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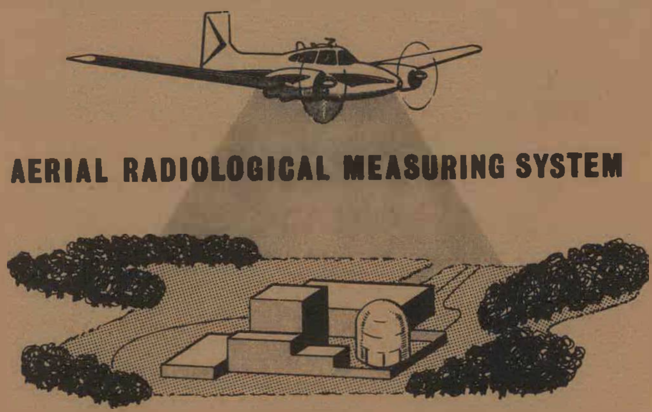

MASTER

THE AERIAL RADIOLOGICAL MEASURING SYSTEM (ARMS)

SYSTEMS, PROCEDURES AND SENSITIVITY (1976)

~~To ERDA Offices and ERDA Contractors~~

JULY 1976

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LAS VEGAS AREA OPERATIONS
EG&G, INC., 680 E. SUNSET RD.,
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July 1976

THE AERIAL RADIOLOGICAL MEASURING SYSTEM (ARMS)

SYSTEMS, PROCEDURES AND SENSITIVITY (1976)

by

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Approved for Publication

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This Document is UNCLASSIFIED

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Classification Officer

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This work was performed by EG&G, Inc. for the U.S. Energy Research and Development Administration, Division of Operational Safety.

ABSTRACT

This report describes the Aerial Radiological Measuring System (ARMS) designed and operated by EG&G, Inc., for the Energy Research and Development Administration's (ERDA)* Division of Operational Safety with the cooperation of the Nuclear Regulatory Commission. Designed to rapidly survey large areas for low-level man-made radiation, the ARMS has also proven extremely useful in locating lost radioactive sources of relatively low activity. The system consists of sodium iodide scintillation detectors, data formatting and recording equipment, positioning equipment, meteorological instruments, direct readout hardware, and data analysis equipment. The instrumentation, operational procedures, data reduction techniques and system sensitivities are described, together with their applications and sample results.

*Formerly the U. S. Atomic Energy Commission (USAEC).

FOREWORD

The Aerial Radiological Measuring System (ARMS) has been maintained and operated for the U. S. Atomic Energy Commission and the U. S. Energy Research and Development Administration, first by the U. S. Geological survey (1958-1960) and subsequently by EG&G, Inc. (1960-present). The ARMS program was implemented to perform aerial measurements of ground and airborne radioactivity and to develop techniques for refining these measurements and enhancing their interpretation.[1]

A continuing program of research and development is maintained for improving the detection equipment, data collection procedures, and data reduction and reporting methods. This program includes theoretical and experimental studies of (1) the radiation environment, (2) detector response, (3) operational procedures, and (4) further automation of data reduction processes. This report covers those systems and procedures employed by ARMS.

The ARMS system became operational in November 1960, thus continuing the ARMS I program of the USGS. The first large area survey by ARMS was made in June 1961. During the past fifteen years, ARMS has concentrated efforts on survey procedures for nuclear power reactors.[2-3] Surveys of ERDA facilities, ERDA Test Sites and several successful searches for lost sources have also been conducted during the same period.[4-7]

The ARMS program has been expanded to encompass a wide variety of environmental measurements. The name of the ARMS program will be officially changed to AMS (Aerial Measuring Systems), after publication of this report, to reflect the broader capability of the program.

ACKNOWLEDGMENTS

Special appreciation is given to L. J. Deal, Assistant Director of the U. S. Energy Research and Development Administration's Division of Safety, Standards and Compliance, for his support, encouragement and direction of the ARMS program.

This report is the culmination of all pertinent ARMS data, some of which has been previously published. The individual contributors to the various sections of this report are listed below (in alphabetical order):

Administration and coordination – J. F. Doyle

Computer software and data analysis – C. M. Bluitt and T. J. Hendricks

Electronic design – J. R. Cleland, W. S. Ebeltoft, and G. G. Wallace

Graphic arts – B. F. Hoffman

Navigation techniques – M. D. Sevart

Photographic and IR scanner – R. A. Meibaum

Scientific data – E. L. Feimster, A. E. Fritzsche, J. E. Jobst, and W. J. Tipton

Survey coordination and operations – R. E. Lawson and R. J. Mazurkewiz.

The Nuclear Regulatory Commission has been very cooperative in the ARMS reactor survey program.

A special thanks to T. P. Stuart for his meticulous review of this report.

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1. INTRODUCTION

The U.S. Energy Research and Development Administration (ERDA), Division of Operational Safety in cooperation with the Nuclear Regulatory Commission (NRC), funds the Aerial Radiological Measuring System Program to provide state-of-the-art aerial measurement capabilities in performing the following functions.

1. Respond to a major accident involving radiation sources anywhere in the Continental United States.
2. Perform radiation and other remote sensing surveys at major ERDA facilities.
3. Conduct a large area terrain radiation mapping program around licensed facilities to form a basis for rapid assessment of a major radiation accident at such facilities.

Since 1960 EG&G, Inc. has conducted both a development and operational aerial radiation measurement program. In this period, over 150 large area surveys have been performed, covering an area of 325,000 square miles. Figure 1 shows the nationwide scope of ARMS survey activity.

On several occasions, the ARMS aircraft and crew have successfully located lost sources and have responded to emergency calls involving releases of radiation.

There are now five aircraft which support ARMS missions: a Beechcraft King Air A-100, the Beechcraft Twin Bonanza, a Martin 404, and two Hughes H-500 helicopters. Their primary mission is mapping terrestrial radiation. Because of the addition of many different

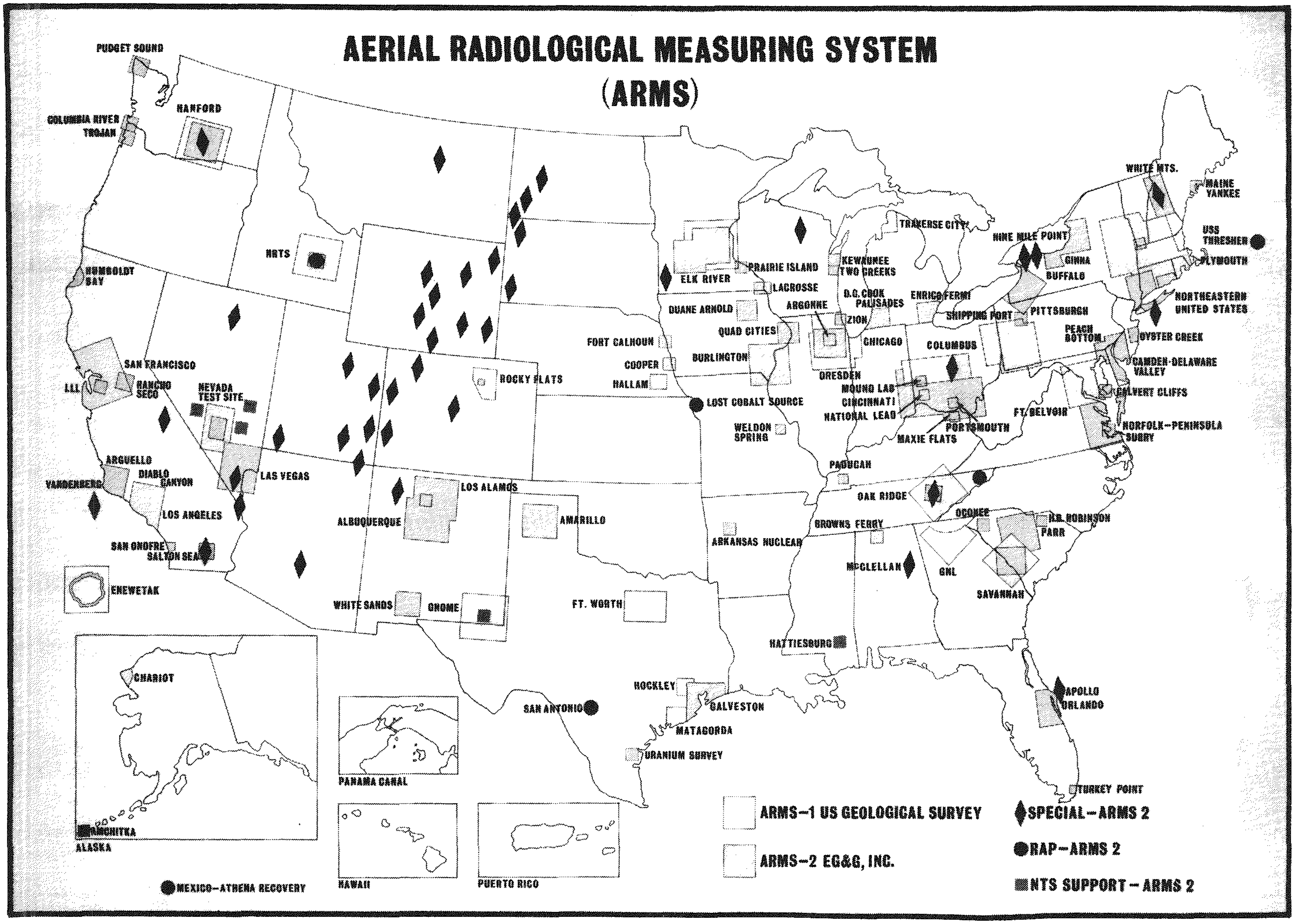

Figure 1. ARMS Surveys: 1958-FY'76

kinds of instrumentation, the system has considerable flexibility. Such gear includes an air sampler, a neutron detector, an alpha particle spectrometer, a Hasselblad multispectral photographic array, a Wild RC-8 camera and a Bendix thermal mapper. The capabilities of each aircraft are summarized in Table 1.

The total capabilities of the two primary radiation mapping platforms, the Beechcraft A-100, and the Hughes H-500 helicopter will be covered in some detail in this report.

Table 1. Performance Specifications for the EG&G-Operated Aircraft Used in Radiological Surveys

	Airplanes			Helicopter
	A-100	Twin Bonanza	Martin 404	Hughes-500
Number of engines	2	2	2	1
Cabin pressurization	yes	no	yes	no
Maximum altitude	25,000 ft	22,000 ft	25,000 ft	15,000 ft
Range	1,200 mi	600 mi	1,400 mi	275 mi
Endurance	5-1/4 hr	4 hr	7 hr	3 hr
Cruising Speed	230 kts	150 kts	200 kts	110 kts
Minimum survey speed	120 kts	120 kts	120 kts	0 kts
Available equipment payload with a minimum of 3-hour fuel	600 lbs	600 lbs	3,500 lbs	---
Minimum flight crew	Pilot, Navigator, Instr. Operator	Pilot, Navigator, Instr. Operator	Pilot, Navigator, Co-Pilot, Instr. Operator	Pilot, Instr. Operator
Navigation and position determination	MRS, INU	Doppler radar, INU	Doppler radar, INU, MRS	MRS
Radar altimeter	yes	yes	yes	yes
Communications system	VHF, HF	VHF, HF	VHF, HF	VHF
Meteorological Sensors	Absolute pressure Temperature Dew point Turbulence* True air speed Wind speed & direction Pressure altitude	Pressure altitude Absolute pressure Temperature Wind speed & direction	Pressure altitude Absolute pressure Temperature Dew point Turbulence True air speed Wind speed & direction	Pressure altitude
Radiation detectors	28 4x4" NaI(Tℓ)	8 6x6" NaI(Tℓ)	Various	20 5x2" NaI(Tℓ)
Air sampler	Particulate (isokinetic)* Whole gas*	Particulate	Particulate	---
Photographic equipment	4-camera Hasselblad RC-8 WKD 9x9" aerial photogrammetric system	4-camera Hasselblad	4-camera Hasselblad	4-camera Hasselblad*
Thermal mapping equipment	Bendix IR scanner (LN-3)	Bendix IR scanner (LN-3)	Bendix IR scanner (LN-3)	---

*To be installed.

