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CIVIL EFFECTS EXERCISE

AERIAL RADIOLOGICAL MONITORING
SYSTEM. I. THEORETICAL ANALYSIS,
DESIGN, AND OPERATION OF
A REVISED SYSTEM

R. F. Merian, J. G. Lackey, and J. E. Hand

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CIVIL EFFECTS TEST OPERATIONS
U.S. ATOMIC ENERGY COMMISSION

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Aerial Radiological Monitoring System, Part II, which will contain operational data, will be issued later under another number in the CEX series.

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July 1960

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ABSTRACT

The Division of Biology and Medicine (DBM), Atomic Energy Commission, requested that Edgerton, Germeshausen & Grier, Inc., perform a system analysis of the Aerial Radiological Monitoring Survey (ARMS) program. The objective of the analysis was to determine the feasibility of reducing the volume and the weight of the radiation-detection instrumentation and of making other possible improvements, including navigation and data reduction to yield ground-radiation-contour maps at a reduced operating cost.

The present Division of Biology and Medicine—U. S. Geological Survey cooperative ARMS program is reviewed, and a philosophy of an optimum approach covering only the area of DBM interest is developed. The existing aerial radiometric measurement system is unsuitable in the light of present DBM requirements.

The electronic design of a revised ARMS system is outlined in detail. Necessary modifications and accessories required with the aircraft are described. The envisioned integrated installation in a Beech Model 50E aircraft is given. Operating procedures are developed for both normal survey conditions and disaster situations. Systems error is discussed on the basis of the accuracy required with the integrated system for radiation measurements and space positioning of the aircraft.

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Chapter 1

INTRODUCTION

1.1 BACKGROUND

The Division of Biology and Medicine (DBM), U. S. Atomic Energy Commission, faces a continuing and expanding requirement to determine radiation background levels in locales maintaining or utilizing radioactive materials. Such a base line allows the rapid assessment of the magnitude of a change in radiation levels or defines the hazard area in the event of a nuclear accident.

Specially adapted radiation-detection instrumentation mounted in low-flying aircraft is used for the rapid survey of large land areas. Experimental aerial measurements of surface radioactivity were conducted in the United States as early as 1948 to establish the feasibility of aerial prospecting; the results were sufficiently promising to warrant extensive development of instrumentation and techniques. Continued tests¹ showed conclusively that materials containing 0.01 per cent uranium in areas of small outcrop could easily be detected at 500 ft above the ground and at an air speed of 150 mph.

The U. S. Geological Survey (USGS) and the Oak Ridge National Laboratory (ORNL), in cooperation with DBM, conducted experimental and theoretical studies that led to the development of instrumentation and techniques using medium-range multiengine aircraft.² In June 1950, the first systematic aerial survey of a large area (1600 square miles) in the United States was undertaken by USGS.

As the requirement for low-level radiometric surveying expanded, it became apparent that some modifications were needed in equipment and methods to enhance the capability of this type of surveying. During Operation Teapot the Civil Effects Test Group of DBM successfully extended the mission of the USGS-ORNL system to include the measurement of radioactive debris from nuclear detonations.

Since Operation Teapot the medico-legal aspects and general health-physics problems associated with reactor installations and possible nuclear accidents, together with general background surveying such as that required for Plowshare projects, have further crystallized the need for a more efficient low-level radiation-measuring system providing accurate data collection and rapid presentation.

At present, USGS performs the radiation survey in aircraft; in addition to the radiation information, magnetic data are being secured. However, the requirement for large-area radiation surveys has expanded to such an extent that, from a standpoint of task accomplishment and economy, it is necessary to investigate the feasibility of designing an Aerial Radiological Monitoring System (ARMS) which will serve DBM more expeditiously in this area. The requirement for action is further hastened by the desire of the USGS to discontinue its radiation-survey operations.

1.2 OBJECTIVES

Since an aerosol containing radioactive debris can relocate at great distances from the source, the area of interest surrounding possible sources of radioactivity is approximately

10,000 square miles. Because many such sites exist and more are coming into existence each year, the assignment is indeed prodigious.

Two problems must be resolved:³ first, radiation levels on the ground must be reliably determined from measurements made in the air; second, accurate space positioning of the aircraft relating to the radiation measurement must be achieved.

Any system designed to cope with these problems must be sufficiently versatile to perform the following services:⁴

1. Document background radiation levels existing in the areas surrounding such sites
2. Periodically resurvey the areas to determine any increase in radiation levels and to identify any sources of increase before a radiation level of significance is reached
3. Provide a capability of rapidly determining the area of hazard in the event of a radiation disaster

An acceptable system must provide a means for the rapid survey of large land areas and, shortly thereafter, a presentation of the data in the form of radiation contours related to geographical location. The radiation information must be comparable to existing USGS-ORNL aerial-survey data.

In addition to the preceding criteria, efficient operation with minimum operating costs is paramount. This dictates the need of economical aircraft operation, maximum automation of equipment, and the reduction of manpower wherever possible. Consequently the acquisition of data should be a rapid and simple procedure, and manual data reduction should be held to a minimum. The optimum situation will occur when radiation-contour information in a desirable form can be presented to the responsible AEC agency immediately upon completion of an aerial survey.

1.3 REVIEW OF THE EXISTING SYSTEM

The detector system presently in use (developed by F. J. Davis and P. W. Reinhardt of ORNL) utilizes six thallium-activated sodium iodide scintillation crystals, each 4 in. in diameter by 2 in. thick, as the detector.⁵ The crystals are viewed by six 6364 DuMont photomultiplier tubes whose high voltage is supplied by a commercially available relay-rack-size power supply. The output signal of the photomultiplier tubes is passed through a mixing preamplifier, a linear amplifier, a base-line discriminator, a pulse-shaper circuit, an integrator circuit, and vacuum-tube voltmeters. The output of the vacuum-tube voltmeters is read on chart recorders. Three chart-recorded outputs are presented: (1) the undisturbed rate-meter output, (2) the rate-meter output corrected for altitude above the ground, and (3) the altitude above the ground.

In the original design, standard nonminiaturized laboratory type equipment was used for convenience and reliability; the equipment is mounted in a DC-3 aircraft. The entire flying operation requires a crew of eight people.

In operation the equipment is flown first at an altitude of 2000 ft to calibrate the cosmic-ray background. Next, a 500-ft-altitude test strip is flown as a relative calibration to check for subsequent drift. Three people are required to operate the radiation instrumentation. One person operates the chart recorder that records direct radiation, non-altitude-compensated. He also operates the chart recorder that is radar altitude-compensated to give a corrected count rate at 500 ft. A drift-sight operator is responsible for charting geographical location, and there is an alternate electronics technician for relief of the two principal data-collection personnel.

The location system used by USGS utilizes a gyrostabilized 35-mm strip-film camera. A camera speed of approximately 2 ft/min is used at the 500-ft altitude and at the 140-mph air speed that is normally maintained.

Before a survey is undertaken, the best available maps of the area are obtained. These are usually 1/24,000 or 1/62,500 scale topographic maps, 1 in. being equal to 2000 ft and about 1 mile, respectively. The flight lines to be flown on the survey, usually spaced 1 mile apart, are drawn on two sets of the maps. The pilot and copilot use one set, and the drift-sight operator, or observer, uses the other set. The observer views the direct area of interest through

the optical drift sight, and, by means of an appropriate marking system, places edge-marks on the chart recorders and the film when recognizable check points are crossed.

The subsequent data reduction of the gathered information is rather an arduous task. Since the radiation information corrected for altitude is gathered continuously, it must be reduced by selecting data points that crossed preselected radiation levels. Radiation levels of interest must then be correlated with the geographical position. This information must be presented on a map of the area. For every hour spent in acquiring data in the air, approximately seven hours is required on the ground for data reduction.

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Chapter 2

DISCUSSION OF AN OPTIMUM SYSTEM

2.1 PHILOSOPHY

There are two aspects to the ARMS task which must be considered and which impose somewhat different requirements on the measuring system.

First, the problem of determining background levels at various sites of quite extended size and at many locations dictates a system that will produce only the pertinent data required to generate radiation-contour maps of the area. A system that generates continuous data can produce so much information on a project of this magnitude that either the economics of the operation suffer or the true significance of the data becomes hidden.

The second aspect of this system is its utilization as a monitoring device in the event of a nuclear accident. In this case the equipment is flown directly to an area for use in gathering specific data regarding radiation levels on the ground under the aircraft, together with pin-point information about the location of the hot spots.

This dual requirement imposes on the system two modes of operation. The first is the automatic collection of many accurate bits of data from the proper positions and at significant intervals. The second mode is the command recording of information at the will of an observer who is visually checking the radiation levels as the plane flies over a disaster area.

Since the primary interest is in ground radiological-contour information, the question naturally arises concerning the accuracy that can theoretically be attained by surveying at a 500-ft altitude. Many factors enter into this calculation; some of these are the variation in air density as a function of temperature, barometric pressure, humidity, and absolute altitude; effective source energy; concentration of radon daughter products in the air; accuracy of the detector system; the amount of foliage between the aircraft and the ground; and the cosmic-ray background. An assessment of this accuracy is important in that it affects the positional accuracy demanded of the navigation system.¹

Initially, let us examine the effects of these parameters if no correction is applied to the radiation data secured by the aircraft. Data must be collected from ground levels ranging from sea level (Brookhaven National Laboratory) to 10,000 ft (mountains in the vicinity of the Los Alamos Scientific Laboratory). The calculation of the variations to be expected in the counting rate, because of changes in atmospheric parameters, is based on the analysis of aerial radiation measurements described by Davis and Reinhardt.² (The application of these methods to the present problem is described in the Appendixes.)

1. Assume that the aircraft maintains a 500-ft altitude above the ground under conditions of standard temperature and pressure and that the spectral energy and attenuation with density remain constant; then Fig. 2.1 represents the change in count rate seen by the aircraft for various ground elevations.³⁻⁶ The count-rate excursion in the two extremes varies by 63 per cent.

2. Assume that the aircraft maintains a 500-ft terrain clearance with zero humidity over a sea-level area but that the temperature varies from 0 to 120°F. Such a condition would exist in extremes at successive surveys of the same location.^{7,8} Figure 2.2 represents the excursions in count rate due to this effect, and the percentage change at the extremes is 25.9 per cent.

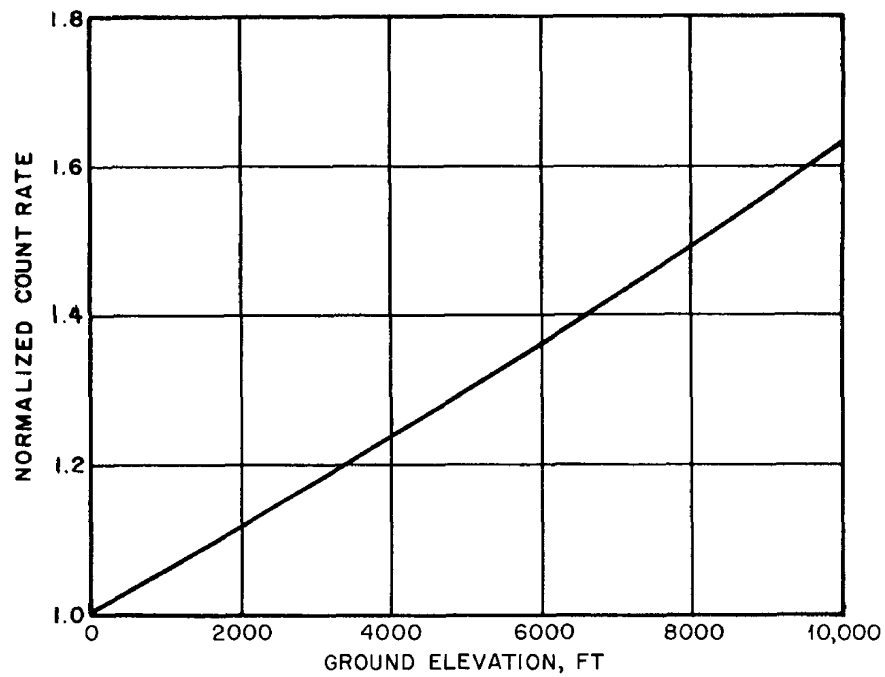


Fig. 2.1—Normalized count rate taken at 500 ft above an infinite-plane source vs. ground elevation. Sea-level pressure = 760 mm Hg; temperature = 32°F; relative humidity = 0 per cent.

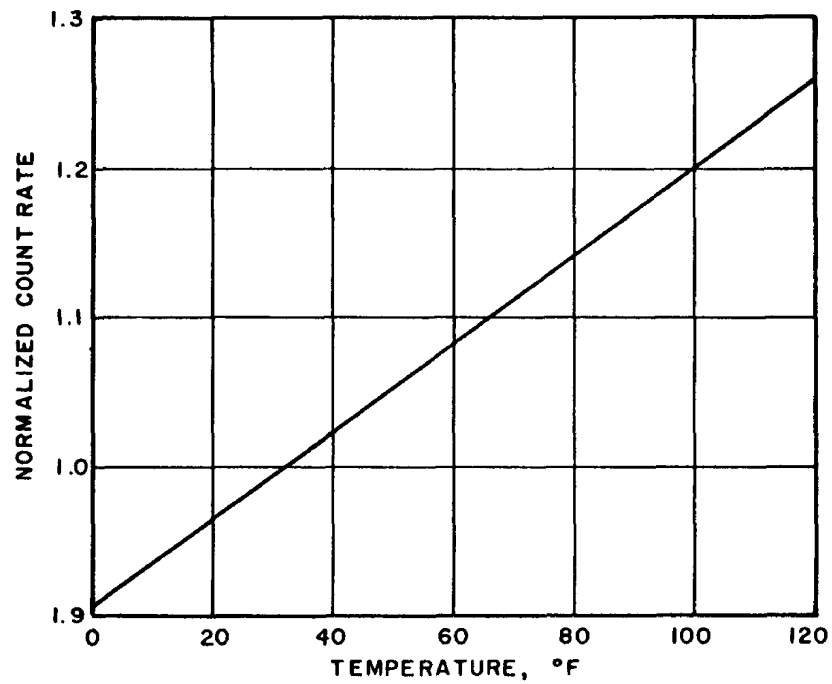


Fig. 2.2—Normalized count rate vs. temperature. Sea-level pressure = 760 mm Hg; relative humidity = 0 per cent.

3. Again assume that at sea level the aircraft maintains a 500-ft relative altitude. Then permit the relative humidity to vary from 0 to 100 per cent for representative temperatures^{9,10} of 0, 40, 80, and 120°F. Such situations can occur as daily variations during one survey or on periodic resurveys. Figure 2.3 shows that the maximum variation at 0, 40, and 80°F is negligible, being significant only at 120°F, when it is 5.0 per cent of the count rate. This condition does not represent actual precipitation, in which case the change would be greater.

4. For a sea-level condition with constant temperature, permit the barometric pressure to vary from 740 to 780 mm Hg while the aircraft maintains a 500-ft relative altitude. Figure 2.4 represents the change in count rate as a function of barometric pressure and at extremes shows a change of 9.4 per cent.

