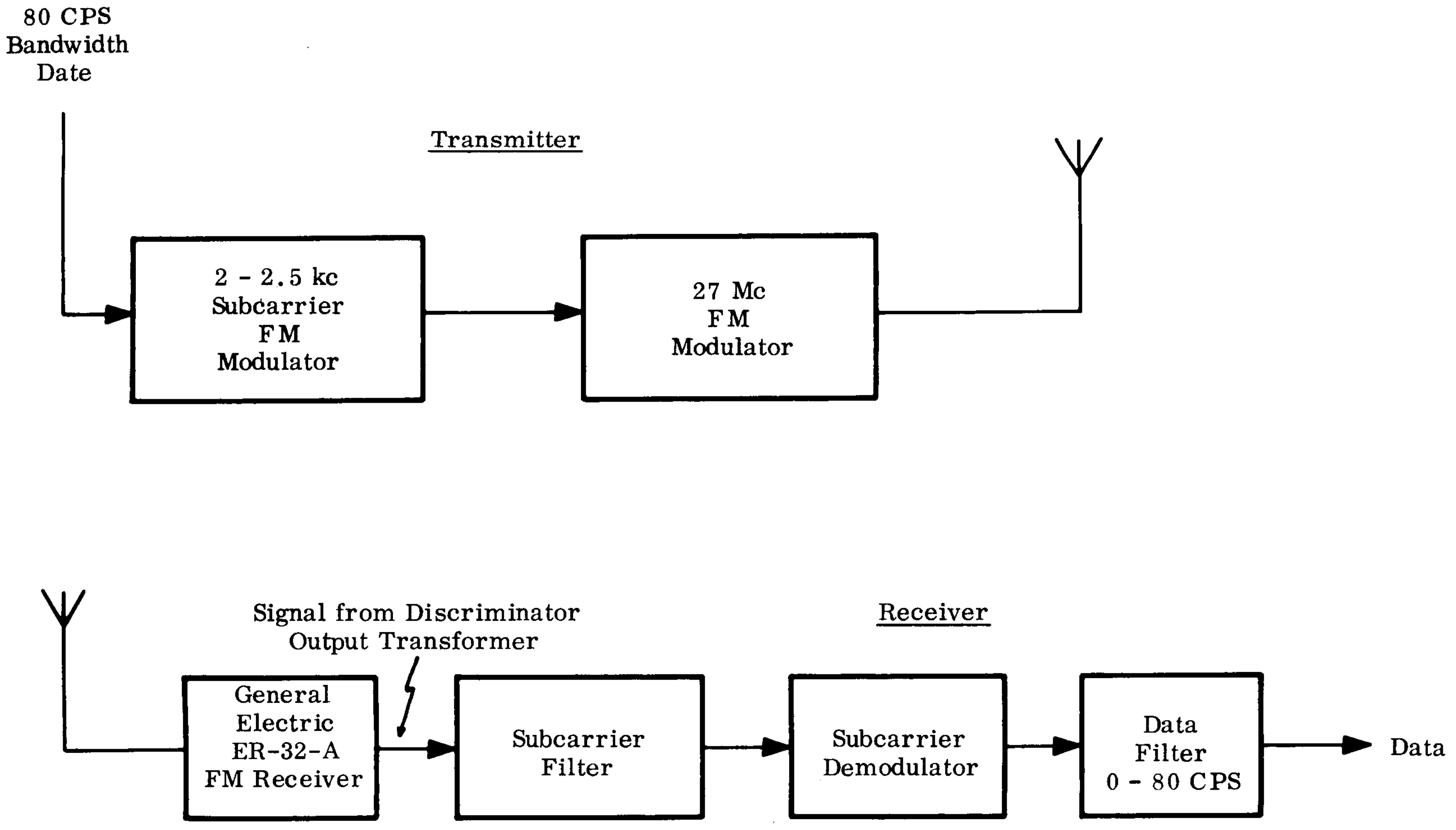


Figure B-1. Single Channel of an FM/FM Instrumentation System