2. AIRBORNE SYSTEMS

2.1 KING AIR FIXED WING AIRCRAFT

2.1.1 Aircraft Specifications

The ARMS survey aircraft (shown in Figure 2) is a King Air A-100, manufactured by the Beech Aircraft Corporation. The A-100 is a turboprop twin-engine aircraft with a cruising velocity of 128 m/sec (419 ft/sec) and a maximum operational altitude of 9450 m (31,000 ft). At the normal survey altitude of 150 m (500 ft) above terrain, the A-100 has a minimum velocity of 61 m/sec (200 ft/sec). Additional specifications and performance data are shown in Table 2.

The radiation detection system includes four detector arrays, each of which weighs 42 kg (168 kg total). The data acquisition system is housed in two equipment racks weighing 170 kg. Aircraft position data are derived from three independently-operable systems: an inertial navigation unit, a microwave ranging system, and a radar altimeter. Their combined weight is 40 kg.

The flight crew on survey missions consists of a pilot, a navigator, and an electronic systems operator. With this crew and the equipment described above, the A-100 has a flight endurance of four hours.

2.1.2 Radiation Detectors

The radiation detection system consists of 28 (4 in. diameter by 4 in. thick) NaI(Tℓ) crystals. The detectors are packaged in four boxes, each containing seven detectors mounted in ethafoam insulation to reduce thermal and mechanical shock. The top of one

Figure 2. ARMS Aircraft, Beechcraft King Air A-100.

Table 2. Beechcraft King Air A-100

SPECIFICATIONS

Weights	
Maximum Ramp Weight	11,568 lbs.
Maximum Take-Off Weight (Gross Weight)	11,500 lbs.
Maximum Landing Weight	11,210 lbs.
Maximum Zero Fuel Weight	9,600 lbs.
Empty Weight	6,728 lbs.
Useful Load	4,772 lbs.
Wing Area and Loadings	
Wing Area	279.7 sq. ft.
Wing Loading	40.8 lbs./sq. ft.
Power Loading	8.38 lbs./shp
Dimensions	
Wing Span	45 ft. 10.5 in.
Stabilizer Span	22 ft. 4.6 in.
Length	39 ft. 8.5 in.
Height to Top of Fin	15 ft. 4.2 in.
Cockpit Height	57 in.
Cockpit Width	52 in.
Cockpit Door Width	20 in.
Cabin Length (Excludes Pilot's Compartment)	200 in.
Cabin Width	54 in.
Cabin Height	57 in.
Entrance Door	27 in. x 51.75 in.
Electronic Compartment Volume	16 cu. ft.
Aft Baggage Compartment Capacity	410 lbs., 62.0 cu. ft.
Pressurization (4.6 Differential)	Cabin Altitude
Actual Aircraft Altitude...10,500 ft.	Sea Level
Actual Aircraft Altitude...21,200 ft.	8,000 ft.
Actual Aircraft Altitude...24,700 ft.	10,000 ft.

PERFORMANCE

Cruising Speeds	
Average Cruise Weight	10,500 lbs.
(High Cruise Power)	
At 10,000 ft.	248 Kts. (285 mph)
At 16,000 ft.	243 Kts. (280 mph)
At 21,000 ft.	235 Kts. (270 mph)

Table 2. Beechcraft King Air A-100 (Continued)

Cruise Range for 470 Gal. Usable at 6.7 Lb./Gal.
(Includes allowance for fuel used during starting, taxi, take-off, climb, descent, and a 45-minute reserve at maximum range power and standard atmosphere conditions.)

High Cruise Power	
At 10,000 ft.	900 Naut. Mi. (1,035 Mi.)
At 16,000 ft.	1064 Naut. Mi. (1,225 Mi.)
At 21,000 ft.	1212 Naut. Mi. (1,384 Mi.)
Low Cruise Power	
At 10,000 ft.	982 Naut. Mi. (1,130 Mi.)
At 16,000 ft.	1149 Naut. Mi. (1,322 Mi.)
At 21,000 ft.	1287 Naut. Mi. (1,481 Mi.)
Maximum Range Power	
At 10,000 ft.	1152 Naut. Mi. (1,326 Mi.)
At 16,000 ft.	1272 Naut. Mi. (1,464 Mi.)
At 21,000 ft.	1340 Naut. Mi. (1,542 Mi.)
Rate of Climb at Sea Level - Two Engines	
At 11,500 lbs.	1963 Ft./Min.
At 10,600 lbs.	2225 Ft./Min.
Rate of Climb at Sea Level - Single Engine	
At 11,500 lbs.	452 Ft./Min.
At 20,600 lbs.	598 Ft./Min.
Service Ceiling - Two Engines (100 Ft./Min.)	
At 11,500 lbs.	24,850 ft.
At 10,600 lbs.	26,250 ft.
Service Ceiling - Single Engine (50 Ft./Min.)	
At 11,500 lbs.	9,300 ft.
At 10,600 lbs.	11,600 ft.
Stall Speeds (Power Off at 11,500 Pounds)	
Gear Down and Flaps 100%	75 Kts. (86 mph)
Gear Down and Flaps 30%	81 Kts. (93 mph)
Gear Up and Flaps Up	90 Kts. (104 mph)

Table 2. Beechcraft King Air A-100 (Continued)

Take-Off Distance – Flaps Up (Normal Procedure at 11,500 Pounds)	
Lift-Off Speed	99 Kts.
Ground Roll	2060 ft.
Total over 50-ft Obstacle	3245 ft.
Take-Off Distance – Flaps 30% (Normal Procedure at 11,500 Pounds)	
Lift-Off Speed	94 Kts.
Ground Roll	1855 ft.
Total over 50-ft Obstacle	2681 ft.
Obstacle Take-Off Distance – Flaps 30% (11,500 Pounds)	
Lift-Off Speed	80 Kts.
Ground Roll	1349 ft.
Total over 50-ft Obstacle	2255 ft.
Landing Distance (3° Approach Angle without Reversing at 11,210 Pounds)	
Approach Speed	98 Kts.
Ground Roll	1302 ft.
Total over 50-ft Obstacle	2246 ft.
Obstacle Landing Distance (6° Approach Angle with Reversing at 11,210 Pounds)	
Approach Speed	90 Kts.
Ground Roll	866 ft.
Total over 50-ft Obstacle	1843 ft.
Distance to Accelerate and Stop at 11,500 Pounds – Flaps Up	
Decision Speed	99 Kts.
Total Distance	4275 ft.
Distance to Accelerate and Stop at 11,500 Pounds – Flaps 30%	
Decision Speed	94 Kts.
Total Distance	3877 ft.

Mission Profile

(Operation based on the following conditions: 6790 lbs. Empty Weight, 11,568 lbs. Ramp Weight, 11,500 Take-Off Weight, High Cruise Power at 21,000 ft. and 45 minute reserve).

Table 2. Beechcraft King Air A-100 (Continued)

Eight occupants, plus 269 lbs. baggage, and 3149 lbs. of fuel before engine start.

Range	1394 Mi. (1212 Naut. Mi.)
Speed (Average)	273 mph (237 Kts.)
Mission Time	5 Hours, 14 Minutes

of the arrays has been removed in Figure 3 to display the configuration of the seven detectors. The four arrays are attached to the seat rails in the aft section of the A-100 (Figure 4).

The preamplifier signal from each detector is calibrated with a ^{88}Y or ^{22}Na source. Normalized outputs of each detector in the array are combined in a 7-way summing amplifier (upper left hand corner in Figure 3). Outputs of the four arrays are matched and combined in a 4-way summing amplifier located in the main acquisition system package. Finally this signal is adjusted in the analog-to-digital converter (ADC) so that the calibration peak appears in a pre-selected channel of the multichannel analyzer of the REDAR (see Section 2.5). A functional block diagram of the data acquisition and recording system is shown in Figure 5.

2.1.3 Positioning System

The construction of accurate radiation isopleth maps depends on precise aircraft position data. The A-100 employs three independent systems for this purpose: an Inertial Navigation System (INS), a Microwave Ranging System (MRS), and a radar altimeter.

2.1.3.1 Inertial Navigation System (INS)

Position data are obtained from a Litton Inertial Navigation System,* model LTN-51. The INS has a precision, gyro-stabilized, 4-gimbal, all attitude inertial platform and a general-purpose digital computer. The inertial platform is a reference plane, undisturbed by aircraft motion, from which the roll, pitch and yaw of the aircraft are measured. The digital computer performs data computation and

*Manufactured by Litton Systems, Inc.

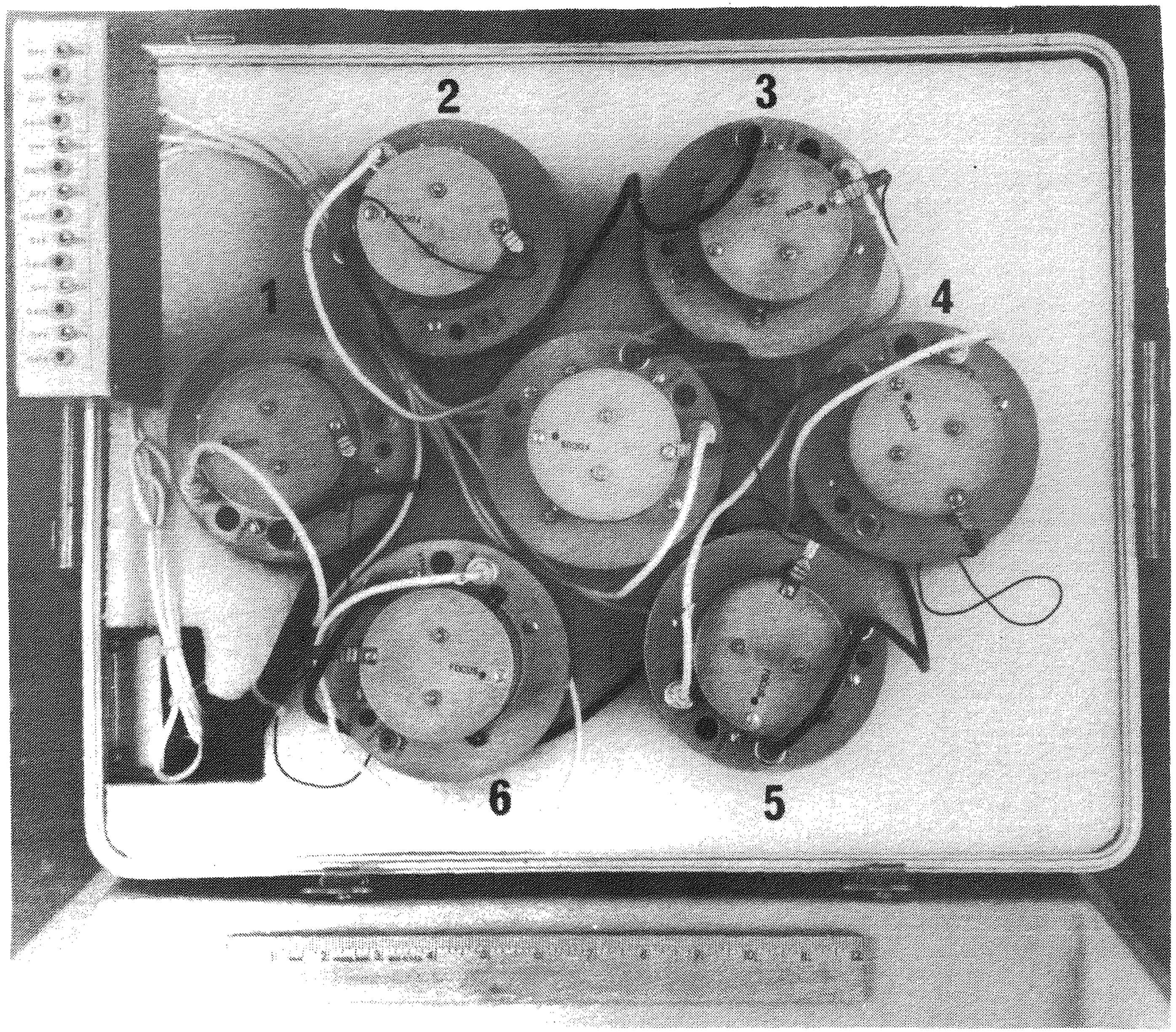

Figure 3. One of the ARMS detector arrays with the top removed to display the geometrical arrangement of the detectors and seven way summing amplifier.