5. Assume that, at sea level with constant pressure, temperature, and humidity, the aircraft is unable to maintain its 500-ft altitude above the ground either because of hilly terrain

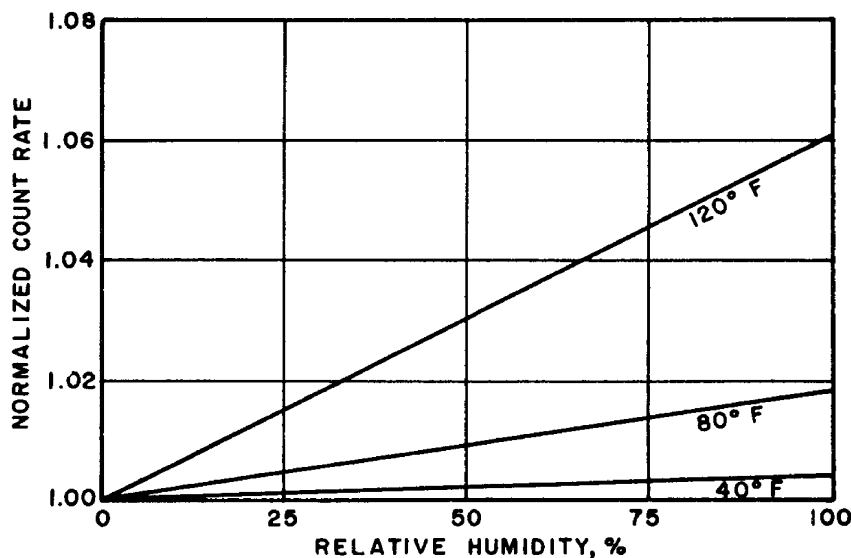


Fig. 2.3—Normalized count rate vs. relative humidity. Sea-level pressure = 760 mm Hg.

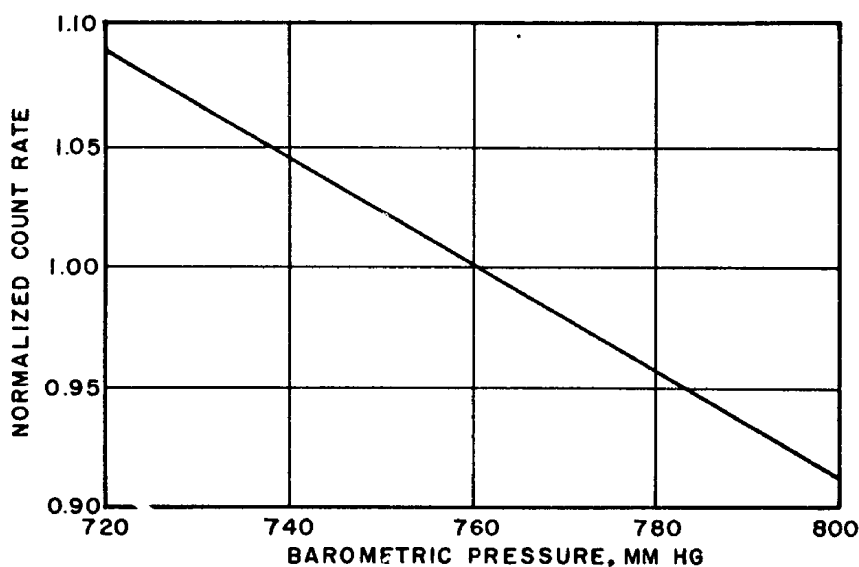


Fig. 2.4—Normalized count rate vs. barometric pressure. Temperature = 32°F; relative humidity = 0 per cent.

or the inability of the pilot. Figure 2.5 shows the effect of this variation from 200 to 800 ft, which represents an error of +152 and -58.3 per cent in count rate about a 500-ft normal value.

6. Since the aircraft may be surveying large land areas with extremes in ground cover foliage, this attenuation to the count-rate signal should also be taken into account.^{11,12} The least attenuation would be represented by the flat desert condition, such as that existing in some portions of the Nevada Test Site. The greatest attenuation would be represented by the dense-forest condition that exists in some areas surrounding the Oak Ridge National Laboratory. An average attenuation mass is calculated by assuming all the radiation to be on the ground and by assuming a mean mass for a tree and a mean number of trees per unit area. Under this condition the forest will attenuate the count-rate signal by as much as 11 per cent.

7. Figure 2.6 gives the variation in cosmic-ray background count as a function of altitude for a constant cosmic source rate. It will be noted that from sea level to 10,000 ft the count rate has increased because of cosmic background by 64 per cent. Furthermore, the cosmic source rate is not constant but varies at a maximum as much as a factor of 5 during periods of high cosmic activity, which occur fairly frequently. For the geometry under consideration, this represents an excursion from approximately 100 to 500 counts/sec, with a mean at approximately 200 counts/sec. If it is assumed that the lowest signal strength of interest from the ground is 50 counts/sec, then the cosmic background without correction circuits represents an error of from 200 to 1000 per cent, with the mean at 400 per cent. At high contamination levels of 50,000 counts/sec, it is seen that the cosmic contribution represents a maximum error of 1 per cent.

8. The usual condition is for the radon-progeny concentrations to remain more or less constant throughout the day and to build up during the night under temperature inversions to a maximum in the morning just before the inversion lifts. Radon concentrations changing by a factor of 10 under these conditions are not unusual. Furthermore, the amount of radon progeny present is a distinct function of the locale being surveyed; New Mexico, for instance, because of the natural radioactivity of the mineral deposits, will contain much higher radon concentrations than areas along the Atlantic seaboard. Radon-progeny concentration can then vary under the discussed geometry from approximately 50 to 800 counts/sec, 80 counts/sec being a mean and the higher value representing 1600 per cent of the assumed lowest ground-radiation level of interest.

If, then, a system with no corrections is assumed and all the errors of the afore-mentioned sources of error are combined, the total root-mean-square (rms) error would be of the order of 1900 per cent for the lowest radiation level of interest. Certainly this magnitude of error cannot be tolerated, and therefore corrections for some of the variables must be made.

A system error will now be evolved predicated upon a *corrected system operating under the worst circumstances*. Assume that the aircraft radiation instrumentation is calibrated by some suitable method at the site on the day when a surveying operation is to occur.

Also assume that the variation in ground elevation from the point of calibration will not vary more than 2000 ft. If this 2000-ft excursion ranges from -500 ft to +1500 ft, then the count rate will differ from the calibration by -2.9 to +8.5 per cent. The temperature excursion during survey will change at an extreme no more than $\pm 10^{\circ}\text{F}$; this represents a ± 5.9 per cent change in count rate. Because of radical changes in attenuation factors, a survey cannot be made during the presence of visible moisture; assume, therefore, that the relative-humidity change can be no greater than ± 15 per cent during a survey period. This represents an error in the extreme of ± 2 per cent. The barometric pressure during the same period would not be expected to vary more than ± 0.015 in. Hg. This represents an additional error of ± 0.15 per cent.

For the afore-mentioned reasons, the relative altitude must be known, and, with presently developed radar altimeters, the error in terrain clearance is within ± 20 ft. This presents an added error of ± 6 per cent, which is significantly less than the uncompensated error of +152 per cent. The ground-foliage error remains as previously stated.

The cosmic background can be subtracted by calibrating the apparatus at 2000 ft, as is presently done. The error due to altitude change for cosmic calibration and the variation in cosmic intensity should not vary more than ± 5 per cent. At a normal background rate of 200

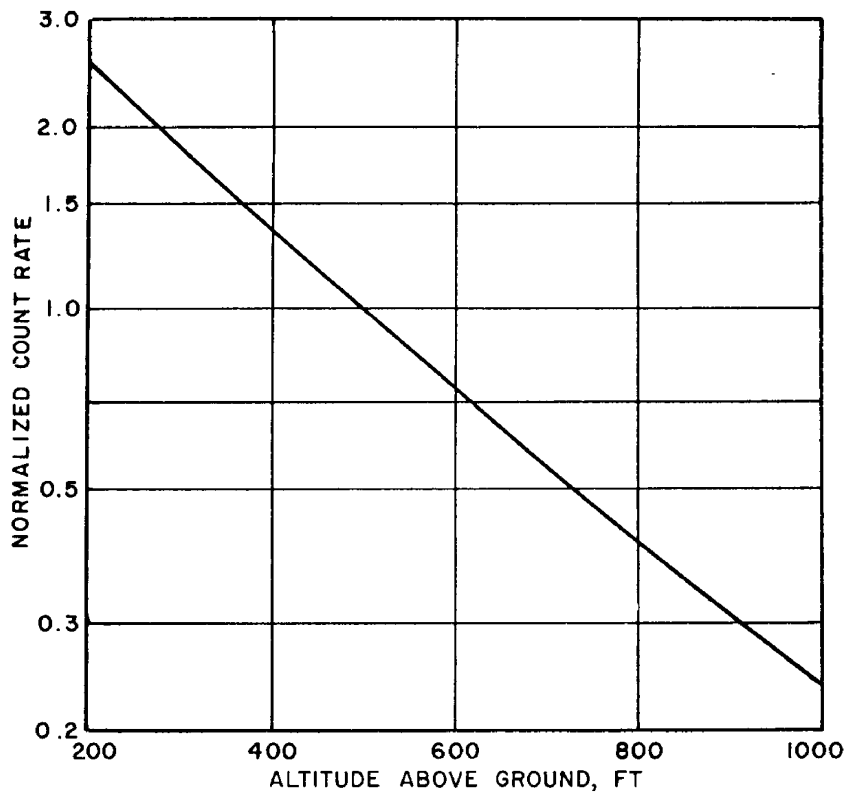


Fig. 2.5—Normalized count rate vs. altitude. Infinite-plane source; ground elevation = sea level; temperature = 32°F; sea-level pressure = 760 mm Hg; relative humidity = 0 per cent.

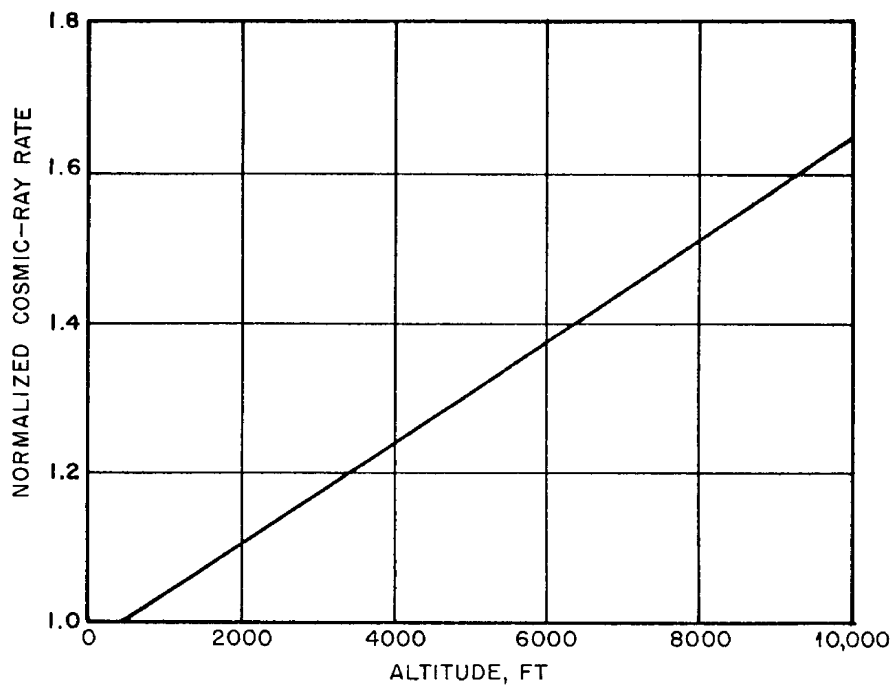


Fig. 2.6—Cosmic-ray background vs. altitude. Sea-level pressure = 760 mm Hg; temperature = 32°F; relative humidity = 0 per cent.

counts/sec, this represents ± 10 counts/sec, which is, in turn, a change of ± 20 per cent in count rate for the lowest 50 count/sec level of interest.

Similarly, the radon progeny are accounted for during the air calibration. During the survey, which is conducted when no low-altitude inversions take place, i.e., from late morning through the afternoon, the maximum variation to be expected is ± 8 per cent; for a mean background of 80 counts/sec, this represents ± 7 counts/sec, or ± 14 per cent of the low-level signal.

It is obvious that, owing to the constant background sources of radiation, the over-all rms error is a function of signal count rate; whereas the other sources of error are independent of count rate. Therefore, if it is assumed that a level of 50 counts/sec corresponds roughly to $1 \mu\text{r/hr}$ at a position 3 ft above the ground, the over-all probable error as a function of count rate can be outlined as in Table 2.1.

The preceding remarks and the ground area viewed by the detector (see Fig. 2.7) would indicate that the criterion for space-positioning accuracy presently used is not real and thence can be somewhat relaxed in the interests of economy and speed of data reduction. Furthermore, when a disaster situation is predicated, the accuracy required in space positioning is proportional to the population density in the area of concern. This fortunately coincides with the fact that the number of ground check points and the accessibility of an area are also roughly proportional to the density of population. Hence a space-positioning system whose accuracy is a function of the number of ground check points, which is, in turn, proportional to the density of population, can be hypothesized.

TABLE 2.1—OVER-ALL RMS ERROR AS A FUNCTION OF COUNTING RATE

Source count rate, counts/sec	Over-all probable error, \pm counts/sec	Over-all probable error, %
50	14.15	28.3
500	72	14.5
5,000	710	14.2
50,000	7,100	14.2

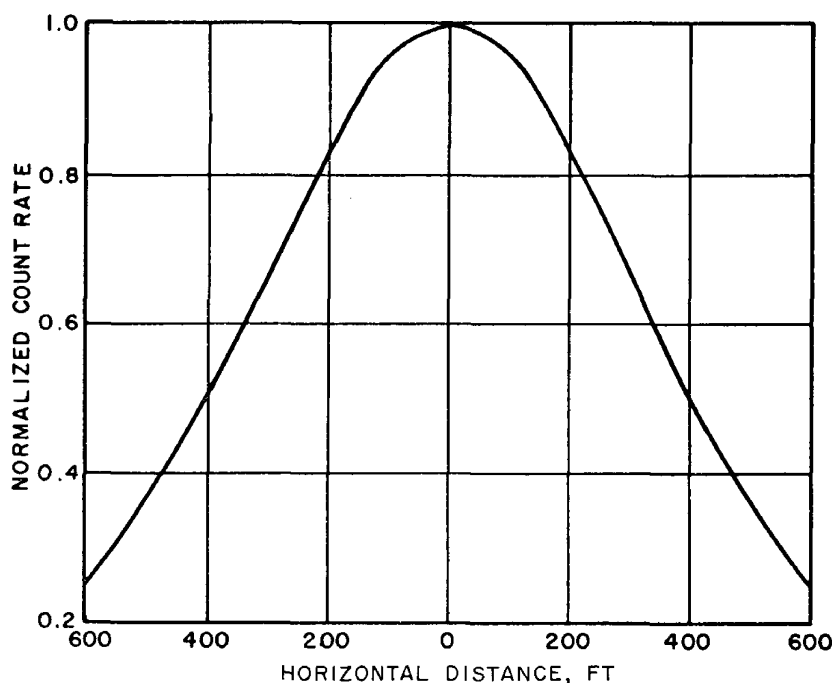


Fig. 2.7—Normalized count rate vs. horizontal displacement from Ground Zero (500 ft above a point source). Sea-level pressure = 760 mm Hg; temperature = 32°F ; relative humidity = 0 per cent.

2.2 APPROACH

An optimum system would then consist of instrumentation that will furnish radiation and positional information when preselected radiation levels are reached in a form reduced to true count rate 500 ft above the ground and the coordinates of that point.¹³ The flight planning to survey a given area should be minimal. The space-positioning data should be available immediately so that contour information will be directly available or can be reduced within a few hours after the flight.

Ideally, all required instrumentation should be air-borne so that, in the event of an accident, data can be taken and the results presented in a minimum period of time after notification of a disaster. As much of the system as is feasible should be automatic to permit a minimum operating crew in the interests of economy and to eliminate, as much as possible, the elements of human error.

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Chapter 3

TECHNICAL APPROACH TO A REVISED SYSTEM

3.1 GENERAL

The physical approach to the problem taken by Davis and Reinhardt¹ of ORNL is very good, but it must be remembered that the equipment was designed several years ago to test the feasibility of such a program and that no thought was then given to miniaturization or continued expansion of surveying responsibilities. As a consequence the system designed to do a particular task, which it did well, is now in the position of having to meet a vastly expanded program. The design of such a system is now predicated on rapid acquisition and reduction of the radiation information;² hence the elaborate photographic space-positioning system presently used (which is used for other purposes besides the ARMS program) is now obsolete. These new system specifications plus the advance in the state of the art permit redesign of this equipment at considerable savings in weight and volume; this, coupled with electronic rather than photographic positioning, allows the utilization of a smaller, less expensive airplane.