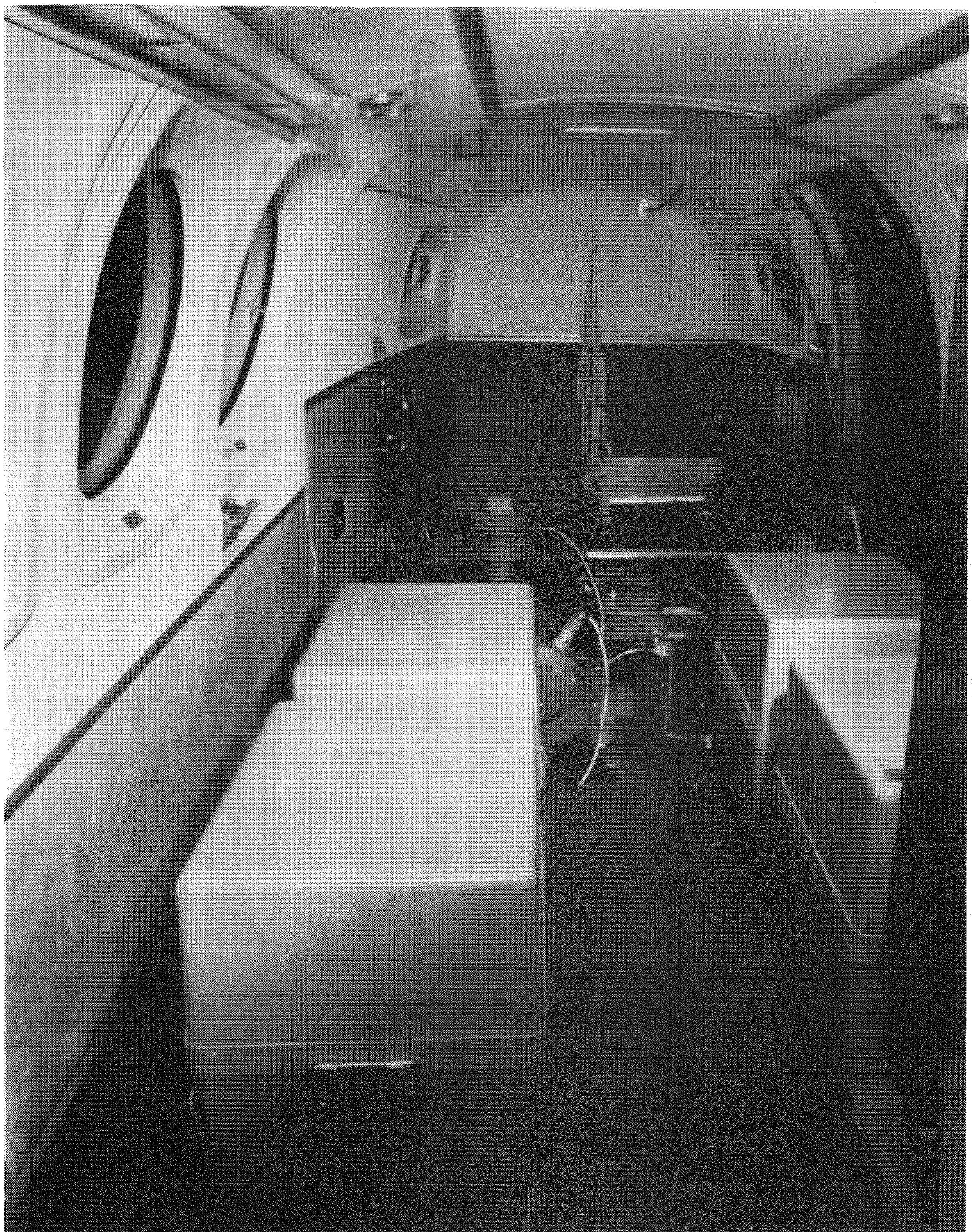

Figure 4. The four detector arrays mounted in the aft section of the ARMS aircraft.

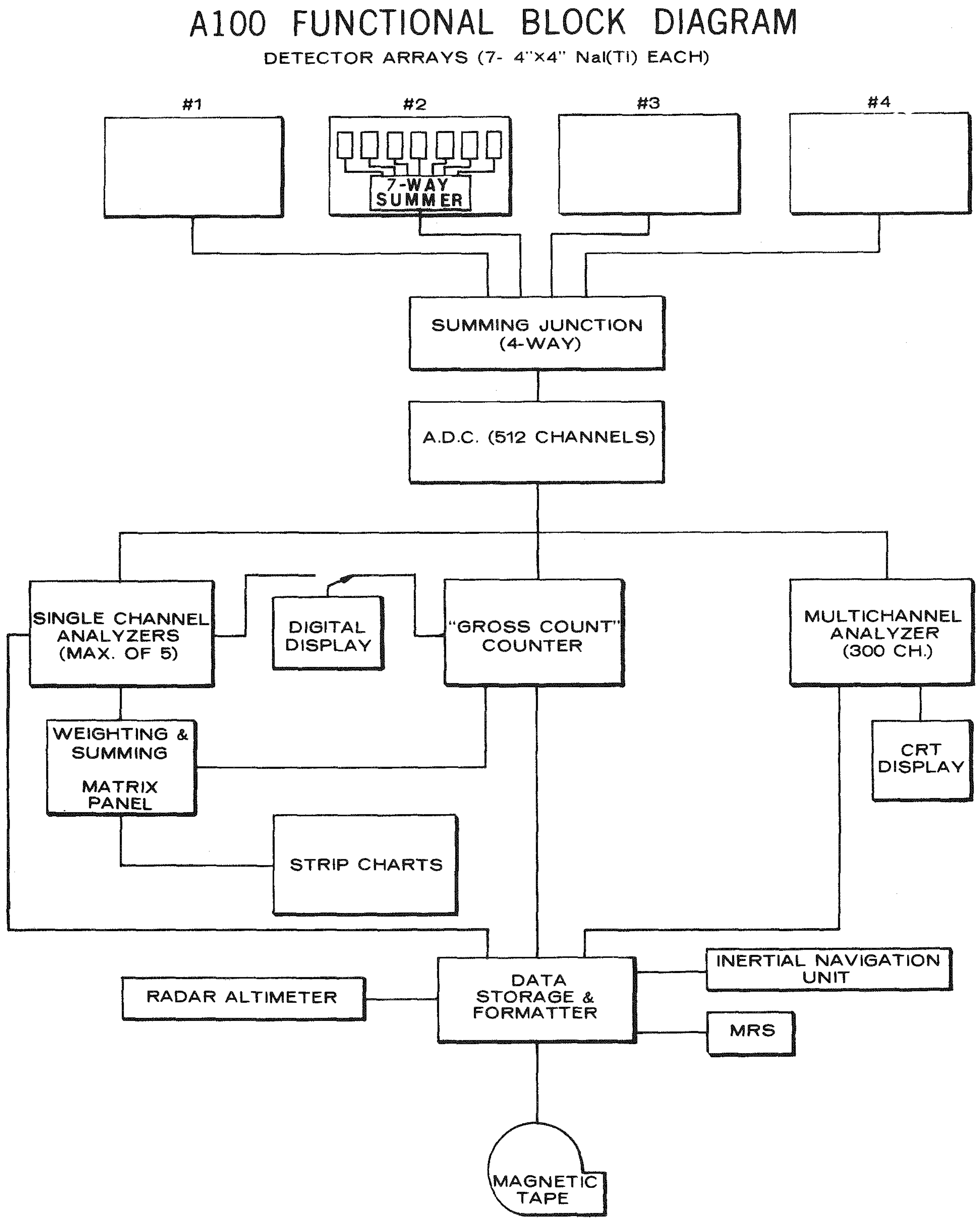

Figure 5. A100 Functional Block Diagram

event programming. The latter function provides accurate navigation information based on a great-circle route from a known position.

Prior to departure for a survey mission, the airport longitude and latitude are entered in the INS, which then computes the changing coordinates as the survey progresses. Latitude and longitude are recorded on magnetic tape once every second. Special INS software, prepared by Litton to our specifications, allow these data to be recorded with a minimum detectable distance increment of 4.6 meters (15 feet).

The inherent drift rate of the INS is approximately 1900m (one nautical mile) per hour. Hence, position data must be corrected before map preparation. Data required for such corrections are provided by flying the aircraft directly over a landmark whose coordinates can be precisely determined from a U.S.G.S. topographic map. Updates are executed every 5-10 minutes and indicated on the magnetic tape by a "hack" mark inserted by the navigator and documented on the navigation maps by an appropriate symbol. Alternatively, accurate coordinates for topographic features may be obtained from the MRS position data, which are simultaneously recorded.

2.1.3.2 Microwave Ranging System (MRS)

The Microwave Ranging System is a Trisponder/202A,* which consists of a master station in the aircraft and two remote transceivers on the ground. The remote stations are repetitively interrogated by the master; the average roundtrip time of travel for the pulsed microwave signal is measured every 250 milliseconds. These data are used to establish the position of the aircraft with respect to the remote stations.

*Manufactured by Del Norte Technology, Inc.

The distances r_1 and r_2 (see Figure 6, a typical set-up) are recorded on magnetic tape once every second. In order to relate r_1 and r_2 to the survey coordinate system the MRS base (b) is measured after the trisponders have been positioned. Then distances H_o and V_o and the angle θ (between the MRS and survey baselines) can be calculated and used as inputs to a software routine. The computer plots all data relative to the survey coordinate system, in terms of H and V:

$$H = x \cos\theta - y \sin\theta - H_o \tag{2-1}$$

$$V = V_o - x \sin\theta - y \cos\theta \tag{2-2}$$

where

$$x = 1/2 \left[b + \frac{(r_2 - r_1)(r_2 + r_1)}{b} \right] \tag{2-3}$$

$$y = \left[(r_2 - x)(r_2 + x) \right]^{1/2} \tag{2-4}$$

The uncertainty in aircraft position varies over a survey area because it is a combination of systematic, geometric, and statistical uncertainties. The systematic error, shown in Figure 7, is electronically compensated. The maximum error is 4m, at a range of approximately 30.5 km. The position error magnification, in Figure 8, is due to the angle between the aircraft (master unit) and the two remote stations.

Statistical uncertainty is due primarily to variations in signal propagation time in the atmosphere and in the electronic circuitry of the master and remote transceivers. The manufacturer quotes the following uncertainties in range accuracy: typical ±3m, long term ±6m.

In a survey these uncertainties are combined. Typically the position of the aircraft can be determined with an accuracy of ±15m at distances up to 80 km from the remote transceivers.

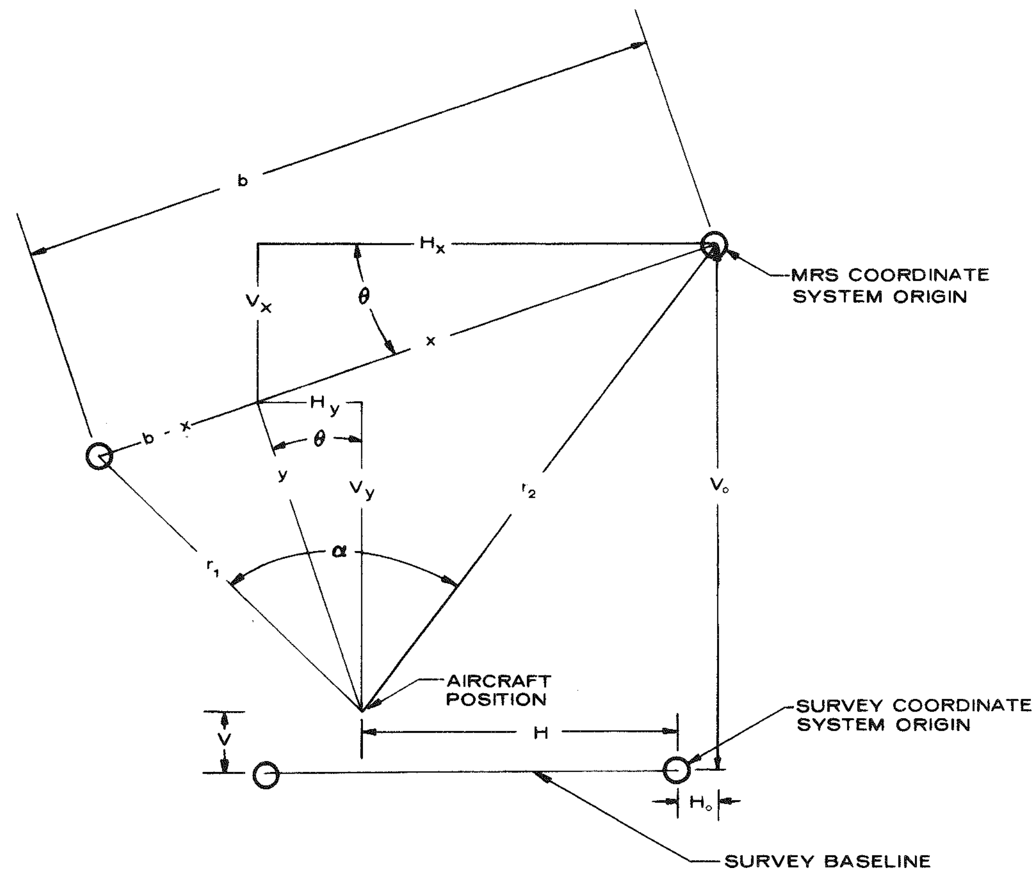

Figure 6. Typical MRS set-up to relate the aircraft position relative to a survey coordinate system.