The system to be described³ is illustrated by a block diagram (Fig. 3.1), which represents functional units rather than physical entities. Sodium iodide, NaI(Tl), crystals coupled to suitable photomultiplier tubes are used as radiation detectors. The electronic circuitry necessary to convert the photomultiplier-tube output into usable data consists of compact transistorized modules. The radiation level is electronically correlated with the space position of the aircraft, and the result is automatically recorded in flight by a dual print-out system. A punched-tape printer and a decimal printer are used simultaneously to record the data. The decimal printer provides a means whereby rapid presentation of the data is immediately available; whereas the punched-tape printer output is used subsequently with a computer and recorder to yield automatic data processing.

3.2 DETECTOR ASSEMBLY

3.2.1 Detector Module

Since normal survey operation involves monitoring very low radiation levels, the gamma detector must be extremely sensitive. A large thallium-activated sodium iodide, NaI(Tl), scintillation crystal was selected to provide the required sensitivity.⁴ This crystal is 9 in. in diameter by 3 in. thick. The size was selected upon considerations of sensitivity, simplicity of associated electronics, and mechanical strength. During the survey operation the usable count rate can vary at a maximum from 50 to 50,000 counts/sec, or by a factor of 1000. The low value is dictated by nuclear statistics; whereas the high value is limited by the electronic circuitry.⁵ A decreased-sensitivity companion crystal and detector are included to give the system sufficient range to survey radiation-disaster situations. This crystal also is a NaI(Tl) scintillation crystal, 1 in. in diameter by 3 in. long. The small crystal and tube provide a decrease in sensitivity approaching a factor of 1000 due to geometry factors and to the lower probability of total absorption of photons within the smaller crystal. Hence, used alternately,

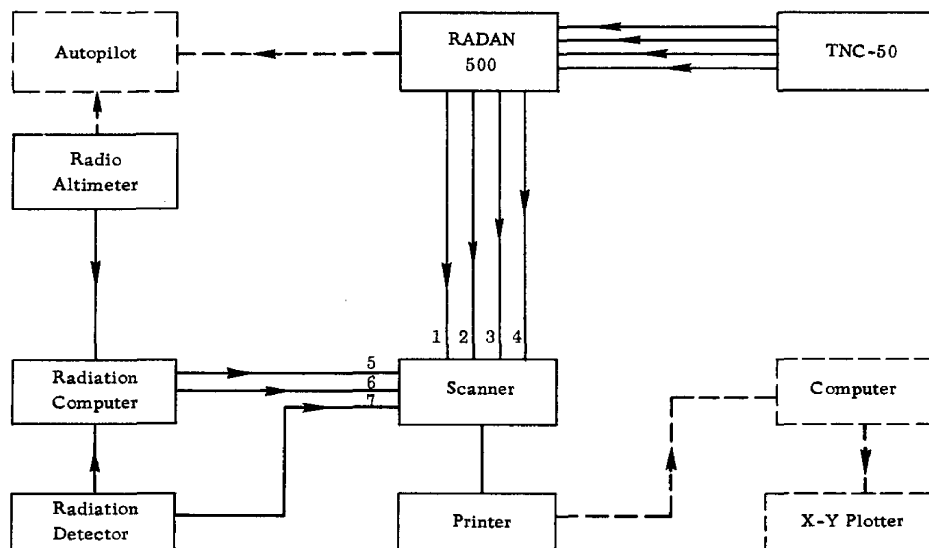


Fig. 3.1 — Block diagram of the ARMS system. The numbers are defined as follows: 1, distance to go on segment; 2, segment number; 3, right or left of segment; 4, distance across segment; 5, print command; 6, radiation channel; 7, sensitivity range.

the two crystals possess the capability of measuring radiation levels that differ at the extremes by a factor of one million.

The multiple-detector assembly, as shown in the cutaway diagram (Fig. 3.2), includes the crystals, photomultipliers, high-voltage power supplies, and preamplifiers. The large crystal is optically coupled to the face of an EMI type 9545B photomultiplier tube. The tube is surrounded by a magnetic mumetal shield. Optimum values of the dynode voltages will be determined by the factory and confirmed by experiment. The smaller crystal is similarly coupled to a DuMont type 6291 photomultiplier tube. Owing to the composition, size, and weight (94 lb) of this assembly, extreme care has been given to the mounting design to isolate mechanical-shock factors. In addition, sufficient insulation must surround the crystals to reduce thermal drifts to an acceptable value of 60°F per hour, regardless of the ambient temperature.

3.2.2 High-voltage Supply

Each photomultiplier tube is powered by an independent power supply. This choice was made over a single supply because of the differing voltage requirements to eliminate switching high voltages and to prevent perturbation of the high-voltage supply to the small crystal when large flux signals are incident upon the large crystal. Each power supply will deliver 0.5 ma at 1500 to 2300 volts. The output voltage is regulated to be constant to 0.005 per cent, with reliable operation from -20°F to +120°F. The supplies are solely solid state, operating from the 115-volt 400-cycle single-phase aircraft power. The circuit incorporates a step-up transformer and rectifier. Regulation occurs both at the high-voltage output and at the supply-voltage input. Each unit consumes approximately 2 watts of the aircraft power.

3.2.3 Preamplifier

The preamplifiers are physically mounted at the base of the photomultiplier tubes and serve the function of impedance matching the output from the photomultiplier tube to the input of the amplifier while preserving pulse linearity. The circuitry is transistorized, consisting of a compensated emitter-follower with a voltage gain close to 1 and a current gain of approximately 1500. The preamplifiers obtain regulated power from the radiation-instrumentation power supplies. The design and construction of the preamplifiers emphasize environmental stability and mechanical ruggedness.

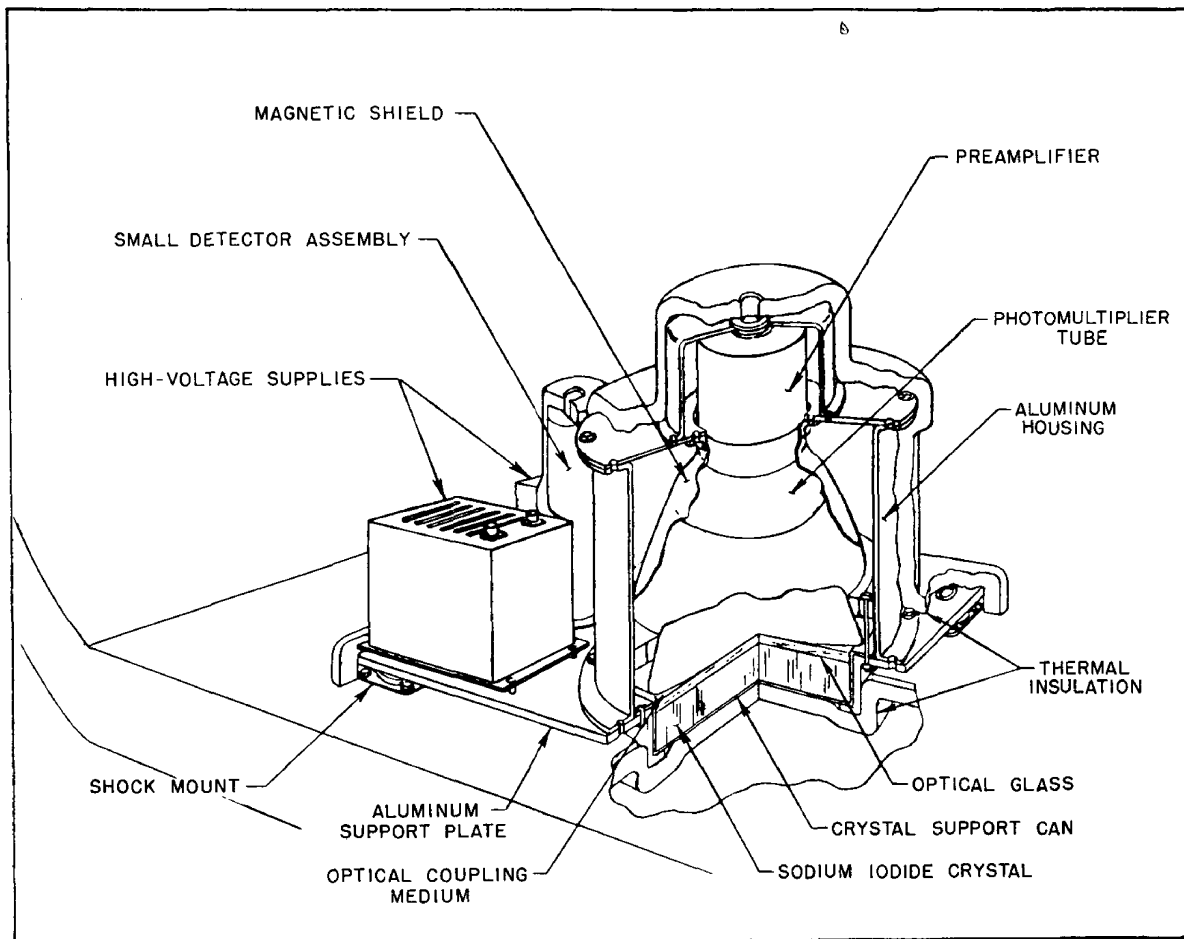


Fig. 3.2—Detector assembly.

3.3 RADIATION INSTRUMENTATION

The radiation-instrumentation electronic system treats the pulse output from the preamplifiers of the detector assembly as follows:

1. Accepts electronic pulses representing radiation interactions in the detector system
2. Rejects certain small pulses that represent gamma background, noise phenomena, or other false information
3. Subtracts pulses at a rate equal to the time rate of arrival of pulses due to cosmic and similar radiation backgrounds incident on the scintillation crystal
4. Calculates the remaining pulse rate by accumulating the number of pulses arriving during a finite sampling time
5. Corrects the rate of arrival of pulses for altitude variations from 500 ft by changing the finite sampling time according to a correction signal supplied from the radar altimeter
6. Displays the measured count rate to provide visual monitoring and to allow calibration to be carried out on the system
7. Classifies the count rate into several different categories, as shown in Table 3.1
8. Supplies a digital designation of the count-rate category
9. Gives a command-to-print signal to the printer (a) when the measured count rate changes from one category to another, (b) periodically at the end of timed intervals, (c) upon manual command, or (d) upon transfer of the navigation system from one flight leg to another

The count-rate values listed in Table 3.1 for each category, or channel, can be selected as desired. The system is designed in such a manner that the channel boundaries can be expanded to include large count-rate ranges or contracted to contain fewer counts. In addition, the number of channels can be changed if necessary.

The scheme employed for accomplishing the preceding nine functions is diagrammed in Fig. 3.3. It should be noted that functions 1 to 3 represent operations of individual pulses. On the other hand, functions 4 to 8 represent operations with respect to the number or rate of pulses. In terms of actual hardware, functions 1 to 3 are separated from functions 4 to 8. The circuits to accomplish functions 1 to 3 are referred to as pulse-handling equipment. The circuits to accomplish functions 4 to 8 are referred to as computing equipment.

In general, all the components of the radiation-instrumentation electronics system consist of solid-state devices. The devices are designed in such a manner that they will operate under the shock, vibration, and temperature conditions expected during field operations. The system will accept random pulses from the detectors at a rate up to 100,000 pulses/sec with less than 1 per cent counting loss.

3.3.1 Pulse-handling Equipment

Physically, the pulse-handling equipment is packaged in a module approximately $5\frac{1}{2}$ by $7\frac{1}{2}$ by $10\frac{1}{2}$ in. The module itself will contain 5- by 7-in. circuit boards on which the components to accomplish the functions depicted in Fig. 3.3 will be constructed. In addition, the module will contain a power supply that accepts 400-cycle 110-volt power, with provisions for applying the appropriate potential to the components of the pulse-handling subsystem. The radiation-computing portion of the system in Fig. 3.3 is explained in Secs. 3.3.2 to 3.3.8.

3.3.2 Background Corrector

(a) *Description.* A potentiometer control adjusts the frequency of a variable-frequency oscillator, which feeds a temporary storage scale-of-16 counter. The zero state of the scaler arms a flip-flop gating circuit to permit the radiation pulses to pass through the system. However, when the scaler is at other than the zero state, the gate is closed and radiation pulses enter the scaler, running the scaler count backward toward the zero state.

(b) *Function.* The background corrector will adjust the input gate so that the pulses from the radiation detector, due to background, will be subtracted from the over-all count rate. In addition, the temporary storage scaler acts as a smoothing function for the time spread in radiation-pulse arrival due to nuclear statistics, permitting accurate background subtraction in the presence of low ground-signal levels.

During the background calibration the potentiometer is initially set at zero; the recorded count on the visual display unit is then the background rate. The potentiometer is then set on its calibrated scale to this value.

3.3.3 Sample-period Gate Generator

(a) *Description.* An analog current is fed from the radar altimeter to the period generator, where it is converted to a gating signal with a width dependent upon the amplitude of the analog current. The pulse produced varies the "on-off" time of the input gate.

(b) *Function.* For altitudes above the normalized value, the sample-period gate will be lengthened; whereas for altitudes below the normalized value a shorter gate will be generated. A calibration switch will be provided on the control panel, which, when activated, will cause the gate generator to produce a constant gate width normalized to the 500-ft value.

3.3.4 Input Gate

(a) *Description.* The input gate consists of a coincidence, or "and," circuit, in which all inputs must be energized simultaneously for an output to occur.

(b) *Function.* The input gate is simply open or closed, depending upon the signals from the background corrector and sample-period gate generator. When the gate is open, it admits pulses from the detection system and allows them to be counted by a 16-bit binary counter.

TABLE 3.1 — RADIATION COUNT-RATE CATEGORIES

Count rate, counts/sec	Category
0 to 50	1
50 to 100	2
100 to 150	3
150 to 200	4
200 to 250	5
250 to 300	6
300 to 350	7
350 to 400	8
400 to 450	9
450 to 500	10
500 to 550	11
550 to 600	12
600 to 650	13
650 to 700	14
700 to 800	15
800 to 1,000	16
1,000 to 2,000	17
2,000 to 4,000	18
4,000 to 8,000	19
8,000 to 15,000	20
15,000 to 30,000	21
30,000 to 60,000	22
Above 60,000	23

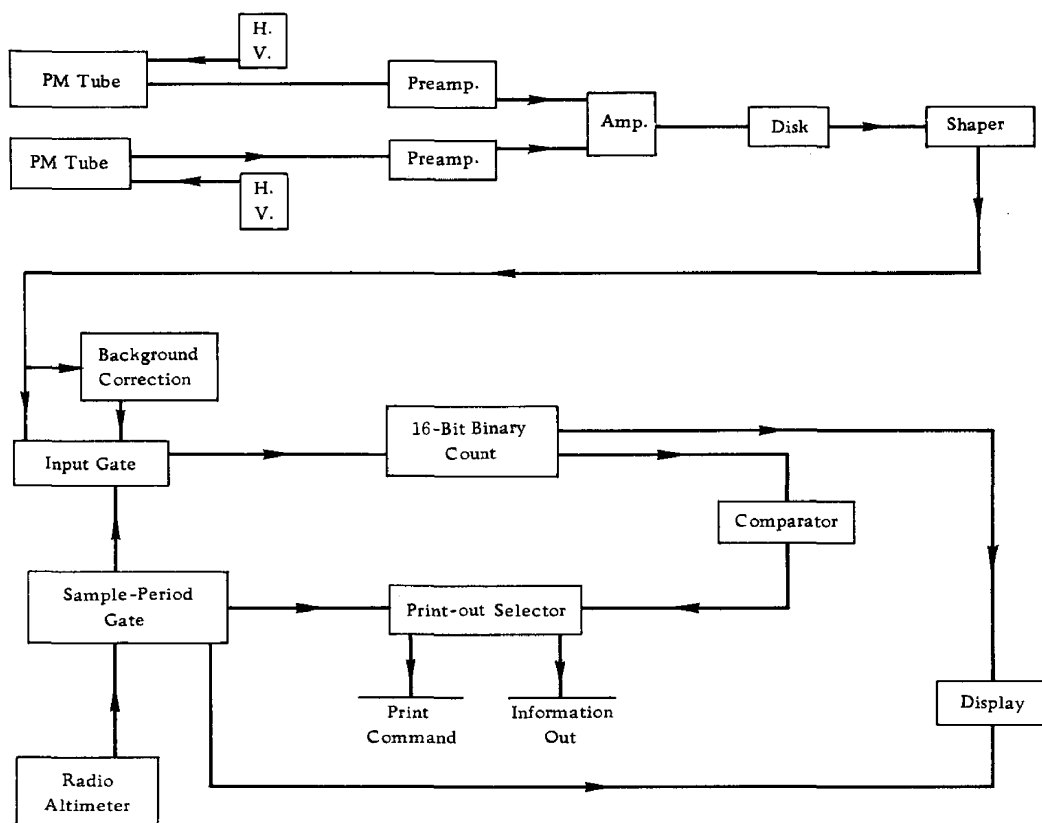


Fig. 3.3—Block diagram of the radiation-measurement system.