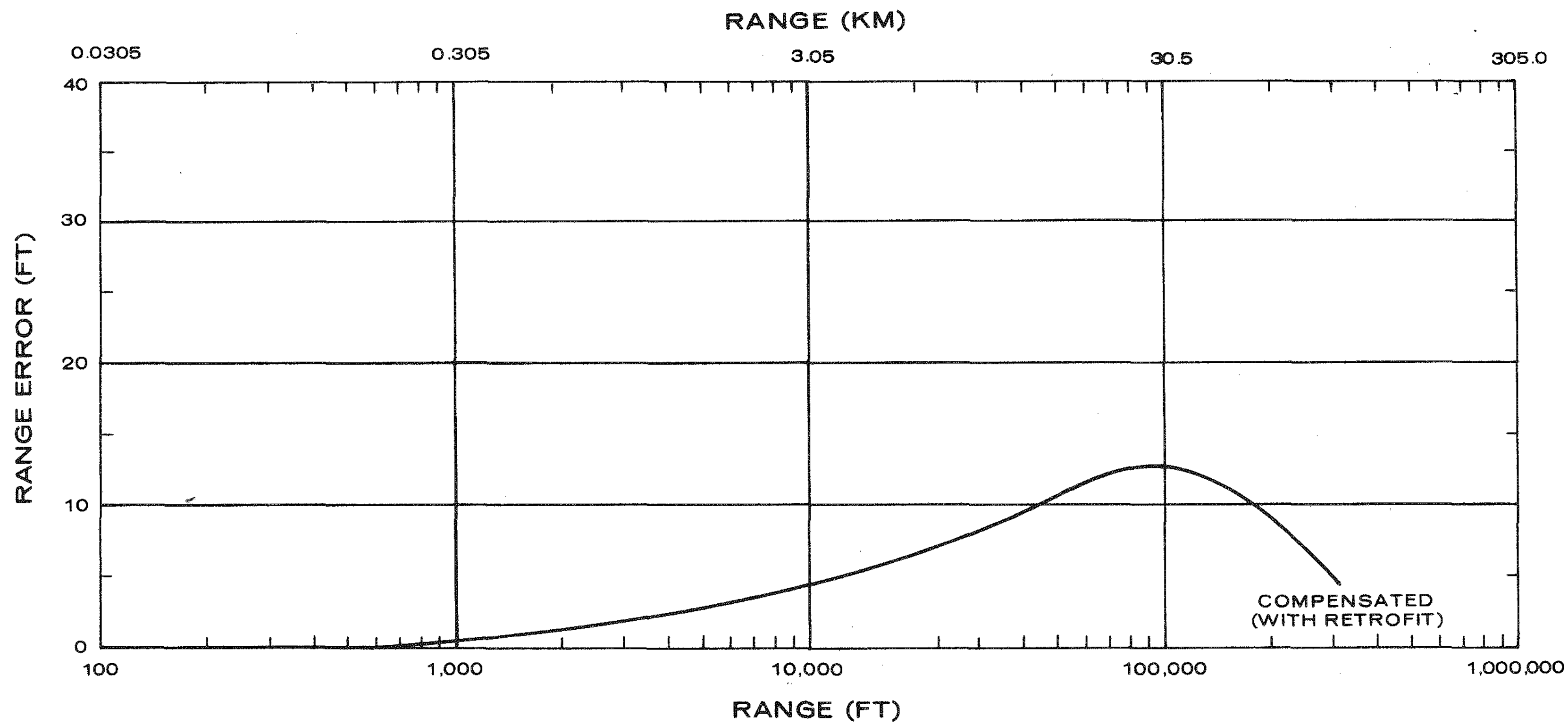

Figure 7. Systematic Range Error Curve for Del Norte Microwave Ranging System

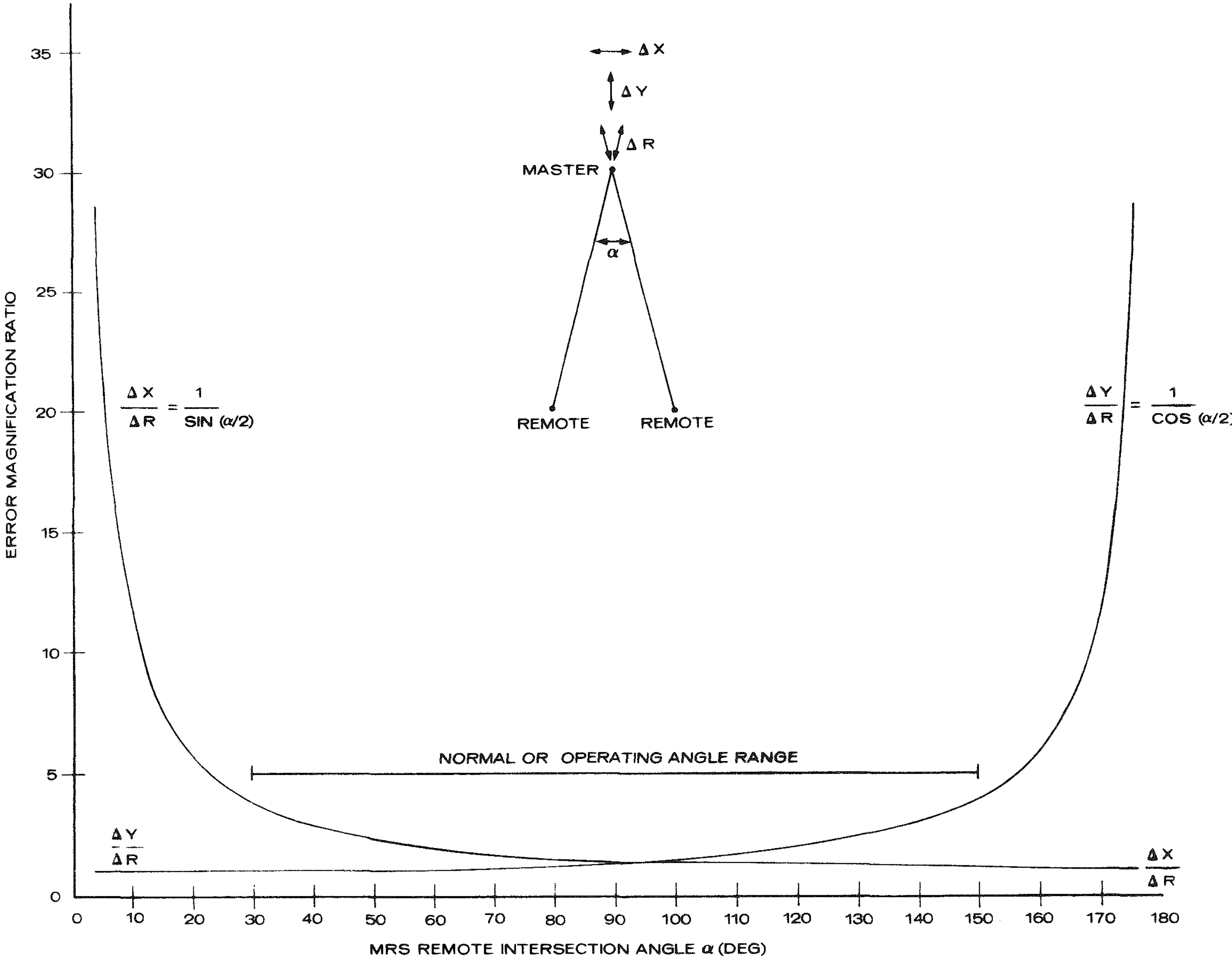

Figure 8. The errors in the magnification rates $\Delta X/\Delta R$ as a function of the MRS remote intersection angle α.

The MRS transceivers operate at frequencies of 9350 MHz (master unit) and 9450 MHz (remote units). The peak transmitter power is 1000 watts (minimum), with a pulse repetition frequency which varies from 581 to 1381 pulses per second. The pulse length is approximately 0.5 μsec.

2.1.3.3 Radar Altimeter

The radar altimeter transmits a pulsed rf signal. Pulses reflected from the nearest ground object are detected by a receiving antenna on the aircraft. The A-100 has a Collins ALT-50 radar altimeter, which transmits at 4300 ±15 MHz with a 3-db bandwidth of 1.5 MHz. The transmitter power is 150 milliwatts.

The elapsed time of the return pulse is converted to an altitude measurement with an accuracy of ±1.5m, plus three percent of actual altitude. For typical A-100 surveys the altitude is 150m. Hence, the altitude uncertainty is ±6m. The altitude is also recorded on magnetic tape once every second.

2.1.4 Meteorological Sensors

The A-100 is equipped with several transducers for accurate measurement of meteorological parameters. These include absolute barometric pressure, outside air temperature, dew point, wind speed and wind direction. All of these digital data inputs are displayed and recorded on magnetic tape at one-second intervals.

2.1.4.1 Absolute Barometric Pressure

Absolute barometric pressure is measured in the A-100 with an LX3702A linear pressure transducer.* It consists basically of a diaphragm and a piezo-resistive strain sensor, assembled in a

*Manufactured by National Semiconductor Corporation.

small, hybrid integrated circuit package. The pressure range is 0 to 15 psia. Since the transducer is internally thermostatted to provide a precisely-controlled temperature environment, it has an accuracy of ±0.23 psi and a stability of ±0.04 psi.

2.1.4.2 Outside Air Temperature

Outside air temperature is measured with a Model 101AA total temperature sensor.* The transducer is a 500-ohm platinum resistance wire, hermetically sealed in a platinum shell. Its temperature range is -70° C to +350° C. The resistance R_T of the wire changes precisely with the temperature T of the outside air. The R_T vs. T calibration tolerance is ±0.25° C plus 0.5 percent of the magnitude of the temperature in degrees Celsius. After appropriate signal conditioning the temperature is displayed and recorded in digital form on the REDAR.

2.1.4.3 Dew Point

The dew point measurement is provided by a model 137-C3-53 sensor,** which has a range of -50° C to +50° C. The sensor contains a platinum resistance wire (R_0 = 100 ohms, approximately) which is one leg of a bridge circuit designed to convert the output to a low impedance linear 0-5 volts dc signal. The sensor has sufficient mirror cooling capability to measure dew points corresponding to 10 percent relative humidity at the sensor operating temperature. The dew point is measured with an accuracy of ±0.5° C above 0° C, ±1° C below 0° C.

*Manufactured by Rosemount, Inc.
**Manufactured by Cambridge Systems.

2.1.4.4 Wind Speed and Wind Direction

Wind speed and wind direction are derived from the INU described in Section 2.3.1. The INU establishes an inertial reference platform which is not perturbed by aircraft motion. Roll, pitch, yaw and translation in any direction are measured with respect to this platform. Accelerometer measurements are transmitted to the computer where the desired quantities are calculated. In this case the measured airspeed V_A is vectorially subtracted from the ground velocity V_G by resolving the airspeed into platform coordinates. The components of wind velocity are:

$$V_{WX} = V_X - V_A \cos \theta_Z \qquad \text{(x - component)}$$

$$V_{WY} = V_Y = V_A \sin \theta_Z \qquad \text{(y - component)}$$

where V_X and V_Y are the x- and y-components of V_G and θ_Z is the heading of the platform with respect to the aircraft, as measured by the platform azimuth synchro. Hence:

$$V_W = \sqrt{(V_{WX})^2 + (V_{WY})^2} \qquad \text{(wind speed)}$$

and

$$\theta_W = -\left[\alpha + \tan^{-1} \frac{V_{WY}}{V_{WX}}\right] \qquad \text{(wind direction),}$$

where α is the platform wander angle.