3.3.5 Sixteen-bit Binary Counter

(a) *Description.* The binary counter consists of a conventional string of Eccles-Jordan flip-flop circuits.

(b) *Function.* The binary counter registers all the pulses allowed through the input gate. It is capable of counting approximately 64,000 pulses/sec.

3.3.6 Comparator

(a) *Description.* The comparator consists of a diode matrix preset to yield numbers from 1 to 23, depending on the count level registered in the counter (see Table 3.1). Each number corresponds to a band of radiation counts.

(b) *Function.* The comparator converts the binary-coded number registered in the counter to a channel number from 1 to 23.

3.3.7 Display

(a) *Description.* The display unit is a decimal representation of the count with the use of electro-optical indicators.

(b) *Function.* This unit gives a visual display on the control panel of the counts obtained over the sampling period. A manual hold button is provided so that the operator can observe the reading for a period longer than the normal sampling period.

3.3.8 Print-out Selector

(a) *Description.* For time-interval print (every 3 sec), a reset pulse is channeled to the printer from the time-period gate generator. For channel-level read-out the channel level is stored in a register from the previous sampling period and compared to the current reading. If no difference exists, no command is given; if a difference exists, a comparator commands the printer to print the new channel-level number.

(b) *Function.* The print-out selector provides two types of print-out modes. A two-position switch on the control panel will determine whether print-out will be at the end of each 3-sec period or for each crossing of a channel level. The printer will also receive a command-to-print signal from an external manual command or when a navigation flight-plan leg is changed.

3.3.9 Controls

The circuitry that comprises the count-integrating equipment consists of two modules. One module will have the approximate dimensions of 10 by 12 by 20 in. and will be referred to as the "computer." The other module will have the approximate dimensions of 8 by 16 by 4 in. and will be referred to as the "operator's control panel." The controls and indicators located on the operator's panel, as shown in Fig. 3.4, are listed as follows:

1. Function (four-position rotary switch)
 - (a) Power off
 - (b) Stand-by
 - (c) Calibrate
 - (d) Run
2. Count-rate Display (five digital-display tubes)
3. Display Hold (push button)
4. Print Mode (four-position rotary switch)
 - (a) Off
 - (b) Level
 - (c) Period
 - (d) Transfer
5. Manual Print (push button)

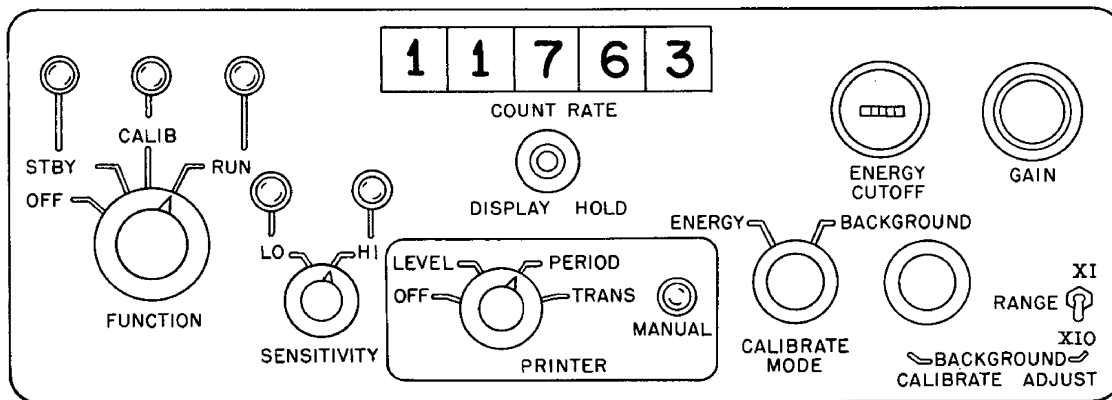


Fig. 3.4 — Operator's control panel.

6. Calibration Controls

(a) Mode (two-position rotary switch)

- (1) Energy (source in)
- (2) Background (source out)

(b) Energy cutoff (10-turn helipot)

- (1) Calibrate; set at 6.61 (discriminator)
- (2) Run; set at 0.50

(c) Gain (10-turn helipot amplifier gain)

(d) Background (three-position center-off toggle switch plus a one-turn calibrated potentiometer)

- (1) Low (20 to 200 counts/sec)
- (2) High (200 to 2000 counts/sec)

7. Sensitivity (two-position rotary switch)

- (a) Low
- (b) High

3.4 SPACE-POSITIONING SYSTEM

3.4.1 Selection

The initial investigation of the space-positioning system suitable for use in the modified ARMS system revealed the following specifications:

1. The system should be self-contained aboard the aircraft, requiring no ground station and thus providing maximum mobility of the survey system.
2. The system must be capable of determining space-position information over an area 100 by 100 miles at an altitude of 500 ft above the terrain.
3. The system should, by simple economic procedure, yield an accuracy of space position within 200 ft over particular areas.
4. The air-borne installation should be miniaturized in a small-volume lightweight package requiring minimum power for installation in a light twin-engine aircraft.

The first approach was to examine conventional available radio aids to aerial navigation to determine how they would apply. This investigation revealed that the use of low-frequency range, low-frequency homers, VOR-omni, or VOR-DMET systems admitted an operational error that prohibited their use for any kind of accuracy beyond just a few miles. For exam-

ple, low-frequency ranges can drift 7 deg in orientation before realignment, and VOR equipment is permitted a latitude of ± 3 deg in radial calibration.

The next step was to contact the Cornell Aeronautical Institute at Buffalo, N. Y.,⁶ which does government-contract research in the field of space-positioning systems and is indeed a nationally recognized authority in this field. A subsequent visit to this agency brought about a discussion of the space-positioning problem of the ARMS system. Then followed a presentation by Cornell personnel of all known physical systems that might be applicable for this purpose. The types of systems discussed included all types of radio, radar, photographic, optical, and inertial guidance schemes. Many schemes were discarded because of the cost involved; in some cases cost exceeded one million dollars. Other methods, e.g., an optical-photographic system, were discarded because of the amount of manual data reduction. Others were discarded because of the inaccuracies involved, such as the many radio navigation and inertial guidance methods. The discussions led to the pursuit of three systems, none of which completely satisfied the initial requirements.

The first was a Bendix-Decca low-frequency phase navigation system. Subsequent investigation revealed that the accuracy obtainable was marginal. The system required the use of three ground stations that were semiportable, involving the use of 100-ft-high antennas and 36 ground radiators per station. Considerable prepreparation of a survey site was necessary for calibration involving the use of an electronic-computer installation.

The second system recommended was the International Telephone and Telegraph Corporation Lacrosse system developed for the U. S. Army Signal Corps to provide position and control information to aircraft. This scheme utilized a small portable ground-based pulsed radar system with a transponder in the aircraft. The Lacrosse apparatus provided excellent accuracy with a ground station that could be moved with little effort. However, since a ground station was used with very high frequency signals, the range is limited to the line of sight. For flat terrain at a 500-ft altitude, this restricted the effective range to 30 miles. For irregular terrain the range is, of course, appreciably shortened.

The last system recommended was the General Precision Laboratory, Inc. (GPL), Doppler navigation system⁷ or the equivalent. This scheme is a wholly transistorized, hence miniaturized, system that is self-contained in the surveying aircraft. The system provides automatic guidance and position information from referenced ground fixes. Some data reduction was necessary to meet the accuracy requirement. However, this reduction was so minimal that an individual could accomplish it on the ground with the same rapidity at which the data are acquired. In addition, the method of data reduction easily leads to the incorporation of automatic equipment to accomplish this. Thus the Doppler navigator appeared to be the only method capable of meeting all specifications listed.

Predecessors of this type equipment have been used for aerial surveys in Africa and Canada. This technique employs an air-borne Doppler radar system that can accurately measure ground speed and drift by measurement of phase shifts in the longitudinal and transverse courses. Such a system utilizes no ground stations and operates independently of terrain. Since it is essentially a corrected dead-reckoning type navigation, an initial fix must be taken to establish a reference space position. Accuracy is a function of distance flown from the fix, and the error is normally 2 per cent of that distance, or 2 miles at 100 miles. However, GPL has just completed a modification of this system⁸ for Canadian surveying operations which possesses an accuracy within 800 ft at 30 miles, or 0.5 per cent. A modified system wholly self-contained in the aircraft will weigh 328 lb and require a power of 950 watts.

In operation a flight plan of as many tracks as are desired would be prepared on maps relative to given ground fixes. In the air the pilot starts the equipment over a known fix, and an associated instrument gives his position by indicating the distance to the right or left of his desired track and the number of miles remaining on the desired leg of his track. This indicator can also be connected into an autopilot to effect automatic track guidance. There are two sets of indicators so that, while one track is being flown, the next one can be prepared.

As the aircraft progresses along the desired track, radiation data are recorded in the aircraft, along with the space position on the track. When a new check point is reached, the pilot repositions his aircraft, and the position error is recorded. After completion of a flight, data reduction then consists in relating the space-position errors to the true location on a map and

in plotting radiation-contour levels. The data produced are readily susceptible to rapid machine computation.

3.4.2 Doppler Radar System

Figure 3.5 is a block diagram of the complete navigation system. The J-4 compass system was chosen because it is the most accurate reference available. The magnetic heading output of the J-4 system is fed to the Doppler navigation system, where it is used by the Doppler and the navigation computer in computing along- and across-track components of distance. The J-4 and the RADAN 500 are the input sensors that provide heading, ground speed, and drift, all of which are required by the track navigation computer (TNC-50). The TNC-50 provides outputs as indicated in Fig. 3.5. The basic units are production items, and the numerous systems now in use indicate widespread acceptance.

The outputs of the TNC-50 are fed to the commutator and thence to the analog-to-digital converter. The commutator, or sampling device, permits passage of the signals to the analog-to-digital converter each time a command signal from the radiation instrumentation or an external command is furnished. Thus signals are fed to the converter and printer only when the recording-command signal is supplied. The output-position data are always and instantaneously available to the commutator.

The analog-to-digital converter supplies the proper digital inputs to the printer for recording. A print-command signal is supplied to the printer in the modes previously described.

A detailed discussion of each of the Doppler subsystems and its controls is as follows:

1. The RADAN 500 control panel contains a function switch to activate the system, a "Land-Sea" switch for over-water flight, and a "Speed-Drift" control switch. The "Speed-Drift" switch provides a means of setting the RADAN 500 outputs for manual operation of the computer if desired.

The TNC-50 control panel contains dual displays of "Desired Track, Nautical Miles To Go," and "Nautical Miles Off Track," together with manual input knobs for these quantities, an "Off-Stand-by-Run" function switch, and two transfer buttons. The two displays function alternately; while one is displaying precise navigation information for the current flight segment, data for the next segment can be inserted in the other. "Run" and "Set" flags are provided to denote these conditions.

At the start of a flight, the RADAN 500 function switch is placed in the "On" position, and the TNC-50 function switch is placed in "Stand-by." The desired track and distance ("Nautical Miles To Go") for the first segment are manually inserted into the "Run" display. Immediately after take-off the TNC-50 function switch is placed in the "Run" position at a predetermined ground-reference point. The display of "Nautical Miles To Go" and "Nautical Miles Off Track" begins. In normal flight, as the aircraft moves along the segment, the "Nautical Miles To Go" indication decreases toward zero, and, if the aircraft stays on track, the "Nautical Miles Off Track" reading remains at zero.

At any convenient time during the first flight segment, similar data for the second segment are inserted into the "Set" display. When the "Nautical Miles To Go" of the "Run" display reaches zero (end of first flight segment), automatic transfer takes place. The second display now indicates information for the second segment. This procedure is followed for as many segments as are necessary to complete the flight.

2. The TNC-50 includes provision for exponential return to the desired track. Should an intentional or unintentional deviation from the desired track occur, the aircraft will smoothly return to the predetermined track automatically when an autopilot coupling exists or manually when the flight director is utilized.

3. The RADAN 500 transmitter is essentially a conventional radar circuit with a magnetron power oscillator whose pulse-repetition frequency is determined by random voltage pulses from a noise generator.