2.1.5 Data Acquisition System

Data are continuously acquired and recorded in the A-100 by a system known as REDAR (Radiation and Environmental Data Acquisition and Recorder). The REDAR system, shown in Figure 9, records all of the following data at the indicated rates:

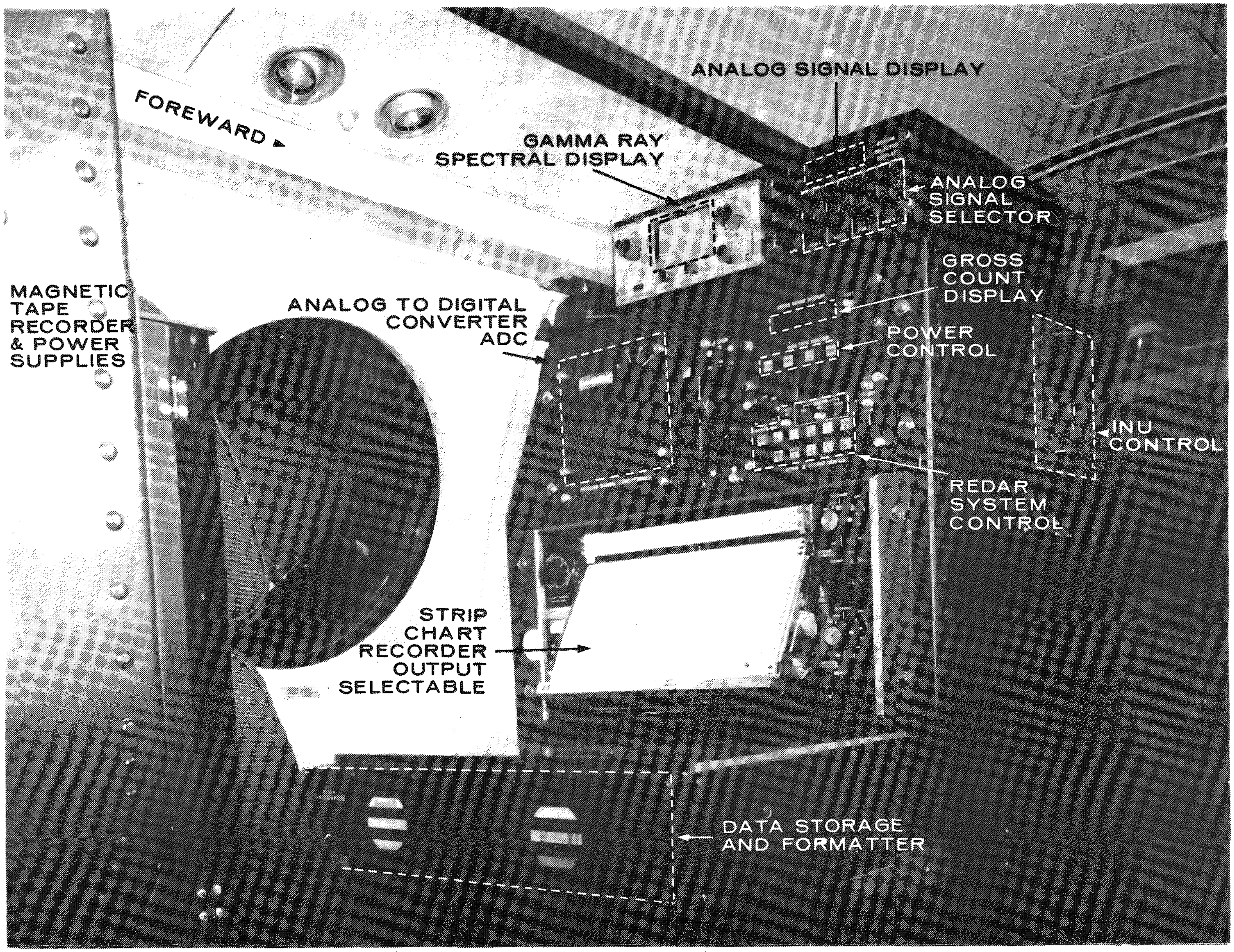

Figure 9. REDAR System in the ARMS Aircraft.

	Parameter	Frequency
1.	305-channels of pulse-height data, 2^{16} counts full scale (each channel) and live-time, accurate to 0.01 second	3.0 sec
2.	Five single-channel analyzers, upper and lower discriminators adjustable with digital switches	0.2 sec
3.	Gross count channel (sums all counts)	0.1 sec
4.	Position measurement (INS)	1.0 sec
5.	MRS distance measurements	1.0 sec
6.	Radar altimeter	1.0 sec
7.	Absolute pressure	1.0 sec
8.	Outside air temperature	1.0 sec
9.	Wind speed	1.0 sec
10.	Wind direction	1.0 sec
11.	Dew Point	1.0 sec
12.	True air speed	1.0 sec
13.	On-top marker	As required (operator push-button)
14.	System configuration	1.0 sec
15.	Time-of-day clock (HRS-MIN-SEC)	1.0 sec

Outputs from all detectors are mixed before being processed by the multichannel or single-channel analyzers. Windows are set on the single-channel analyzers to monitor regions of the spectrum pertinent to isotopes of interest.

All of the above data inputs may be displayed by the electronic system operator for real-time monitoring. Digital data, such as count rates, meteorological information or time of day, are displayed on several LED readouts. Gamma ray spectral data may be examined on the oscilloscope as the data accumulate. At any point in time a spectrum may be frozen for critical examination, without affecting the continuous acquisition and recording of data. A dual pen analog strip chart recorder permits visual monitoring of the time variations in any two of the following: gross count rate, count rate in any single-channel window, radar altitude, absolute pressure, outside air temperature, dew point or true air speed.

Digital data are permanently recorded on a nine-track recorder* capable of recording continuously for five hours (fifty megabits of data). All data are recorded as raw information directly from sensors. The data can be manipulated after the flight by ground-based computers.

The single-channel data can be weighted, then added or subtracted from any combination of five channels with a matrix panel (Figure 10). The single-channels can be set to monitor natural, cosmic or man-made gamma-ray-emitting radionuclides. These data can be filtered and plotted in real time on the strip chart recorder with RC time constants between 0.2 and 16 seconds. If one is searching for a particular radionuclide, the appropriate single channels and matrix panel settings can be set to enhance the capability of detecting the source in real-time.

*Cipher Data Products Recorder, Model 85H.

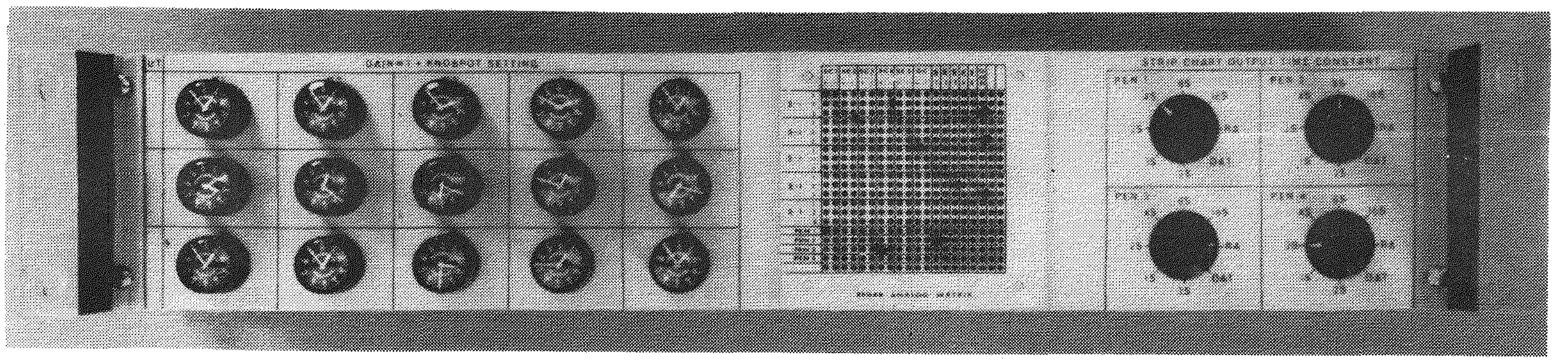

Figure 10. Matrix panel for summing, weighting and filtering single channel digital data for real time strip chart display.

2.1.6 Air Sampling System

The A-100 aircraft has been equipped with an air sampling system capable of both particle and whole gas sampling.[8] Particulate sampling is achieved with a four-stage cascade impactor and fiber glass filter paper. A pair of motors and blower pumps provide the necessary 0.5 atmosphere pressure and achieve an isokinetic flow rate of 50 cfm.* A nuclear counting system on board the aircraft permits measurement of α, β, or γ activity on air filter samples. Whole gas sampling is accomplished with different types of cryogenic sampling systems incorporating molecular sieves.

The A-100 may also be called upon to survey an area experiencing an explosion or fire which could produce airborne radioactive particles. Hence a cascade impactor is required to determine the size distribution, the concentration and the radioactive species of particles larger than 1μ. These data, coupled with information derived from the filter paper, would be invaluable for fall-out predictions.

Operating nuclear power plants, nuclear processing plants, and conversion plants continually generate radioactive gases such as Ar, Xe, Kr and I. Hence, the system is designed to accommodate cryogenic sampling systems which trap the radioactive species in molecular sieves.

The system is also flexible enough to add on special instrumentation, such as a nephelometer. This will enable the A-100 to support general air pollution studies as part of its broader ARMS responsibility to ERDA's Division of Operational Safety.

*Final installation of the air sampling system is in progress as this report is being published. Operational data are design criteria or test bench measurements.

2.1.6.1 Air Sampler Design

The air sampler was designed to satisfy three survey mission requirements: (1) airborne radon daughter measurements, (2) measurement of airborne particles and gases from a nuclear accident or incident, and (3) monitoring of radioactive gases from stacks of operating plants. Radon daughters are heavy metal nuclei which preferentially attach themselves to aerosol particles in the lower micrometer sizes. The concentration of radon daughters is highly dependent on atmospheric conditions. Since the radon daughters generate a significant gamma ray background, accurate surveys of natural terrestrial gamma radiation require frequent measurements of their concentration. Quantitative measurement requires high efficiency filter paper and isokinetic sampling of the air.

2.1.6.2 Cascade Impactor

The sampling probe is mounted on a removable modified escape hatch cover, behind the co-pilot's seat, as shown in Figure 11. The intake aperture has an inside diameter of 2.21 cm, followed by an expansion chamber. The entrance to the 13-cm diameter sampling chamber can be controlled with a large shut-off valve.

The sampling chamber (detailed diagram Figure 12) accommodates the cascade impactor and the filter paper. Both are accessible from the cabin interior and can be changed manually during flight. The cascade impactor consists of four slotted metal discs. The slot width decreases in each successive disc; the higher impaction velocities created by the narrowing flow jets causes separation into three particle sizes: $>10\mu$, $10\mu \rightarrow 5\mu$, and $5\mu \rightarrow 1\mu$.