The radio-frequency from the transmitter is fed to the antenna, from which two radiation patterns are emitted alternately at $\frac{1}{2}$ -sec intervals. Each pattern consists of two lobes, one transmitted to the right-front and left-rear and the other to the left-front and right-rear of the aircraft. The radio-frequency energy in these lobes strikes the ground at the corners of a rectangular pattern. Thus the echo returned from the ground always contains the reflections

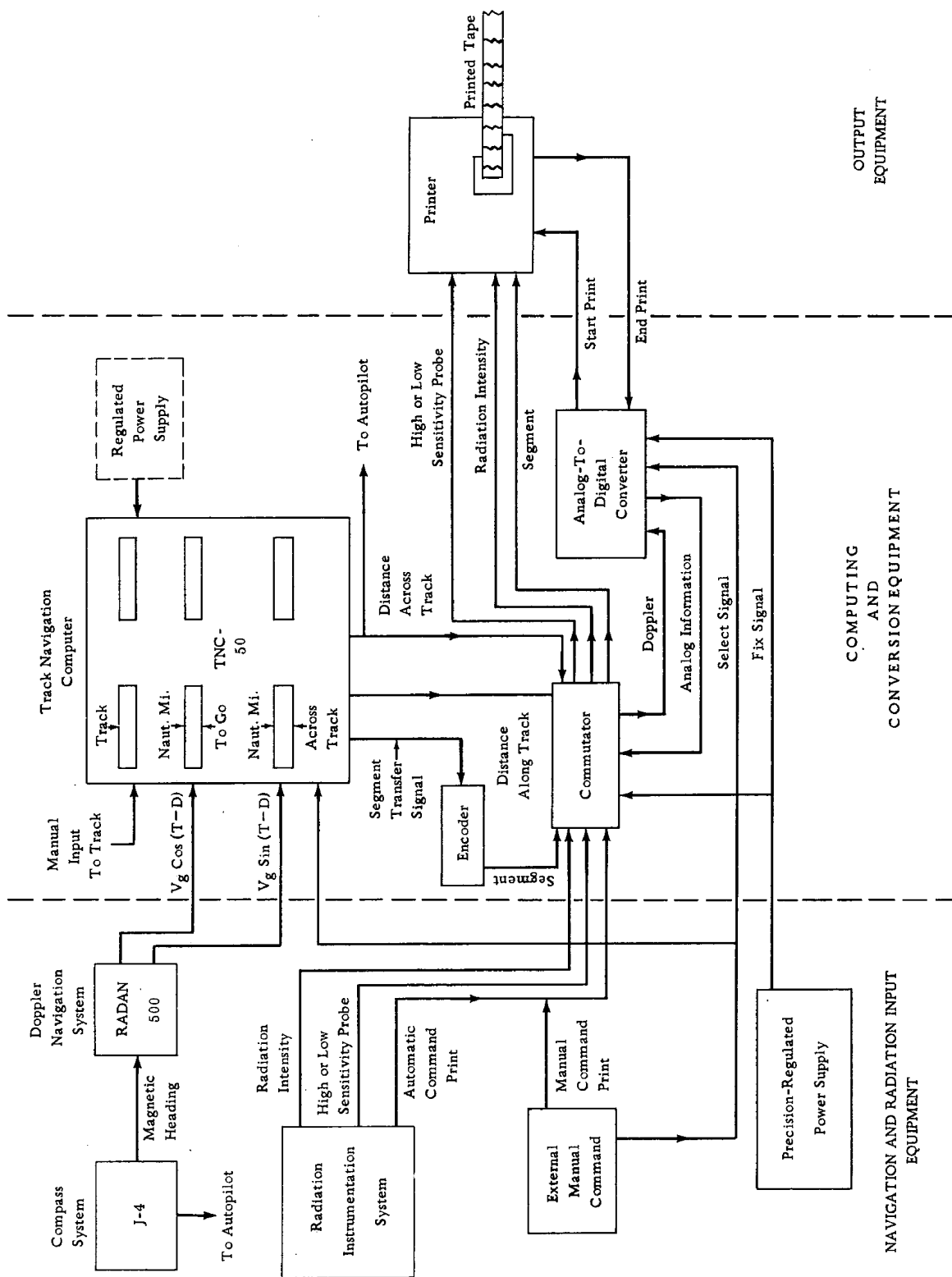


Fig. 3.5 — Block diagram of the Doppler navigation system.

of both a front- and a rear-pointing lobe, with the frequency of the reflected waves shifted as a result of the aircraft motion (Doppler effect). The received echoes are fed to a microwave superheterodyne receiver and converted to intermediate frequency. The two signals are then amplified in the intermediate-frequency amplifier, mixed, and detected. They appear at the output of the detector as a single audio-signal. This audio-signal is filtered, amplified, and fed to the frequency tracker. Here the audio-frequency is mixed with a reference frequency from the frequency generator. Phase differences in the resultant signal are amplified and detected in the main tracking loop. The resulting voltage is integrated and applied to the frequency generator, making its frequency equal to that of the audio and proportional to ground speed.

The cycle counter develops a voltage proportional to the frequency of the frequency generator and, through a servo, sets the position of the ground-speed counter in the indicator, as well as a synchro-shaft position for remote computer operation.

In the main tracking loop the two audio-signals derived from the alternating patterns are compared. Any difference between these signals produces an error signal in the detector following the main tracking loop. This signal is fed to the antenna azimuth servo, which positions the arrays parallel to the aircraft drift angle which, by a follow-up servo in the frequency tracker, is displayed on the indicator. A differential generator on the servo shaft in the frequency tracker accepts headings from an external reference and develops a three-wire track-made-good signal for the TNC-50 computer.

A signal-to-noise detector monitors the main tracking loop for the presence of audio-signals. If audio from both patterns are absent simultaneously, "Off" flags appear on the indicator, and the ground-speed and drift-angle shafts are locked at the last correct readings. The frequency generator is then swept downward through its range until audio once again appears. The ground-speed shaft is then unlocked and displays the present ground speed derived from the signal in one pattern. The antenna then automatically slews in the direction of decreasing drift-angle error until audio is acquired from the other pattern, at which time the frequency-tracker drift-angle shaft unlocks and the drift-angle repeater in the indicator begins its display.

Manual slew of ground speed and drift angle is effected by a control-panel switch that inserts slew voltages into the frequency-tracker servo amplifiers. When the function switch is placed in the "Stand-by" position, all power except magnetron high voltage is applied.

4. Required signal inputs to the TNC-50 are a three-wire signal of track-made-good (T) and a 400 cycle/sec voltage analog of ground speed (V_g); the TNC-50 supplies a 400 cycle/sec reference voltage for the latter.

In the control panel a synchro-differential compares track-made-good with desired track (D); the output is the track-angle error ($T-D$). This controls a servo in the computer-amplifier to provide a shaft-position analog of this quantity. A resolver on this shaft accepts the 400 cycle/sec V_g signal and has as outputs $V_g \sin (T-D)$ and $V_g \cos (T-D)$. The computation of nautical miles to go is as follows: $V_g \cos (T-D)$ (along-track component of ground speed) drives a rate servo, consisting of a servo amplifier and integrating tachometer, whose output is a shaft-rpm analog of $V_g \cos (T-D)$. A synchro-transmitter geared to this shaft excites a torquer (in the TNC-50 control panel) which follows at the same rate as $V_g \cos (T-D)$. This torquer drives the "Nautical Miles To Go" counter, whose total revolutions are thus made to represent distance traveled from the start of computation. Since the counter was initially set to segment length, the instantaneous reading is the present distance to go on the segment.

The computation of nautical miles off track is as follows: $V_g \sin (T-D)$ is integrated similarly to $V_g \cos (T-D)$ [a synchro-receiver in the control panel turns at rate $V_g \sin (T-D)$]. This receiver is geared to a counter initially set at zero (in most cases). The total revolutions of the counter represent the distance traveled across the track, left or right.

The transfer from the running counters to the stand-by counters is effected automatically through a system of relays when the running "Nautical Miles To Go" counter reaches zero. This can also be accomplished manually by pressing the "T" button associated with the "Set" counters.

Output signals, representing off-track deviation, desired track angle, nautical miles to go, and track-angle error, are provided for flight directors, autopilots, and remote indications as are required.

TABLE 3.2—NAVIGATION-SYSTEM ERROR

Item	Cross-track error	Along-track error
Computer	0.25% 0.25% of distance traveled across track	0.25%
Doppler	0.4%	0.25%
Compass system (N-1)	1/2%*	
Cross-track error = $[(0.5)^2 + (0.4)^2 + (0.25)^2]^{1/2} = \pm 0.728\%$		
Along-track error = $[(0.25)^2 + (0.25)^2]^{1/2} = \pm 0.35\%$		

*This accuracy is based on experience of GPL in making compass calibrations with the N-1 compass system.

5. The over-all navigation-system error is based on a root-mean-square summation with the use of the data in Table 3.2.

3.5 DATA-RECORDING SYSTEM

The air-borne radiation instrumentation will provide a command input signal to a recording instrument that prints a combined record of radiation level, sensitivity range, route segment, distance along track, and transverse displacement from track referenced to a prescribed ground track. The space-position output is processed through an analog-to-digital converter, which drives the printer.

The printer is a dual print-out mechanism that simultaneously prints a decimal tape and a punched coded tape. Both methods of data recording are accommodated with a single scan of the information channels by running the two tapes at different speeds through the printer. The decimal type print-out prints a 13-character one-line group in red or black in the form shown in Table 3.3.

TABLE 3.3—PROPOSED PRINTER DISPLAY

241:23:0847:022R
241:23:0840:021R
241:23:0835:020R

The grouping in Table 3.3 illustrates three separate data-point group print-outs of the decimal printer. Not illustrated is the fact that, when the high-sensitivity probe is in use, the line is printed in black and, when the low-sensitivity probe is used, the line is printed in red. A single print-out consists of one line of characters. In the top line of Table 3.3, the first three digits, 241, represent flight leg or segment number 241. The next group of two digits, 23, refers to radiation channel number 23. The next group of four digits, 0847, refers to the distance to go along the track segment at which the radiation level was recorded and represents 08.47 nautical miles. The last group of three numbers, 022, represents the distance displaced transversely from the desired track segment and is read as 0.22 nautical mile. The last character, R, states that the transverse displacement was to the right of the track. Similarly, an L is printed when the displacement is to the left of the track. Thence, if the discussed sample data point were printed in black, it would represent radiation channel 23 (above 60,000 counts/sec) on the high-sensitivity probe. This value was recorded at 8.47 miles to go on segment 241 with a right transverse displacement of 0.22 mile.

It is believed that, with the preceding arrangement of the decimal type print-out, the effort involved in manual reduction of the data will be held to a minimum. Since automatic data processing will not be available when survey operations begin, the data have been grouped to facilitate rapid reduction and plotting on a geographic map.

In anticipation of automatic data processing, the second punched-tape unit will operate simultaneously with the decimal printer and will record the identical information. The punched-tape printer will be operated when survey operations begin so that, when automatic data-reduction equipment is added, all the acquired data can be processed automatically and uniformly.

It does not appear feasible to outline in detail the ground-data processing system because of the project time scale. Technically, it is not an overly complex problem. However, the design of this device depends on the operational errors that exist when the system becomes operational and on the forms the data should take to be of greatest convenience to the user. If present plans materialize, the radiation information will be automatically plotted on maps, and a punched-card or similar system for permanent storage and data manipulation suitable for digital computer input will be possible.

3.6 AIRCRAFT

The type of aircraft selected for the survey operation is dictated by fairly severe requirements. It must be economical to operate and at the same time must afford safe and reliable operation. From consideration of the altitude flown during operation, it would appear mandatory that twin-engine aircraft with excellent characteristics during one-engine operation be used. The aircraft selected must have widespread usage to facilitate the availability of parts and experienced maintenance. It should be capable of carrying the instrument payload, two crew members, and sufficient fuel for a minimum cruising range of 5 hr at a true air speed of approximately 200 mph. Sufficient electrical power must be available to run the radiation and navigation measurement equipment.

The aircraft in use by the USGS team is a DC-3. This airplane serves admirably to transport the equipment and men currently used to obtain survey data. The use of solid-state circuitry, miniaturization techniques, and automatic data processing, however, permits the use of a lighter craft to perform the same task at a reduced operating cost. In addition to the preceding criteria, the selection of an acceptable aircraft is based on the capability of the ship to meet the following requirements satisfactorily:

1. Provide 100-amp engine-driven generators
2. Contain sufficient usable space for installation of the necessary survey apparatus
3. Be readily adaptable to equipment installation, i.e., not require excessive modification or structural reinforcement
4. Operate with a minimum payload of 1100 lb
5. Cruise between 180 and 200 mph
6. Allow economical operation (including amortization of the original cost)
7. Provide the maximum degree of flight safety

These items are self-explanatory. To comply with item 7, it has been decided to consider only twin-engine aircraft since flight over populated areas at a 500-ft altitude demands the higher degree of safety provided by two-engine operation. Several twin-engine aircraft on the market meet a few, but not all, of these requirements. For instance, the Cessna 310 and the Piper Aztec do not satisfy requirement 1, and the Grumman Gulfstream and the larger Beechcraft models do not comply with requirement 6. A survey of the available craft revealed that the most suitable aircraft would be either the Aero-Commander or the Beech Model 50 Twin Bonanza. Both fulfill requirements 1, 2, 5, and 7. Of the two aircraft the Beech better satisfies requirement 6 and will carry slightly higher payloads than the Aero-Commander; more important, the space available in the Beech Model 50 is readily adaptable to the equipment installation, providing greater ease in completing the structural modifications necessary to ensure Federal Aviation Agency (FAA) licensing. Several problems were encountered in engineering the planned installation in the Aero-Commander. Therefore, since the Beech Model 50 Twin Bonanza meets the seven preceding requirements, it has been selected as the survey aircraft.

The installation of the survey apparatus is therefore designed for the Beech Model 50. Figures 3.6 to 3.8 illustrate the proposed locations of the systems in this aircraft.

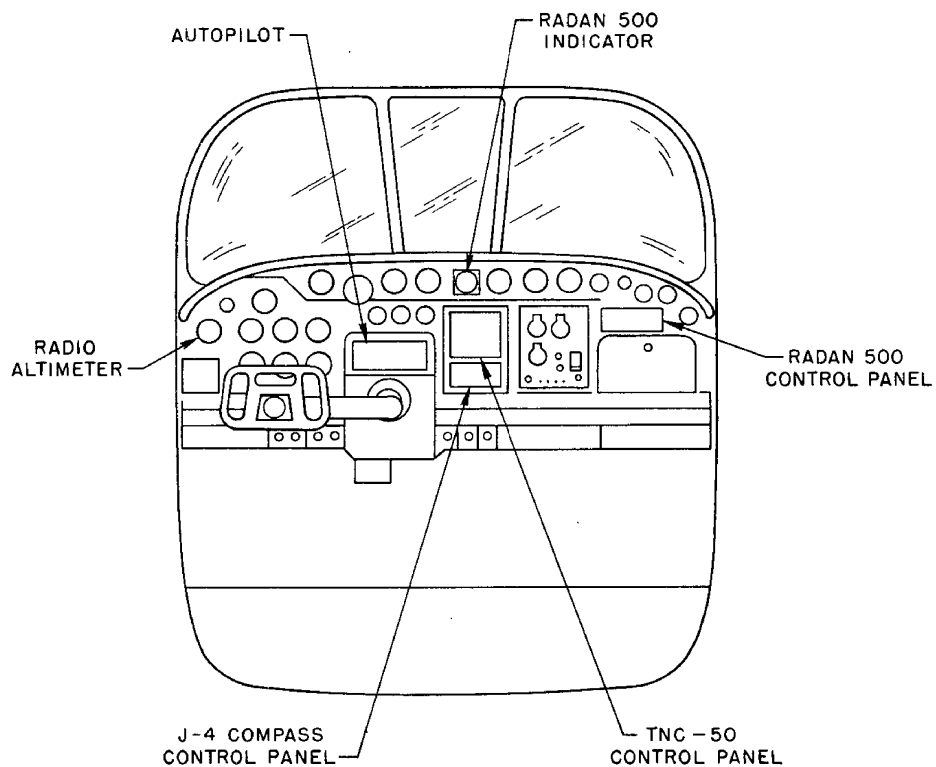


Fig. 3.6—Aircraft instrument panel.

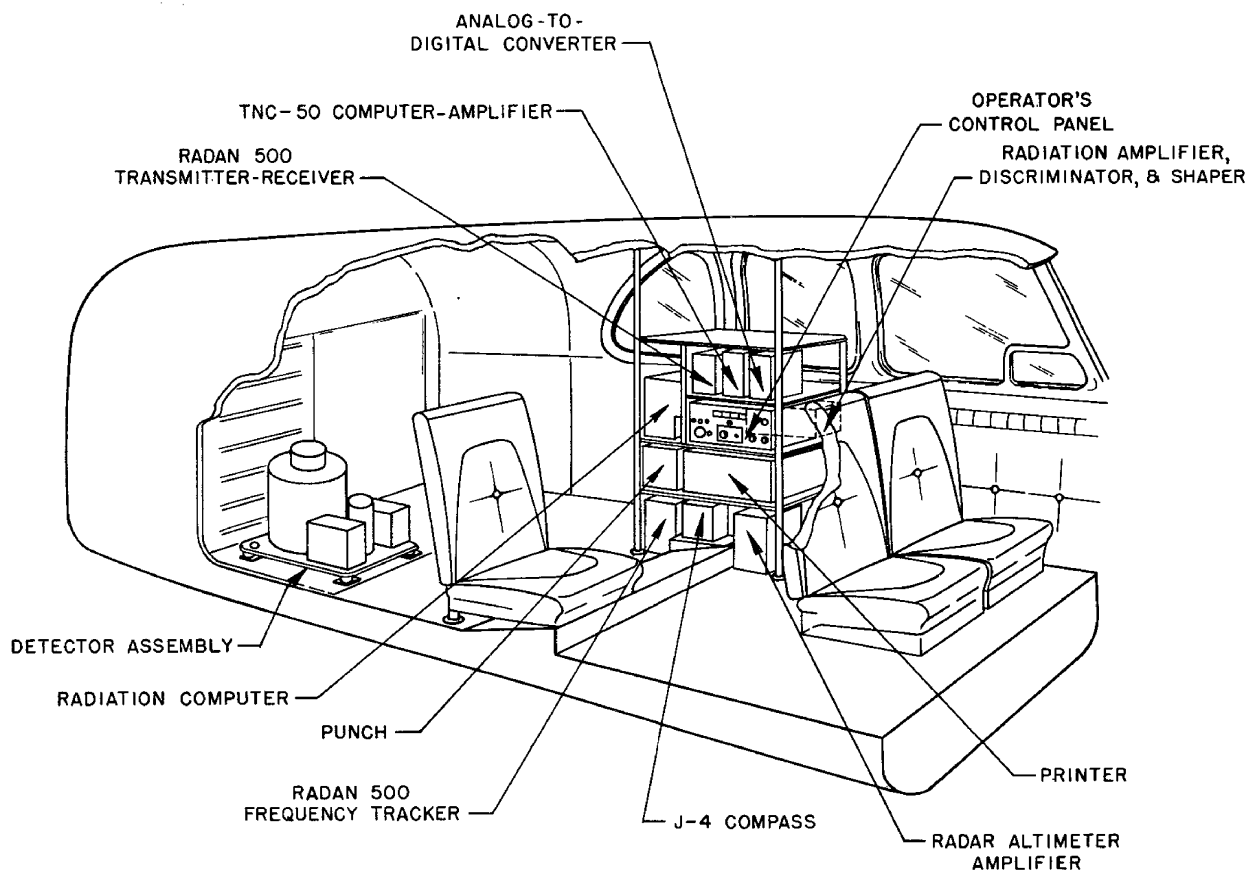


Fig. 3.7—Locations of radiation and navigation equipment.