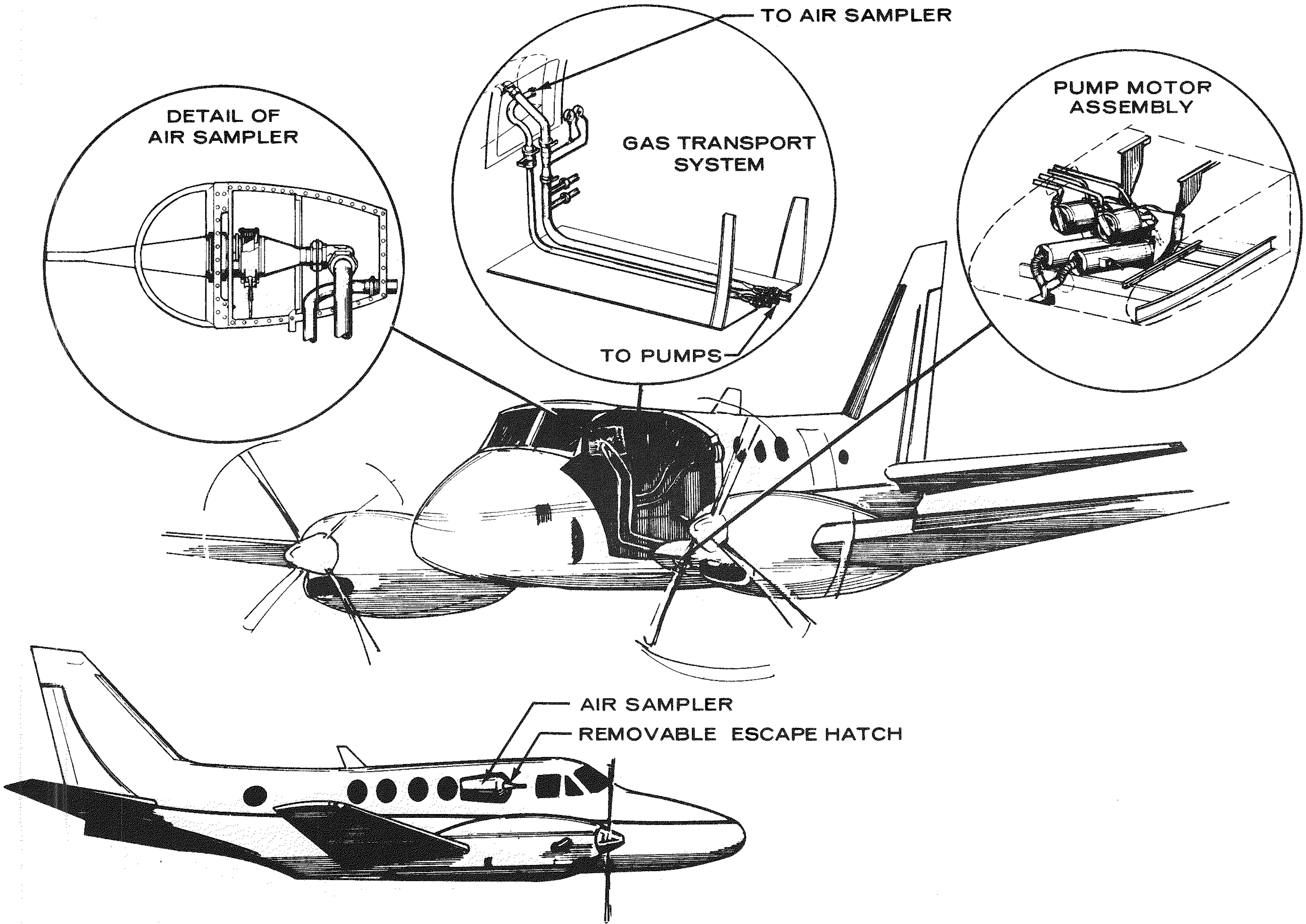

Figure 11. Air sampler installation. The three circled blow-ups (from left to right) are: the isokinetic particle sampler, gas transport system, and pump-motor assembly.

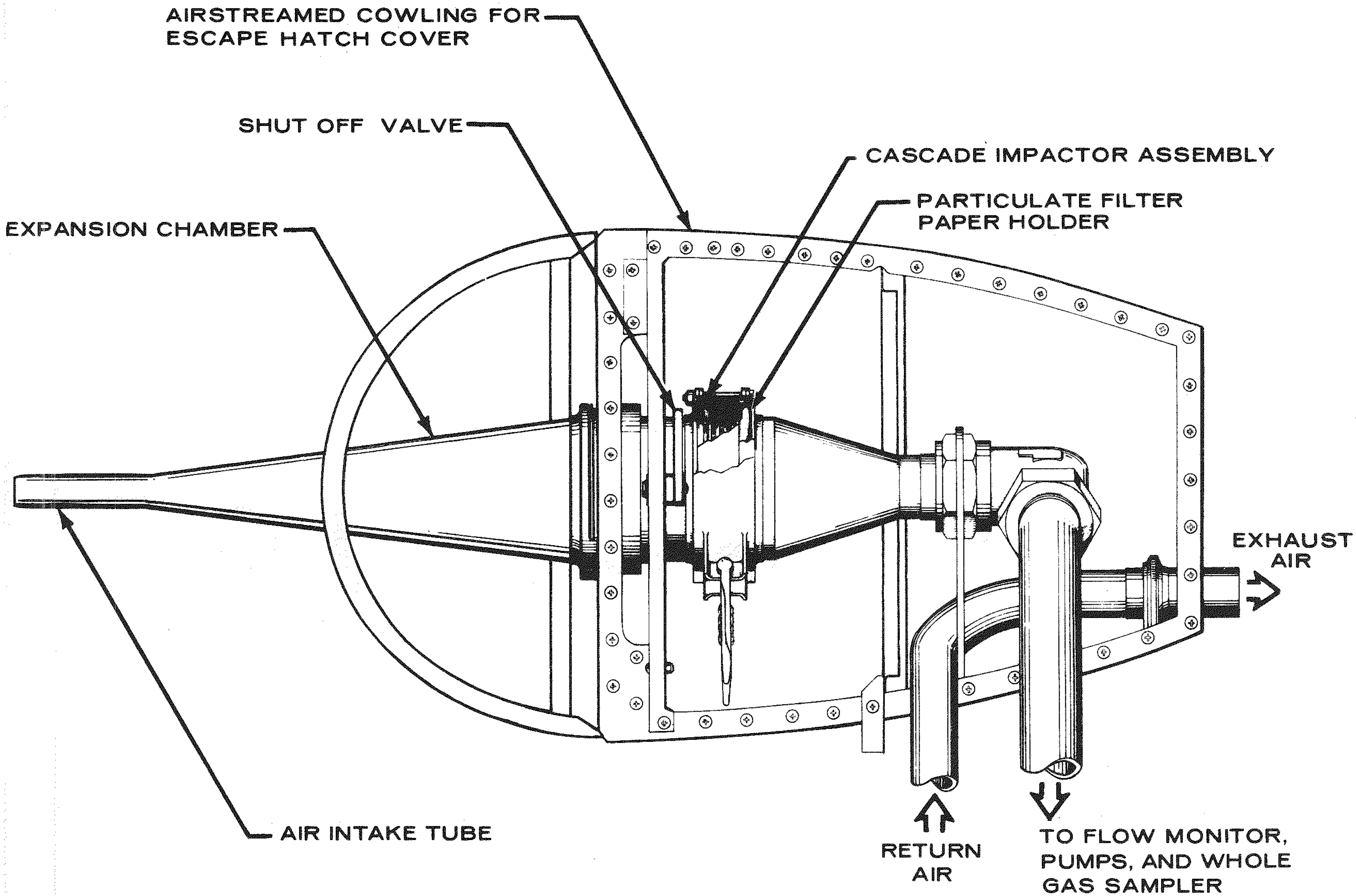

Figure 12. Detailed diagram of the air sampler probe, expansion chamber and particle sampling chamber.

Particles of a diameter less than 1μ are trapped in the filter paper immediately behind the cascade impactor.

2.1.6.3 Air Filter

Accurate sampling of the atmosphere requires that the sample probe project into a region undisturbed by aircraft surface roughness. The probe must sample laminar flow and be parallel to air flow streamlines at that point. The A-100 meets these criteria, both theoretically and experimentally. A calculation using the Milne-Thompson(9) derivation for streamlines around a paraboloid approximating the nose cowling and moving at the aircraft cruise velocity was performed. The results indicate that streamlines just forward of the escape hatch cover are uniformly spaced and parallel to the flight direction to within ±5%.

These results were experimentally verified(8) by a set of in-flight measurements. Cotton tufts taped to the aircraft fuselage were photographed to validate the direction and uniformity of the streamlines. Pitot tubes were also positioned out to six inches from the fuselage to determine the pressure gradient. A zero velocity gradient was measured at all points beyond a 0.2-inch boundary layer. From these results it has been established that the sample probe is properly located.

In order to accurately sample particulate matter in the atmosphere so that the particle size distribution on the filter is the same as that existing in the atmosphere, it is also necessary that little or no fractionation occur at the inlet. This condition, called isokinetic sampling, demands that the linear velocity of the inlet duct be equal to the linear velocity of the free stream. But the requirement for measurement of submicrometer size particles necessitates the use of a high efficiency filter paper which also presents high air flow impedance.

The paper selected for the A-100 sampler is MSA 2206 B glass filter paper.* At the aircraft cruising speed of 62m/sec (120 knots), the 2.21-cm diameter inlet accepts 23.7 ℓ/sec under isokinetic conditions. To achieve such a flow, two pumps were installed (see Figure 11), to maintain a pressure differential of approximately 0.5 atm across the filter. Each pump is driven by an air-cooled 3-hp electric motor.

Filter samples may be analyzed immediately on the aircraft. For high-efficiency gamma spectroscopy, a NaI(Tℓ) crystal detector is used. For high resolution work, a Ge(Li) detector is also available. Beta measurements are made with a thin plastic scintillator.[10] Alpha activity can also be measured on board with an array of silicon diode surface barrier detectors mounted inside a small vacuum chamber.[11]

2.1.6.4 Whole Gas Sampler

Immediately downstream of the sampling chamber is a valve which permits control of flow rate. A venturi flow rate meter and pressure gauges allows flow rate measurements so that airborne contaminant concentrations may be quantified. Below this are various taps for whole gas sampling.

*Manufactured by Mine Safety Appliances Company, 400 Penn Center Blvd., Pittsburgh, Pennsylvania.

2.1.7 Photographic System

An integral part of the A-100's role is its photographic capability. Radiation contour maps and other environmental survey data must often be superposed on aerial photo maps to provide accurate, timely reports. The A-100 is equipped with a 26-inch diameter photo window, made of crown type glass, 0.885 inch thick. The surfaces are optically ground and parallel.

The aircraft can be fully pressurized with the window in place. When the window is not in use, the hatch cover is closed to protect the optical surface, as shown in Figure 13.

The A-100 uses two different camera systems, depending on mission requirements. A 4-camera Hasselblad system is used for multispectral photography. A large-format Wild RC-8 is used for aerial mapping.

2.1.7.1 Hasselblad Camera System

The A-100 has two 4-camera systems, either one of which can be hard-mounted to the aircraft floor as shown in Figure 14. Each system consists of four 70-mm 500 EL Hasselblad cameras, one equipped with 50-mm lenses, the other with 80-mm lenses. At a survey altitude of 3 km, the field-of-view is 3.3 km x 3.3 km with 50-mm lenses, 2.2 km x 2.2 km with 80-mm lenses. The cameras are arranged along parallel optical paths to record identical ground image areas. The frame size is 55 x 55 mm.

The shutters are actuated simultaneously by an intervalometer which can provide between 10 and 80% forward overlap at medium-to-high altitudes. Each magazine holds approximately 80 frames. Magazines are readily interchangeable in flight.