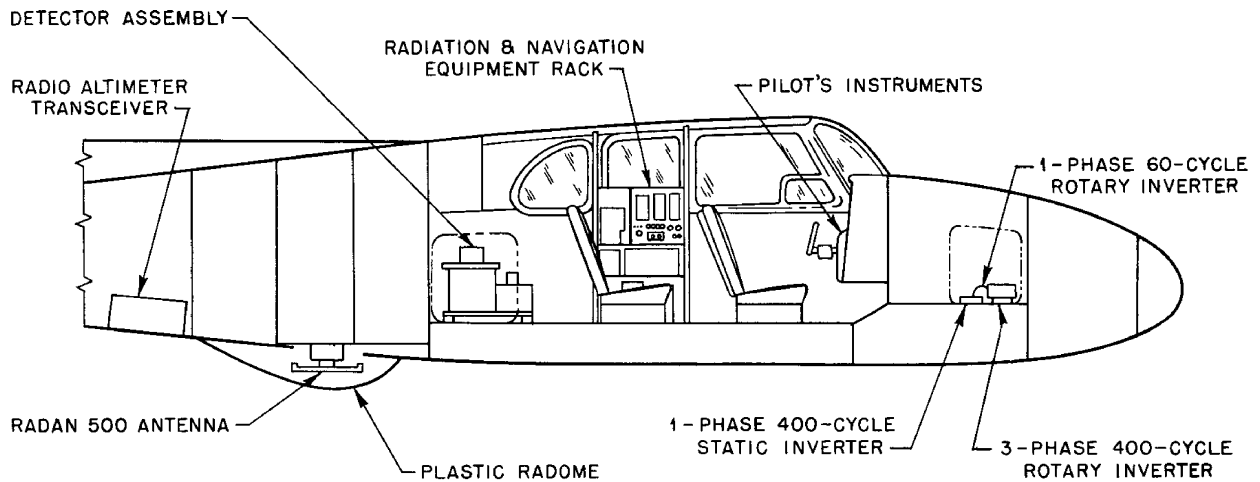


Fig. 3.8—Locations of radiation and navigation equipment.

3.7 ASSOCIATED AIRCRAFT SUBSYSTEMS

3.7.1 Radar Altimeter

The selection of a suitable radar altimeter was based on considerations of reliability, accuracy, and weight. The military type APN-117 fills these requirements. It possesses two ranges: 0 to 40 ft and 40 to 1000 ft, the latter scale, of course, being useful for this application. The manufacturing specifications dictate an accuracy of ± 5 per cent or ± 25 ft at 500 ft; however, operational tests by users state that the device can readily be calibrated to an accuracy of ± 6 ft at an altitude of 1000 ft. The vertical radar beam determines an average altitude over the solid angle viewed by the radar antenna. This angle to the half-power point is 65 deg in the longitudinal plane and 55 deg in the transverse plane. The optimum for any altitude-correction anomalies occurs when the radar altimeter views approximately the same area as does the radiation detector. The time constant of the indicating system is less than 0.1 sec.

Selected voltage outputs are available for the automatic pilot and radiation-system computer. In addition, the height visual indicator is servo operated, and therefore a servo output is available if desired.

The radar altimeter consists of three assemblies, which are listed as follows:

Description	Dimensions	Weight, lb
Receiver-transmitter	$5\frac{45}{64}$ by $4\frac{3}{16}$ by $14\frac{5}{8}$ in. depth	7.0
Control amplifier	$5\frac{1}{2}$ by $7\frac{61}{64}$ by $22\frac{29}{32}$ in. depth	23.5
Height indicator	4 in. dia. by 6 in. depth	

The receiver-transmitter, with associated antenna, is mounted flush with the underside of the rear of the fuselage. The control amplifier performs the necessary computations and presents the required output in a usable form. The radar altimeter control amplifier and height indicators must be modified to secure the most accurate altitude information in a form suitable to control the radiation computer time gate correctly. This is done by first requiring that the altimeter servo output be linear from 0 to 1000 ft. Second, this linear output is transformed into the necessary exponential function vs. altitude for the radiation computer input by a specially wound function potentiometer. The correction is applied in two phases to secure maximum servo travel and hence greatest accuracy. The total power requirement is 192 watts; Fig. 3.9 gives the electrical power requirements.

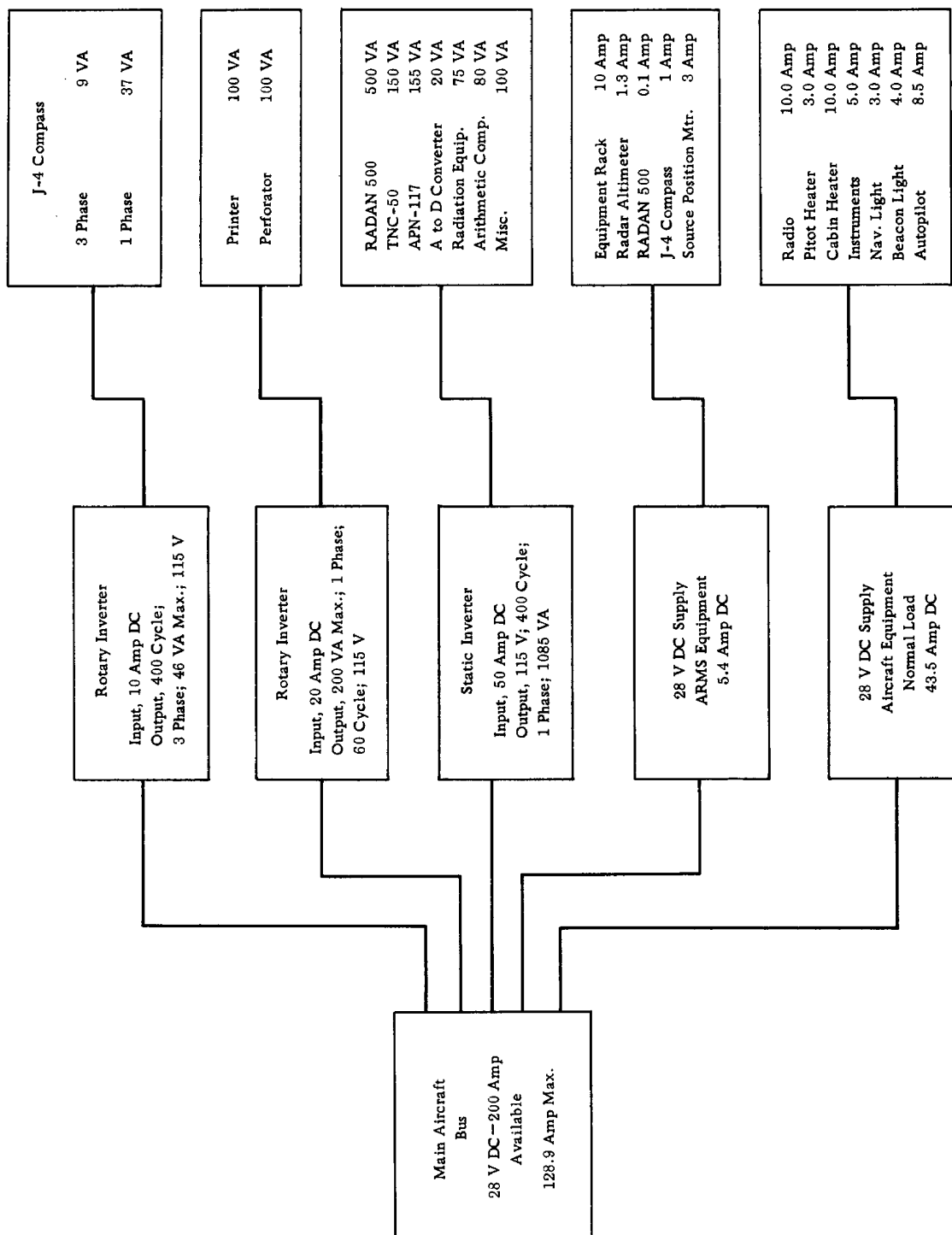


Fig. 3.9 — Electrical power requirements.

3.7.2 Inverters

Two types of 400-cycle inverters are required, one delivering 115-volt three-phase power and the other delivering 115-volt single-phase power. Two inverters are desirable to separate the primary flight a-c power from that used in the installed instrumentation.

The three-phase power will be supplied by a 100-v rotary inverter. The required drain is 9 va to supply power for the J-4 slave compass (an integral unit of the Doppler navigator). Reliable inverters of this type are available from several manufacturers.

The largest amount of a-c power will be supplied by a static solid-state inverter. The maximum load on this unit will be 1200 va supplied to the radiation instrumentation, the Doppler navigator, and the radar altimeter (see Fig. 3.9). The inverter under consideration has a maximum rating of 1600 va during prolonged operation, and, if a 1500-v circuit breaker is used, the manufacturer guarantees the unit for 5000 hr of operation. Under these operating conditions the inverter requires an adequate heat sink, such as the structure of the aircraft.

TABLE 3.4—OVER-ALL WEIGHT DISTRIBUTION OF EQUIPMENT

Equipment	Weight, lb
Radiation Equipment	
Detector assembly	94.0
Amplifier, discriminator, and shaper	7.5
Digital computer	35.0
Control panel	10.0
Subtotal	146.5
Navigational Equipment	
J-4 compass system	20.0
RADAN 500:	
Transmitter—receiver	15.0
Frequency tracker	33.0
Indicator	4.0
Control panel	1.0
Antenna	15.0
Subtotal	68.0
TNC-50:	
Control panel	7.0
Computer amplifier	16.0
Commutator	5.0
Subtotal	28.0
Analog-to-digital converter and buffer	20.0
Printer	60.0
Cabling racks, shock mounts, etc.	48.0
Regulated a-c solid-state power supply (400-cycle)	32.5
Regulated a-c rotary inverter (400-cycle)	8.0
Regulated a-c rotary inverter (60-cycle)	37
Radio altimeter (APN-117)	32.6
Autopilot L-2	55.0
100-amp generators (net change)	26.0
Radome for RADAN 500 antenna (with perforator aircraft structural change)	30.0
Punch	40
Total	651.6

The inverter weighs approximately 32 lb and is $4\frac{1}{2}$ in. high by 5 in. wide by $10\frac{1}{2}$ in. long. The frequency stability is ± 3 per cent, the voltage regulation is ± 2 per cent or less, and the efficiency is greater than 75 per cent under the anticipated load.

In addition, a third 60-cycle 115-volt rotary inverter is necessary to power the printer-punch system. From a survey of the commercial availability of printer-punch systems, the system manufactured by the Clary Corp. appears most suitable. However, the Clary Corp., as well as other manufacturers, is reluctant to guarantee operation on other than 60-cycle power. Since in normal survey flight the printer-punch system presents the only power transient to the aircraft power system, it is deemed advisable to isolate this supply through a separate inverter. The inverter under consideration weighs 37 lb and delivers 200 va of 60-cycle power.

3.7.3 Autopilot

Initial investigation revealed that the Lear L-5B or equivalent autopilot system would meet accuracy requirements for both automatic track and altitude guidance. However, in subsequent pursuit of this problem, it was determined that the cost of a suitable autopilot system to effect precise Doppler track guidance and to maintain a specific radar altimeter was prohibitively high. This is difficult to justify on the basis of total contribution to system performance since the pilot will have available the necessary flight instruments to perform the same task.

The next task undertaken was to pursue autopilot systems that are common in the Twin Bonanza type aircraft. It was determined that the Lear L-2 system or equivalent exists in many aircraft of this type. The approach proposed, then, is to provide a basic compatible autopilot system that is open ended so that, if the cost is justified at a later date, the appropriate autopilot electronic subsystems can be added to effect automatic track and altitude guidance.

3.7.4 Generators

The total aircraft power requirement is supplied by two 100-amp 28-volt d-c engine-driven generators. At present it appears that the total power required will be 130 amp at 28-volt direct current. Generally, aircraft generators are not operated at more than 80 per cent of their rated value, which will provide 160 amp for normal use. Consequently an additional 30 amp over and above the total power requirements is available for any emergency aircraft requirements. The increase of weight per generator and mounting modification is approximately 13 lb.

3.7.5 Weight

The over-all weight distribution of the equipment is given in Table 3.4.

3.8 AIRCRAFT INSTALLATION OF EQUIPMENT

The installed equipment will be located in the aircraft so as to minimize structural modifications and hold the center-of-gravity travel within its prescribed limits. These desirable installation features can be attained by installing the major portion of this equipment in the cabin and baggage compartment (see Figs. 3.7 and 3.8).

3.8.1 Detector Assembly

The detector module consisting of the sodium iodide crystals, photomultiplier tubes, and preamplifiers is housed in a cylindrical aluminum shell mounted to an aluminum flanged plate (see Fig. 3.2). The complete assembly will be shock-mounted to the aircraft structure and thermally insulated. The weight of this assembly is approximately 94 lb; it will be installed on the baggage-compartment floor of the aircraft. The two high-voltage power supplies for the detector are mounted adjacent to the detector assembly.

3.8.2 Radiation and Navigation Equipment

The RADAN 500 (Doppler radar), TNC-50 (track navigation computer), J-4 compass associated equipment, and radiation subsystem will be rack-mounted. The rack (20 by 34 by 42

in.) supporting the navigation and radiation equipment is constructed of aluminum-alloy extruded angles, channels, and aluminum sheets. The four vertical corner members of the rack are attached to the cabin floor at the bottom and to the cabin frames at the top to provide sufficient rigidity for inertial forces in the longitudinal and lateral directions. This installation weighs approximately 390 lb and is located relatively near the center of gravity of the aircraft (see Fig. 3.7).

3.8.3 Seating Requirements

Three seats, for (1) the pilot, (2) the copilot-operator, and (3) an observer, are required for this installation. The pilot and copilot-operator occupy the two forward seats, as shown in Fig. 3.7. The observer's seat is mounted aft with radiation instrumentation and is used alternately by the copilot during calibration and the second observer during disaster situations.

3.8.4 Instrumentation Installation

The instruments added to the pilot's instrument panel (shown in Fig. 3.6) are as follows: autopilot, RADAN 500 indicator, RADAN 500 control panel, J-4 compass panel, TNC-50 control panel, and radio altimeter. The radio-altimeter transceiver is mounted flush with the underside of the aircraft in the aft fuselage. The RADAN 500 antenna is mounted aft of the baggage compartment to the underside of the fuselage.