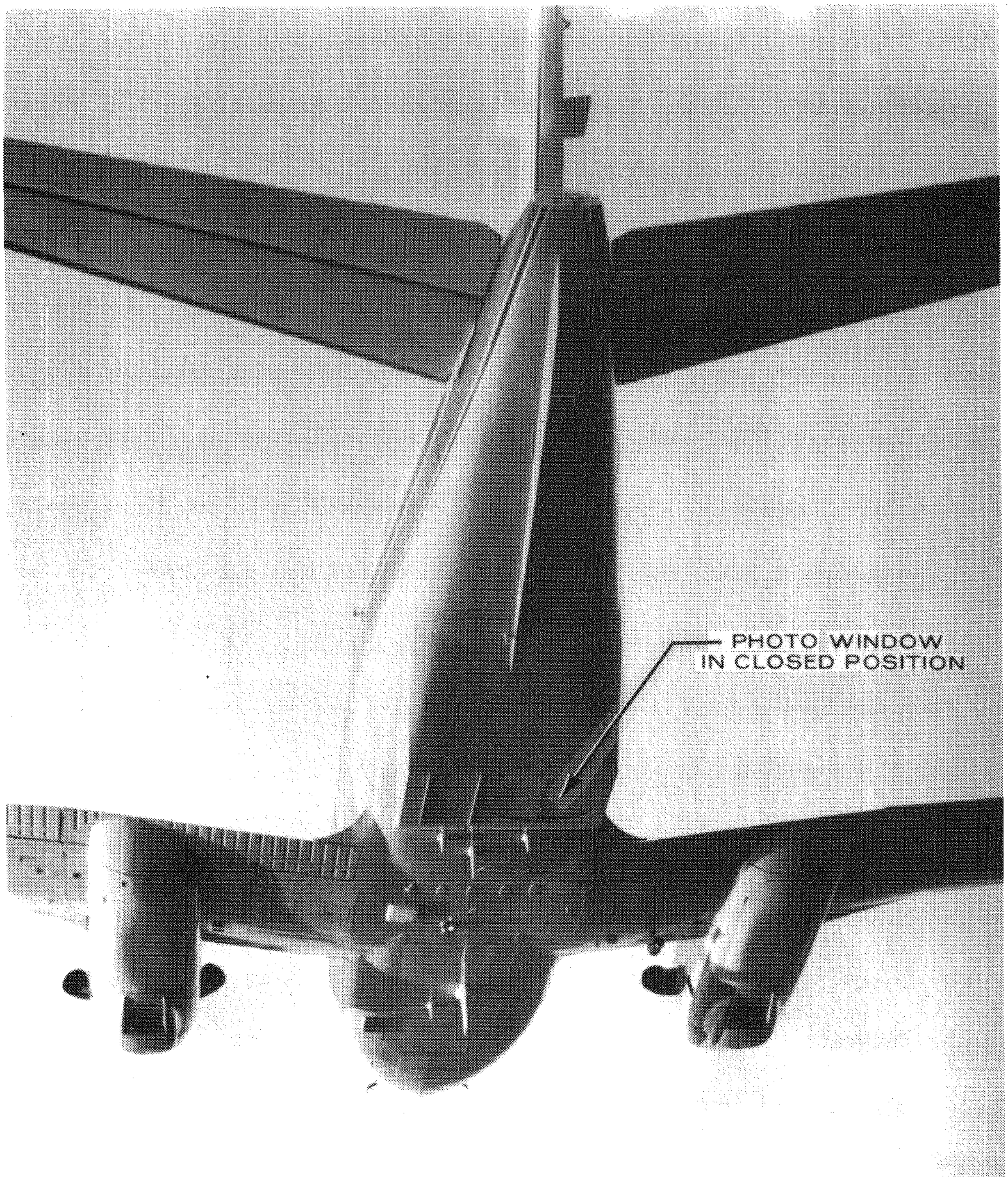

Figure 13. A-100 bottom view with photo window closed.

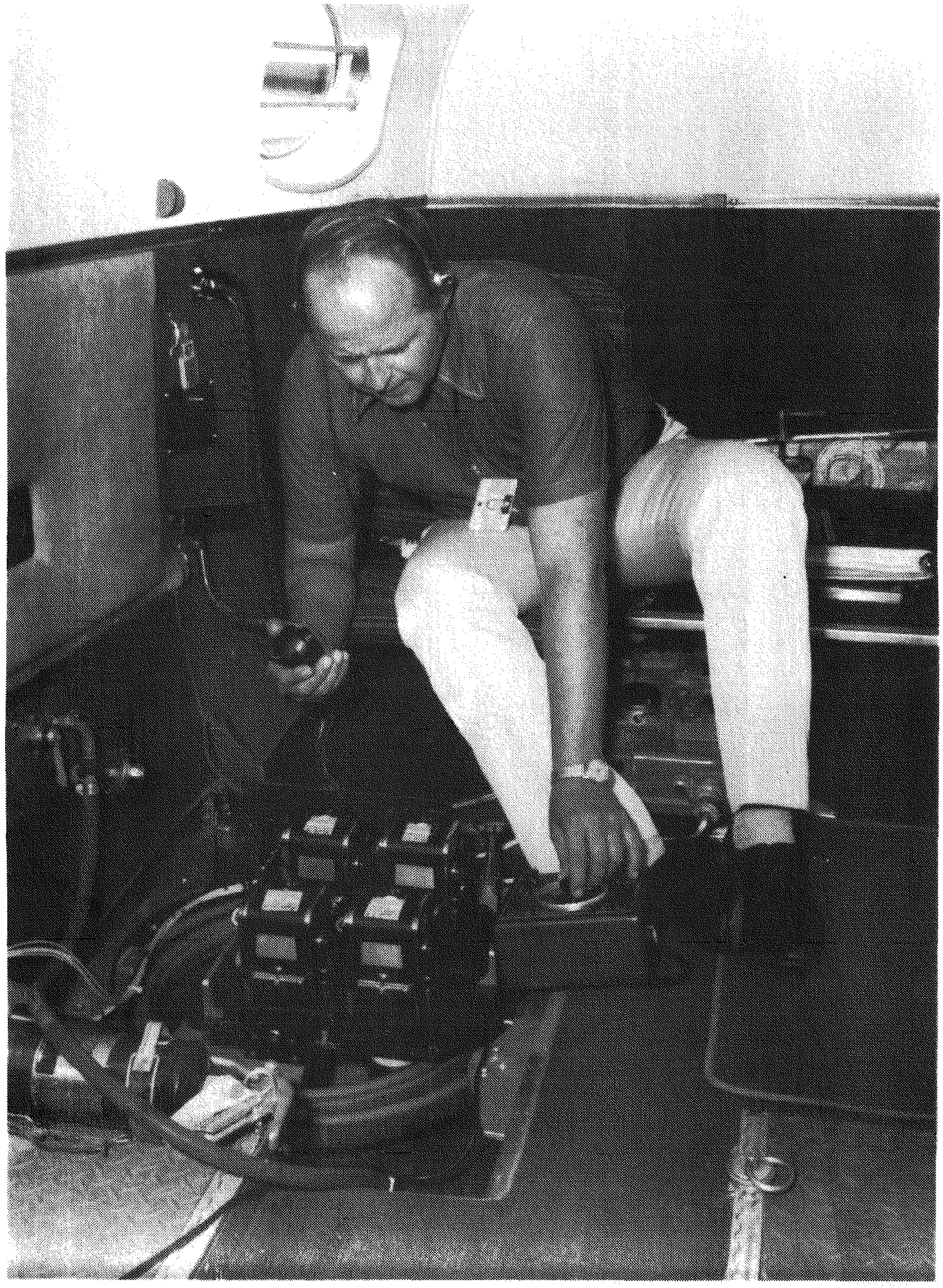

Figure 14. Hasselblad multispectral camera system mounted in the A-100.

By proper selection of film type and lens filter, either system can cover any four wavelength bands in the spectrum from visible to near-infrared (0.4 to 0.9 μm). Four bands that are frequently recorded are the following:

Normal color (w/haze filter)	0.4 - 0.7 μm
Infrared color (w/yellow filter)	0.5 - 0.9 "
Panchromatic (w/red filter)	0.6 - 0.7 "
Infrared black and white (w/infrared filter)	0.7 - 0.9 "

2.1.7.2 Wild RC-8

For large area aerial photography a Wild RC-8 camera with a 6-inch Aviogon lens is mounted in the A-100. The camera mount is manually leveled at the time of each picture. This camera system is also equipped with an intervalometer and a navigation sight. The image size is 9 x 9 inches; the magazine capacity is approximately 300 frames.

For complete coverage of an extended site, the aircraft is typically flown at an altitude of 6 km, which provides a field-of-view of 9 km x 9 km. At medium-to-high altitudes the intervalometer can be set between 10 and 80% forward overlap. Normally, frames are taken with 60% forward overlap to provide photographs suitable for stereo viewing. A variety of color or black and white negative or positive films are used.

2.1.8 Infrared Scanner

Emitted infrared radiation from the wavelength region of 8-12.5μ is recorded with a Bendix Thermal Mapper Model LN-3. The unit consists of an optical-mechanical device that scans an area approximately 100 degrees beneath the aircraft as it moves in a forward direction. A mercury-cadmium-telluride detector cooled with liquid nitrogen is used as the detector. The data are recorded in analog form on tape or on photographic film. Temperature differences of 0.5° C can be determined from the data.

Other detectors of indium antimonide and a photomultiplier detector record radiation in the 4-5.5μ and 0.1 to 0.7 region of the spectrum.

2.1.9 Communications

The A-100 has the standard VHF radios for transmitting and receiving on frequencies between 118.99 to 135.95 MHz in 0.05 MHz increments. For special missions, an HF radio can be installed which has 28,000 channels ranging from 2.000 to 29.999 MHz.

Also available are two frequencies in the VHF HI band approved for nationwide use by the Interagency Radiological Assistance Plan (IRAP). Radio-telephone communication can be established with ARMS aircraft in most sections of the United States. The "King Phone" number is QM50427.

2.2 H-500 HELICOPTER

Hughes H-500 helicopters are used as platforms for ARMS surveys requiring detailed measurements. These platforms are considerably smaller than the King Air, carry less payload, and have less range. Their advantage lies in the fact that they can fly lower and slower than fixed wing aircraft, with a concomitant improvement in spatial resolution.

Two pods, each containing ten 5-inch diameter by 2-inch thick NaI(Tℓ) detectors, are mounted in the auxiliary fuel tanks as shown in Figure 15. A more compact version of the REDAR system (Section 2.1.5) is used for data acquisition.

Position information is provided by the microwave ranging system (Section 2.1.3.2). Altitude data are provided by an AL-101 Radio Altimeter System, which operates at 4300 MHz. Its range is 0 to 760 m (2500 ft). Up to 150 m, its accuracy is ±0.6 m or ±2%, whichever is greater; from 150 to 760 m, the accuracy is ±5%.

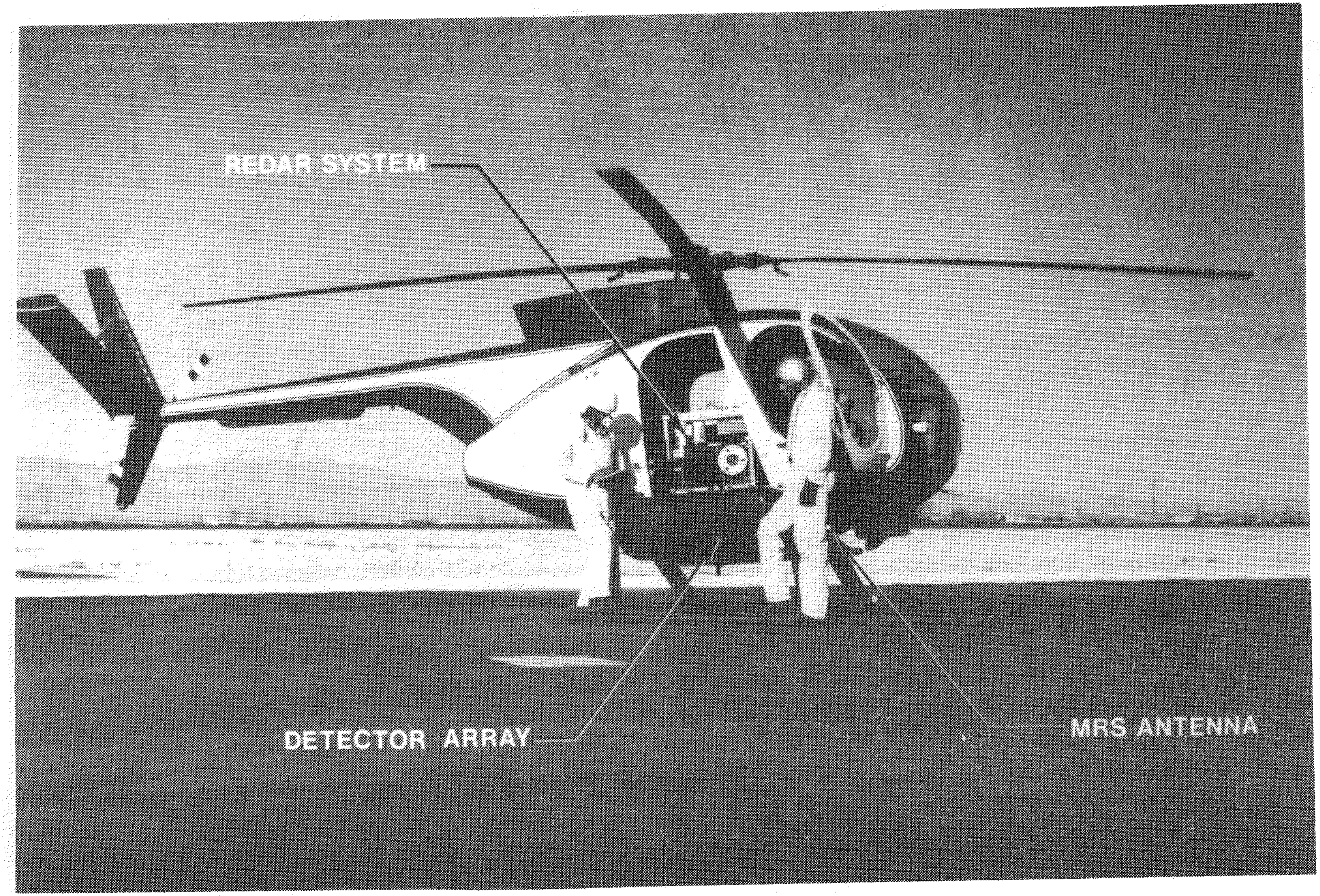

Figure 15. H-500 Helicopter Survey System

3. SURVEY PROCEDURES

3.1 KING AIR

The basic survey pattern consists of a series of parallel flight lines, oriented perpendicular to the direction of any major geological formations in the survey area. Geologic maps of each survey area are reviewed to aid in the orientation of the survey pattern. The flight lines are generally 50 km in length and spaced from 300-900m apart. The line spacing is dictated by the energy and distribution of the radioisotope in the survey area. Figure 16 relates the area on the ground from which the detector at 150 meters receives 90 percent of the uncollided flux due to an infinite planar source of gamma ray energies from 0.20 to 2.62 MeV. The response of the airborne detector system to various gamma ray energies for various source geometries has been published.[12]

Routine background surveys are flown with 900m line spacing. This line spacing represents a compromise between isotope detectability and survey rate.