3.9 SYSTEM ERRORS

It is presently planned to acquire radiation survey data in a form such that continuity is obtained with the data already on file with the AEC. This means that the proposed apparatus must be made to perform in a manner similar to the system currently in use by the USGS group or that a calibrating factor must be obtained relating the data taken by each system. A correlation of the two systems can easily be made through a comparison of the data taken by each at the same survey area.

It is doubtful whether the system proposed by Edgerton, Germeshausen & Grier, Inc., can be made to print out numbers that will correspond exactly with those obtained by the USGS apparatus, but it will be a relatively simple matter to obtain a correlating factor between the performances of the two systems. This factor will be taken into account in the presentation of the data so that no break or discontinuity will occur with respect to the radiation data already accumulated.

The data will be presented as counts per second at a 500-ft altitude, plotted according to geographical location on an appropriate map. The date, time, and survey location will be recorded so that agencies interested in using the data to obtain absolute intensities and dose rates will be able to obtain the meteorological parameters necessary for such calculations.

The data, as presented, will not contain any corrections for the meteorological conditions under which they were obtained. The data will, however, be corrected for altitude variations from 500 ft and for space-positioning errors.

In general, factors affecting the accuracy of the ARMS system data can be classified in the following two categories: (1) parameters that affect the accuracy of the radiation-intensity measurements and (2) parameters that affect the accuracy of associating a radiation-intensity level with a geographic location. Factors in the second category are associated not only with the navigational data but also with the radiation-intensity measurements.

Since the objective of the radiation-measuring system is to determine the rate of occurrence of events that are randomly distributed in time, it is necessary for the system to sample events over a sufficient period to secure a statistically valid sample. Since the system is in motion, the location with which a given collected sample should be associated is uncertain by at least half the distance along the path of motion through which the system moves during a sampling period. Analysis of the two preceding statements leads to the conclusion that, for a specified counting rate and with a fixed survey velocity, increasing the accuracy of the radiation-level measurements means decreasing the accuracy of its association with a geographic location, and vice versa. This statement implies that, once the detector sensitivity

and survey velocity of a system are fixed, there is a limit to the required accuracy of the navigational and radiation-intensity measuring system. Accuracy limitations of this type are inherent in devices that measure space-varying random processes while in motion. The limitation applies whether the device employs a discrete sampling period, as the modified ARMS system does, or a fading-memory device, such as the resistor-capacitor integrator used in the USGS-ORNL system.

Two things should be noted about the limitations of the proposed modified ARMS system:

1. When altitude variations occur, the system tends to maintain an optimum relation between radiation-intensity-measurement accuracy and space-positioning accuracy by varying the sampling time.
2. The accuracy inherent in the circuitry of the radiation-intensity measuring system and the navigational system is sufficient to allow the performance of the over-all system to approach the theoretical limitation mentioned in item 1.

The factors that contribute to the uncertainty in the radiation-intensity measurements are given in Table 3.5 and are based on the following considerations. A survey operation takes

TABLE 3.5 — REPRODUCIBILITY OF RADIATION DATA

Source of uncertainty	Maximum contribution, %
Temperature variation, $\pm 20^{\circ}\text{F}$ (assume mean at 100°F)	± 5.9
Relative humidity, 0 to 100% at 120°F (average, 25%)	± 0.3
Barometric pressure, ± 8 mm Hg	± 0.15
Plane-altitude error, ± 6 ft	± 2.0
Background variation	± 10.0
Instrumental variations	± 2.0
Count-rate statistics	± 4.0
$\sigma = \text{total error} = \pm (5.9^2 + 0.3^2 + 0.15^2 + 2.0^2 + 10.0^2 + 2.0^2 + 4.0^2)^{1/2}$	
$\sigma = \pm 12.6\%$	

place at a ground temperature of 100°F and a relative humidity of 25 per cent. These values were selected to maximize the expected error. The survey is run at an altitude of 500 ft above terrain. During the survey operation the maximum variation occurring in the temperature is $\pm 20^{\circ}\text{F}$, the relative humidity is 0 to 100 per cent, and the barometric pressure is ± 0.03 in. Hg. In Table 3.5, the effect of the preceding meteorological uncertainties is given along with the errors present as a result of plane-altitude variations, background radiation, instrumental variations, and the statistical fluctuation in the count rate. An uncertainty of ± 12.6 per cent in the recorded radiation data results. This can be considered as a merit figure for the system in that it may be interpreted as the degree to which the system will reproduce data. That is, radiation data taken under successive surveys of the same area will produce results that agree within ± 12.6 per cent.

It should not be construed from this discussion that a ground-level dose rate or radioactive source strength can be directly obtained with an uncertainty of ± 12.6 per cent from the recorded data. Information of this nature involves additional uncertainties due to radiation absorption in the intervening air column and the lack of knowledge concerning the effective energy of the radiation source. The true count rate existing at the survey altitude must first be found and then converted into ground-level data. This is accomplished by performing experimentally an absolute calibration of the system under accurately measured meteorological conditions with radioactive sources of known intensity and energy. With these parameters the true count at a 500-ft altitude must be calculated and the result must be compared with the count observed with the ARMS apparatus to give a true-count conversion factor. A complete discussion of the absolute calibration of the ARMS apparatus in terms of ground roentgen level will be presented in Part II of this report, to be published at a later date. A procedure will be described where-

by any interested agency will be able to convert the recorded radiation-intensity data into dose-rate levels for a height of 3 ft above the terrain.

Table 3.6 gives the factors that contribute to the uncertainty in associating a radiation-intensity level with a geographic location.

TABLE 3.6—MAXIMUM RMS ERROR IN UNCORRECTED SPACE-POSITION DATA

Source of uncertainty	Maximum contribution, ft
Doppler system:	
Along track (assume fixes every 30 miles): $\pm 0.35\% \times 30$ miles	± 554
Cross track (assume maximum deviation of 10 miles): $0.728\% \times 10$ miles	± 385
J-4 compass: random drift rate of 1 deg per hour at 30 miles	± 220
Sampling error: time lag at 700 ft = 1.8 sec; 1.8 sec \times 180 mph = 1.8 sec \times 264 ft/sec	± 238
Pilot error on visual ground-fix point	± 50
$\sigma = \text{total error} = \pm (554^2 + 385^2 + 220^2 + 238^2 + 50^2)^{1/2}$	
$\sigma = \pm 750$ ft at 30 miles	

The first two items in Table 3.6 are self-explanatory and are fixed by the behavior of the Doppler navigator and the J-4 compass system. The uncertainty of the third item (sampling error) arises from the fact that the radiation-detection apparatus is moving during the sampling period and that the sampling period varies according to the aircraft altitude. At a sampling altitude of 700 ft above the terrain, the sampling period is 1.8 sec. Traveling at 180 mph, the aircraft covers a distance of 475 ft during this time. Hence the maximum uncertainty in the location of the radiation level, recorded with respect to the earth, is taken as ± 238 ft. The last item is the uncertainty introduced by the pilot in locating the aircraft directly over a visual ground check point. Information gained by querying aerial mapping agencies with experience in operating aircraft under similar conditions indicates that the maximum magnitude of the uncertainty is on the order of ± 50 ft.

As indicated in Table 3.6, the maximum uncertainty in locating the point of the radiation level is ± 750 ft over a 30-mile distance if the aircraft were at 700 ft during the sampling period. The error to be expected during sampling at 500 ft, with a cross-track deviation of 1 mile, would, similarly, be ± 613 ft, representing an over-all uncertainty of ± 0.39 per cent of the distance flown.

Corrections to the errors in position data can be obtained which, when applied to the raw data, will yield accuracies of the order of the pilot's ability to locate himself over a ground fix and the accuracy of the map used.

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Chapter 4

OPERATING PROCEDURE

4.1 CALIBRATION

When the aircraft becomes air-borne and a sufficient time has elapsed for the electronic equipment to stabilize, the radiation instrumentation is then ready for radiation calibration. To accomplish this, the copilot switches the function control knob from "Stand-by" to "Calibrate" (see Fig. 3.4). This normalizes the altitude correction factor to 500 ft, or, rather, a 1-sec counting interval. The calibration mode switch is then positioned to the "Energy" position, which places a small Cs^{137} source adjacent to the crystals. According to the method described by Davis and Reinhardt,¹ the energy cutoff helipot is set to 6.62, and the "Gain" control is adjusted to record a predetermined number on the display unit. The energy cutoff is then reset to 0.50, which infers that all energies less than 50 kev are being rejected by the system. The source is returned by placing the mode switch to the "Background" position, and the calibration is completed. The calibration can be checked each 30 to 45 min; checking requires approximately 25 sec of the operator's time.

The radiation instrumentation is then ready for the cosmic and other background correction to be made at 2000 ft above the ground. The function switch is retained in the "Calibrate" position. The background toggle switch is turned off, and the number of counts present on the visual display unit relates the background in counts per second. The background toggle switch is then set to "High" or "Low"; the background potentiometer knob is set on its calibrated dial to this value, and the background calibration is complete. The background is now automatically corrected, and no further setting is required for the remainder of the flight.

The recorded count rate is normalized to a 500-ft altitude with the rms error previously discussed. The data, as collected, satisfy the requirement that any modified ARMS system be compatible with the existing system. Upon obtaining information concerning the gamma energies of the recorded intensities and the meteorological parameters under which the data were taken, any interested agency can convert the 500-ft intensity readings into dose-rate data.

4.2 NORMAL SURVEY OPERATION

It is believed that the personnel required to operate the system effectively will consist of four men: the team leader, the pilot, the copilot-operator, and the technician.² The team leader is an individual with a background in nuclear engineering or physics who, besides heading the team, is responsible for all technical decisions concerning the pertinency and manner in which data are acquired. The pilot is, of course, responsible for the safe flight of the aircraft along its desired track. The copilot-operator is responsible for any daily maintenance of the aircraft, major maintenance being conducted at home base or at a local qualified agency; in addition, he participates as aircraft observer. His duties as observer require him to (1) perform the required calibration of the radiation instrumentation, (2) act as observer to aid the pilot in locating ground check points, and (3) act as alternate pilot if necessary. The tech-

nician is responsible for the maintenance of radiation and space-positioning equipment and for data reduction.

Upon receipt of an assignment from the AEC to survey a given area, the team leader and the pilot will proceed to make arrangements for FAA waivers, housing, local transportation, and facilities required for the aircraft, i.e., hangar, fuel, etc. During this phase of the planning the pilot and the copilot will plot the survey flight plan. Each significant check point will be noted on the map by its correct Doppler navigation reading, i.e., heading, distance along track, and transverse displacement from track. The maps would then reflect parallel lines indicating the desired track, with circled check points at various intervals with the correct Doppler navigator setting printed beside the point.

The team will then move to the selected site, where they will procure housing, car, hangar facilities, etc. After completion of these arrangements survey operations will begin, depending on the weather, i.e., visual flight rules, no visible moisture, or no low-altitude temperature inversions.

Shortly after take-off the pilot and the copilot will proceed to calibrate the system and determine the cosmic background. The aircraft then proceeds to its initial check point with the check-point Doppler setting set into one Doppler reader, and, as the aircraft flies over the point, the Doppler system is switched from "Stand-by" to "On."³ The pilot then either manually flies or manually commands the autopilot through interpretation of the available flight instruments to maintain the aircraft on its desired track. Interpretation of the position of the aircraft with respect to the desired track will be available through the ID-249 omni-indicator and the TNC-50 reader. Altitude information is available through the APN-117 radar altimeter indicator modified to read linearly from 0 to 1000 ft. It is to be noted that the pilot can, at any time, override the autopilot by exerting pressure on the flight controls. In addition, the autopilot "On-Off" control microswitch is located on the control column only a few inches from the pilot's fingers. As the aircraft progresses along track, radiation information and space position are automatically acquired and recorded either at preselected radiation levels or at constant time intervals (3 sec). The alternate Doppler reader is set to the next check point, and, as the aircraft flies over this point, the alternate reader is switched into use. This records the old reader values over the fix for the purpose of position-data correction and initiates the new track computation. Thence the reader not in use is set on the next check point, and the survey progresses to the end of track. At this time the alternate reader is set up for the next parallel track, the pilot manually accomplishes a 180-deg turn, and during the turn the radiation-instrumentation calibration is checked. The aircraft is then positioned on the new track, and the survey progresses. It should be pointed out that, if local topography will not permit linear track flying, the aircraft may be manually flown up to 10 nautical miles to either side of track without affecting the reliability of space position with one Doppler reader setting. Normally, however, in cases of this nature the flight plan will be modified to consist of a series of linear segments.

The data recorded by the air-borne printer consists of the following information:

1. Radiation level in channel number
2. High- or low-sensitivity detector
3. Segment identification
4. Distance along segment to nearest hundredth of a mile
5. Transverse displacement from track to nearest hundredth of a mile
6. Direction of transverse displacement from track

Data reduction then involves relating the true position to the computed position over check points and plotting the radiation levels of interest at their correct geographical location. In actuality this would be accomplished as follows: Assume that point A (Fig. 4.1) was the last check point. The desired flight track is AB, with B representing the next significant check point. Owing to system errors, which are exaggerated in the figure, the aircraft actually flies track AC. The pilot, repositioning his aircraft over point B and switching to the alternate Doppler reader, records the position of point C. Data reduction then involves locating point C and, subsequently, radiation levels computed at points D, E, and F to their true locations of D¹, E¹, and F¹. Simple plotting tools will facilitate rapid, accurate reduction of the data such that, at the finish of site survey, reduced radiation-contour data will be furnished to the AEC.

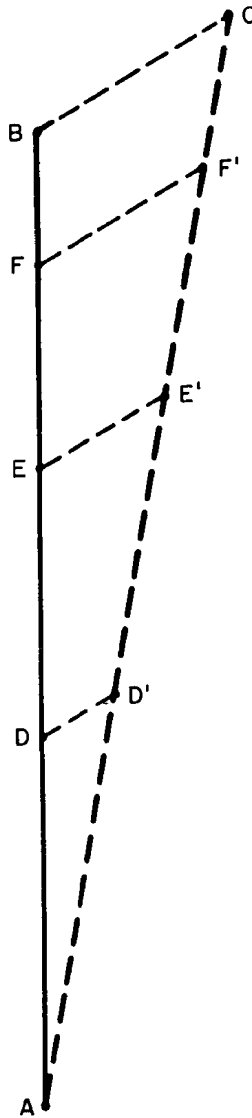


Fig. 4.1 — Data-reduction computation.

These data will be presented as radiation contours drawn on appropriate scale maps of the area as desired by the AEC. Similar maps, along with the digital and punched-tape records, will be maintained on file for future reference by the collection agency.

It should be pointed out that the use of a punched-tape printer leaves the system open-ended to permit future refinement of the equipment in terms of automatic data reduction.

Present thinking on the design of this unit is that a device that generates radiation-contour maps as well as punched IBM cards will provide the widest latitude to the greatest number of users. The system will consist of a small special-purpose computer, an X-Y plotter, and a card puncher. The purpose of the computer when impressed with the data tape and the flight plan will be to correct for Doppler error and relate space position of data points in absolute terms of latitude-longitude. The X-Y plotter is to consist of a 30- by 30-in. plotter on which the manufacturer's specification states a plotting accuracy of 0.015 in. Assuming that a 1/250,000 scale map is used, a 100- by 100-mile area is displayed on approximately 26 by 26 in. The plotting accuracy to this scale is then within 315 ft. Information printed on the map will consist of a red or black dot (high- or low-sensitivity probe) at the datum location and the radiation level printed beside the dot. The companion IBM cards generated would contain the following information:

1. Site identification
2. Date

3. Mean temperature
4. Mean barometric pressure
5. Radiation level
6. High- or low-sensitivity probe
7. Latitude
8. Longitude

It is estimated that approximately four data points can be placed on each card.

This automatic data-reduction system would be maintained at the base of operations of the surveying agency. Here liaison is performed to the field and to the user. All data are reduced in a uniform fashion by this agency and forwarded to the user. A library would maintain the IBM-card system so that all data would be readily available in a form for simple duplication or digital-computer manipulation.

4.3 DISASTER SURVEY OPERATION

Upon notification that a contaminating event has taken place, the team leader will advise the disaster-site personnel of his expected arrival time and of the transmitting frequencies of the aircraft. He will also endeavor to learn as much as possible concerning the magnitude, materials involved, and type of accident and weather conditions. The pilot will gather appropriate maps of the area, and the aircraft will depart to the site with the pilot, copilot, and team leader aboard. The technician will follow by available transportation. En route to the area the team leader will plan the immediate survey operation dependent upon the best intelligency available. As the area is approached, the radiation instrumentation is calibrated and the cosmic background is documented. The initial Doppler check point will probably be selected in the vicinity of the accident. The selection of the initial track and Doppler settings is governed by the prevailing wind conditions at the time of accident. This information, if not previously provided, can be secured en route or at the destination. After establishing the initial fix, the pilot is then free to survey an area 20 miles wide by 100 miles long, gathering accurate radiation and space-positioning information from one Doppler reader setting. The team leader can note the radiation levels on a map and radio the information to ground personnel for immediate action. New check points and Doppler settings will be selected during the flight, based on the fallout pattern. The flight path will be such that an attempt can be made to determine the radiation boundaries of significance and the maximum levels present. The initial survey will be made as rapidly as possible. When the aircraft has landed, the team leader will deliver his rough survey map to the local responsible health and safety authorities. The pilot and copilot will reduce the more accurate data and deliver this to the local authorities. Then, based on the contamination levels observed and information received from local authorities, a detailed flight plan will be laid out. This flight is carried out as described in Sec. 4.2, and the reduced data are presented as rapidly as possible to the responsible individuals.

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1. F. J. Davis and P. W. Reinhardt, Instrumentation in Aircraft for Radiation Measurements, Nuclear Sci. and Eng., 713-727 (1957).
2. Edgerton, Germeshausen & Grier, Inc., Aerial Radiological Monitoring System, Phase I, Analysis of Existing System and Recommended Improvements, EG&G Report L-433, Dec. 4, 1959.
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Chapter 5

CONCLUSIONS

The present system is based on sound scientific principle; however, the equipment, method of data collection, and method of data reduction are uneconomical in view of the present expanded scope and change in requirement of the ARMS program. The radiation instrumentation can be redesigned, and the present state of the art principles can be applied to make the system completely automatic in a lightweight small-volume package. The photographic space-positioning system presently employed is too elaborate and expensive since it maintains an accuracy that is not compatible with the rest of the system. With the use of modern aircraft and electronic techniques for space-position orientation, a savings can be realized in operating cost, personnel, and data-acquisition and data-reduction time, with an over-all accuracy equal to, or greater than, that of the existing system.

The purpose of this study was to modify the present ARMS system to effect the following:

1. Rapid data acquisition and reduction
2. Maintenance of accuracy commensurate with the existing system
3. Minimum survey operating expenses

These goals are met in the design presented in this report. The radiation instrumentation has been miniaturized to effect a savings in weight, volume, and power consumption. Solid-state digital design has been utilized throughout to provide stable operation in all environments and to increase the mechanical ruggedness of the system. The recommended Doppler navigation system is completely self-contained in one survey aircraft at a minimum weight for navigational systems and with an accuracy compatible with the radiation measurement. The minimization of weight and volume permits a light twin-engine aircraft to be used; hence a significant saving in operation costs is realized. Since the integrated system is installed in the survey aircraft, maximum mobility is realized in moving the survey capability from location to location. All survey functions have been made automatic where possible to minimize the manpower required and to eliminate possibilities of human error. Space-position and radiation data are acquired automatically as the aircraft progresses during survey. Data reduction on the ground is accomplished on the same time scale as data acquisition. The data collected by the survey aircraft are compatible with those collected by the existing survey system. The reduced data will be presented as radiation-intensity contours on geographical maps of the survey area.

APPENDIXES

Appendixes A to D explain the basis used in calculating the effect of relative altitude, ground elevation, relative humidity, temperature, horizontal distance, and barometric pressure on the rate of detection of events by the ARMS detector system. The method is based on the one described by F. J. Davis and P. W. Reinhardt, in *Instrumentation in Aircraft for Radiation Measurements*, Nuclear Sci. and Eng., 2: 713-727 (1957).

Appendix A

LIST OF SYMBOLS

Symbol	Definition	Unit of measurement
a_n	The n th constant in a series of constants	Dimensionless
a_1	The first constant in series	Dimensionless
B	Build-up factor	Dimensionless
$E_1(\mu x)$	$\int_{\mu}^{\infty} (e^{-\mu x}/\mu x) d(\mu x)$	Dimensionless
h	Distance	Cm
I	Strength of a monoenergetic plane source	Events/sec/cm ²
I_o	Strength of a point source	Events/sec
i	An integral numerical index	Dimensionless
j	The number of components in a mixture	Dimensionless
K	A constant	Dimensionless
N_{∞}	Rate of detection of events from an infinite-plane source	Counts/sec
$N_{\infty s}$	Rate of detection of events from an infinite-plane source under standard conditions	Counts/sec
N_o	Rate of detection of events from a point source	Counts/sec
N_{os}	Rate of detection of events from a point source under standard conditions	Counts/sec
n	An integral numerical index	Dimensionless
P	Pressure exerted by atmosphere	G/cm ²
P_g	Pressure exerted by saturated water vapor at the temperature existing	G/cm ²
P_{H_2O}	Pressure exerted by water vapor	G/cm ²
P_o	Pressure exerted by dry air at some reference condition	G/cm ²
s	Subscript indicating evaluation at standard conditions	Dimensionless
x	Vertical distance above a horizontal-plane source	Cm
Y	Relative humidity	Per cent
μ	Total absorption coefficient	Cm ⁻¹
μ_i	Total mass absorption coefficient of the i th component in a mixture	Cm ² /g
ρ	Density of air	G/cm ³
ρ_g	Density of saturated water vapor at the temperature in question	G/cm ³

Symbol	Definition	Unit of measurement
ρ_i	Density of the <i>i</i> <i>th</i> component in a mixture	G/cm ³
ρ_o	Density of dry air under reference conditions	G/cm ³
ρ_{H_2O}	Density of water vapor in the atmosphere	G/cm ³
ϵ	Over-all root-mean-square error	Dimensionless
ϵ_k	Fractional maximum error caused by the <i>k</i> <i>th</i> environmental factor	Dimensionless

Appendix B

ASSUMPTIONS

Some appropriate assumptions must be made to facilitate analysis. The more important assumptions, along with a short explanation of why they are appropriate, are listed as follows:

1. Detector efficiency is uniform with respect to energy for all gamma-ray energies above the discriminator setting. [The efficiency of a typical NaI(Tl) crystal 2 in. thick might vary between the limits of 45 and 100 per cent in the energy range of 0.1 to 10 Mev. Although this would seem to be somewhat inconsistent with the assumption, it is considered impractical at this stage of analysis to introduce a more complicated assumption.]

2. Dimensions of the detector sensitive volume are small compared to the separation from the source. (The diameter of the detector will probably be in the neighborhood of 9 in.; whereas the normal operating altitude of the ARMS system above ground is expected to be about 500 ft.)

3. Angular sensitivity of the detector is very large. (Little or no shielding of the detector sensitive volume is anticipated.)

4. All sources emit monoenergetic gamma rays with an effective energy of 0.7 Mev, and there is no significant back-scatter from the ground. There is considerable evidence¹⁻³ to indicate that a good value for the effective energy of gamma radiation from fission products is between 0.6 and 1.0 Mev.)

5. The atmosphere is the only significant material surrounding the detector sensitive volume. (It is believed that the effect of the skin and the structure of the vehicle will have a small over-all effect on the behavior of the detector.)

6. The detector is insensitive to gamma energies of less than 50 kev owing to discriminator action. (Experience with earlier systems indicates that a discriminator setting of 50 kev is satisfactory.)

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2. G. M. Dunning and J. A. Hilcken (Eds.), The Short Term Biological Hazards of a Fallout Field, Symposium, December 12-14, 1958, Washington, D. C., Report M-6637, Division of Biology and Medicine, AEC, and Defense Atomic Support Agency.
3. Hanson Blatz (Ed.), "Radiation Hygiene Handbook," McGraw-Hill Book Company, Inc., New York, 1959.

Appendix C

DESCRIPTIONS

The detector is considered to consist of a sensitive volume and any auxiliary equipment necessary to give a pulse output for each event detected. In this sense any necessary amplifiers, discriminators, or pulse shapers are considered part of the detector.

On the basis of assumptions 1 to 6 in Appendix B, the rate of detection of events from a point source by the detector¹⁻³ can be shown to be

$$N_o = \frac{KI_o e^{-\mu h} B}{h^2} \quad (C.1)$$

For the purposes of this study the build-up factor, B, which is a function of μ and h, can be conveniently described as

$$B = 1 + \sum_{n=1}^{\infty} a_n (\mu h)^n \quad (C.2)$$

It should be noted that

$$\mu = \sum_{i=0}^{i=j} \mu_i \rho_i \quad (C.3)$$

Therefore for point sources the count rate can be described as

$$N_o = \frac{KI_o e^{-\mu h}}{h^2} \left[1 + \sum_{n=1}^{\infty} a_n (\mu h)^n \right] \quad (C.4)$$

If the source is an infinite plane rather than a point, an equation similar to Eq. C.4 can be integrated over a plane to obtain the total rate of detection of events. However, for the purpose at hand Eq. C.4 can be simplified with sufficient accuracy by including only the first term of the summation. This leads to the following result for an infinite-plane source:

$$N_{\infty} = KI[E_1(\mu x) + a_1 e^{-\mu x}] \quad (C.5)$$

The data necessary to determine a_1 are very meager. However, the qualitative behavior of Eq. C.5 is not very sensitive to the magnitude of a_1 if a_1 is large compared to 1 and if the product of μ and x in the range of interest is greater than 1.

For the purpose of calculation, a value of a_1 equal to 5 was estimated. In general, the range of interest of the product of μ and x for the purpose at hand is greater than 1, indicating that Eq. C.5 is applicable.

If it is desired to compare the detector behavior for an infinite-plane source at some condition to the behavior at a reference condition, the comparison can be described as

$$\frac{N_{\infty}}{N_{\infty S}} = \frac{[E_1(\mu x) + a_1 e^{-\mu x}]}{[E_1(\mu x) + a_1 e^{-\mu x}]_S} \quad (C.6)$$

For a point source the corresponding comparison is

$$\frac{N_O}{N_{OS}} = \frac{[e^{-\mu h}(1 + a_1)] (h^2)_S}{[e^{-\mu h}(1 + a_1)]_S (h^2)} \quad (C.7)$$

For the purposes of calculation, it is necessary to have a description of the density of absorbing materials in the atmosphere. For this purpose the density of dry air was assumed to behave as

$$\rho = \rho_O e^{-(\rho_O x/P_O)} \quad (C.8)$$

The density of water vapor⁴ in the atmosphere was assumed to be

$$\rho_{H_2O} = 0.01 \rho_g Y \quad (C.9)$$

The total barometric pressure at any point was considered to be

$$P = P_{H_2O} + P \quad (C.10)$$

where

$$P_{H_2O} = 0.01 P_g Y \quad (C.11)$$

For the purpose of evaluating the effect of ground cover, the density of foliage^{5,6} in grams per square centimeter was estimated. This value was multiplied by an appropriate value of μ_1 , and the value of μx in the pertinent equation was increased by this amount.

The effect of all other factors influencing the behavior of the ARMS system was estimated on the basis of experience with similar systems.

The precision or repeatability of the detector system was evaluated by considering the fractional change in count rate of the detector system caused by the maximum expected excursion of each of the environmental conditions considered. The over-all precision was considered to be

$$\epsilon = \sqrt{\sum (\epsilon_k)^2} \quad (C.12)$$

REFERENCES

1. Herbert Goldstein and J. E. Wilkins, Jr., Calculations of the Penetration of Gamma Rays, Report NYO-3075, Nuclear Development Associates, Inc., June 30, 1954.
2. Theodore Rockwell III, Reactor Shielding Design Manual, Report TID-7004, Division of Reactor Development, AEC, March 1956.
3. W. S. Snyder and J. L. Powell, Absorption of Gamma Rays, Report ORNL-421, Supplement 2, Oak Ridge National Laboratory, Mar. 14, 1950.
4. J. H. Keenan and F. G. Keyes, "Thermodynamic Properties of Steam," John Wiley & Sons, Inc., New York, 1936.
5. T. G. Storey and W. Y. Pong, Crown Characteristics of Several Hardwood Tree Species, Interim Technical Report, AFSWP-968, May 1957.
6. E. C. Crafts, Timber Resources for America's Future, Forest Service, U. S. Department of Agriculture, Forest Resources Report No. 14, January 1958.

Appendix D

RESULTS

Equations C.3 and C.6 to C.9 were used to allow the preliminary numerical evaluation of the effects of various environmental conditions on the behavior of the ARMS detector system. The effects of changes in horizontal distance, ground elevation, altitude, temperature, barometric pressure, and relative humidity were calculated.

The data presented in Figs. 2.1 to 2.7 show the effect of varying each of the aforementioned environmental factors separately. In general, the factors are varied by amounts that are currently considered standard in operating conditions of the ARMS detector system. The figure titles are self-explanatory. For convenience in comparing with previously published data, the figures are plotted with an English system of units.

The calculations concerning the over-all precision of the system are summarized in the report.

CIVIL EFFECTS TEST OPERATIONS REPORT SERIES (CEX)

Through its Division of Biology and Medicine and Civil Effects Test Operations Office, the Atomic Energy Commission conducts certain technical tests, exercises, surveys, and research directed primarily toward practical applications of nuclear effects information and toward encouraging better technical, professional, and public understanding and utilization of the vast body of facts useful in the design of countermeasures against weapons effects. The activities carried out in these studies do not require nuclear detonations.

A complete listing of all the studies now underway is impossible in the space available here. However, the following is a list of all reports available from studies that have been completed. All reports listed are available from the Office of Technical Services, Department of Commerce, Washington 25, D. C., at the prices indicated.

- CEX-57.1 The Radiological Assessment and Recovery of Contaminated
(\$0.75) Areas, Carl F. Miller, September 1960.
- CEX-58.1 Experimental Evaluation of the Radiation Protection Afforded by
(\$2.75) Residential Structures Against Distributed Sources, J. A. Auxier,
J. O. Buchanan, C. Eisenhauer, and H. E. Menker, January 1959.
- CEX-58.2 The Scattering of Thermal Radiation into Open Underground
(\$0.75) Shelters, T. P. Davis, N. D. Miller, T. S. Ely, J. A. Basso, and
H. E. Pearse, October 1959.
- CEX-58.7 AEC Group Shelter, AEC Facilities Division, Holmes & Narver,
(\$0.50) Inc., June 1960.
- CEX-58.8 Comparative Nuclear Effects of Biomedical Interest, Clayton S.
(\$1.00) White, I. Gerald Bowen, Donald R. Richmond, and Robert L.
Corsbie, January 1961.
- CEX-59.1 An Experimental Evaluation of the Radiation Protection Afforded
(\$0.60) by a Large Modern Concrete Office Building, J. F. Batter, Jr.,
A. L. Kaplan, and E. T. Clarke, January 1960.
- CEX-59.13 Experimental Evaluation of the Radiation Protection Afforded by
(\$0.50) Typical Oak Ridge Homes Against Distributed Sources, T. D.
Strickler and J. A. Auxier, April 1960.