The flight lines are programmed on U.S.G.S. topographic maps. The navigator starts the flight line on a selected topographic feature, along a predetermined magnetic heading. The navigator, visually tracking aircraft progress on the topographic map, guides it along the programmed flight line and terminates it over an easily recognized topographic feature. By this method the starting and ending points of each flight line are recorded on the topographic map and on mag tape. In the near future, a steering indicator, which derives position data from the MRS, will be used to help guide the aircraft along each programmed line.

90% CONTRIBUTION FOR 500 FT (152.4 METERS)

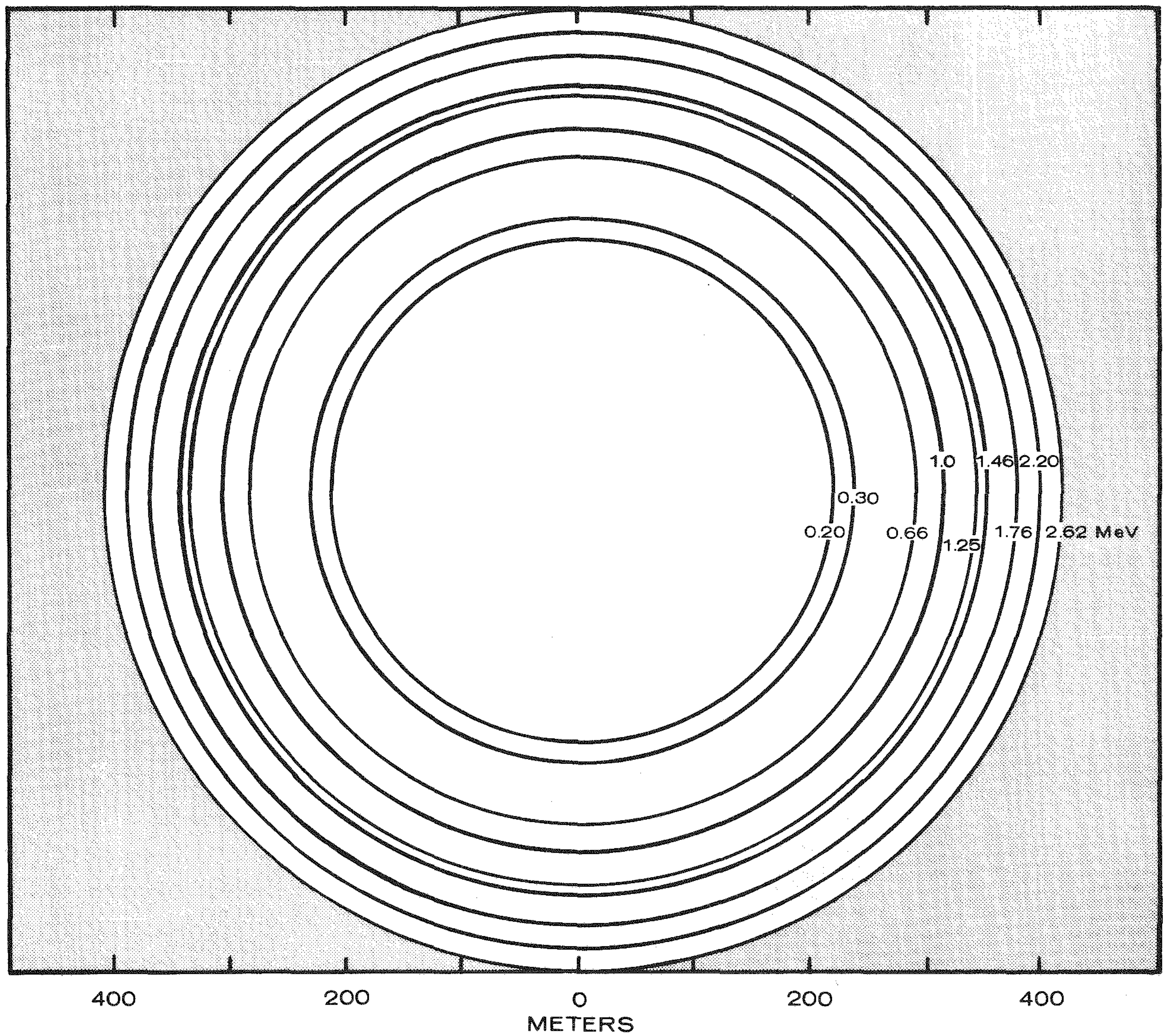

Figure 16. Field-of-View of the detectors at 150m altitude.

3.2 H-500 HELICOPTER

The helicopter system is used when spatial resolution better than ~1,000 feet is required or when low energy gamma rays must be sensed. Altitudes between 100 feet and 200 feet are normally flown with line spacings between 100 feet and 400 feet. Flight lines are laid out on aerial photographs of the survey area and results are presented in the form of radiation contours superimposed on the photograph.

4. DATA PROCESSING SYSTEM

Data are routinely processed in the field with the Radiation and Environmental Data Analyzer and Computer (REDAC). The system is a computer analysis laboratory, mounted in a mobile van, as shown in Figure 17. For most surveys the van and the aircraft are based together at an airport close to the survey site.

The REDAC (Functional Block Diagram, Figure 18) consists of two Cipher Data tape drives,* a NOVA 840 computer,** two Cal-Comp plotters,*** and a CRT display screen≠ with a hard copier.≠ All processing and analysis can be accomplished in the field. An extensive library of software is routinely used for data processing.

Pulse height windows can be selected over any portion of the gamma energy spectrum (0.05 to 3.0 MeV), in addition to the five single-channel windows, and plotted as a function of time or position. Weighted combinations of windows from either the multichannel or single-channel analyzers can be summed together and the result plotted as a function of time or position. By the proper selection of windows and weighting factors, it is possible to extract the photopeak count rates for man-made isotopes deposited on the terrain in the survey area. The photopeak count rates can then be converted to isotope concentrations or exposure rates. Spectral data can be summed over any portion of the survey flight line.

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*Cipher Data Products Company
**Data General Corporation
***California Computer Products, Inc.
≠Tektronix Corporation

Figure 17. Interior of the mobile van which houses the Radiation and Environmental Data Analyzer and Computer (REDAC) system, used in analysis of the survey data.

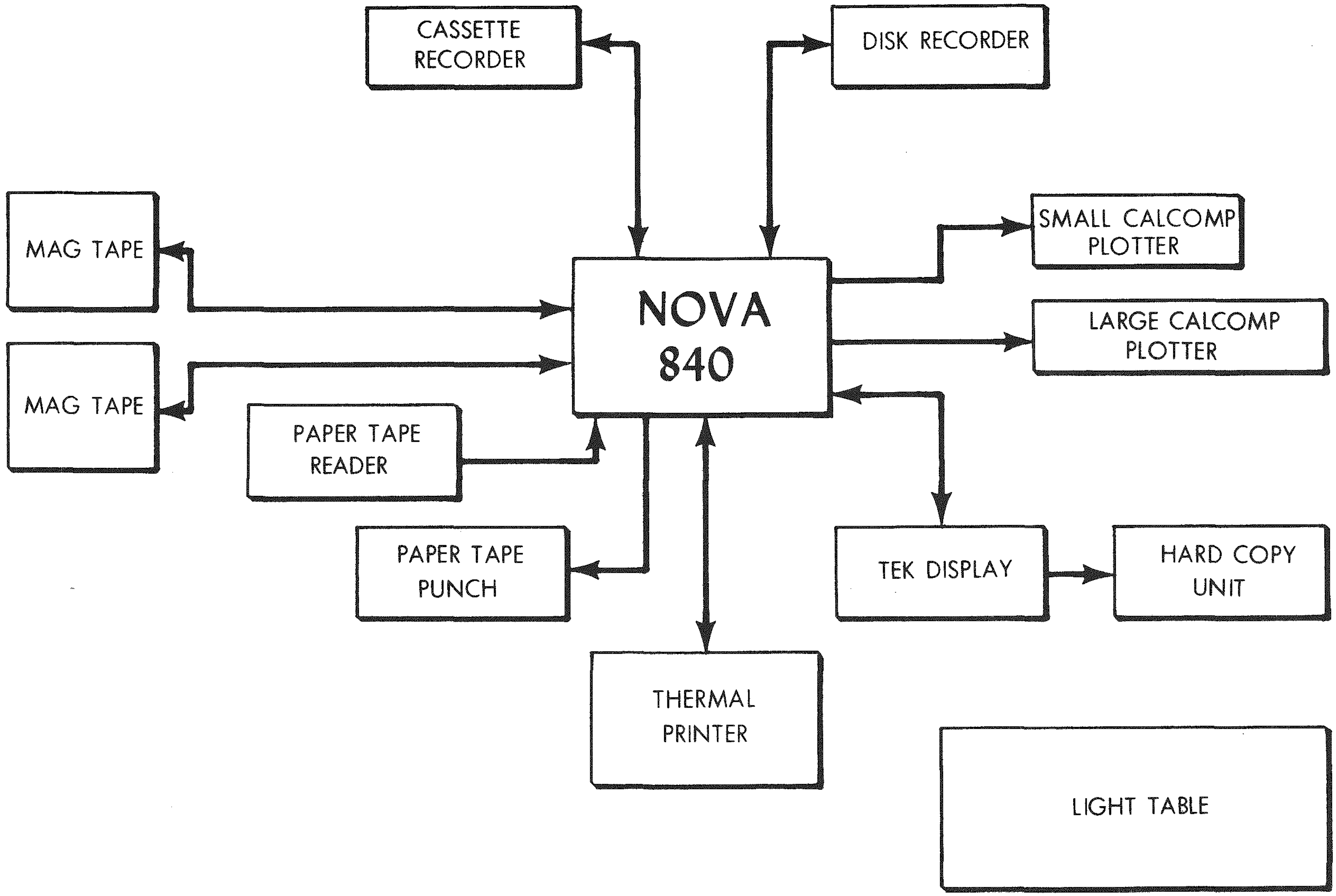

Figure 18. Peripheral equipment associated with the NOVA-840 (REDAC) data reduction system

Various other parameters can be plotted on the CRT or Cal-Comp units, such as radar altitude, outside air temperature, absolute air pressure, MRS data, time, or dew point. Raw or processed data, or selected portions of either, can be transferred from the 9-track tapes to readily-portable cassettes.

5. SENSITIVITIES AND DATA PROCESSING METHODS

5.1 TERRESTRIALLY DISTRIBUTED SOURCES

Interest lies primarily in man-made isotopes, their concentration and contribution to the exposure rate at the 1m level. The factor for converting gross counts (those between 50 keV and 3 MeV) to exposure rate depends on the radionuclides present, their distribution in the soil, survey altitude, and other factors. If the mix of radionuclides is reasonably constant and uniformly distributed in the soil, as in the case of naturally-occurring radionuclides, gross counts can be calibrated against exposure rate. Due to the better counting statistics associated with gross counts, this approach is usually applied to areas exhibiting no man-made contaminants. A different approach is applied to areas where man-made contaminants exist. The latter approach is based on photopeak count rates from these contaminants and is designed to specifically exclude effects from naturally-occurring radionuclides.

The two approaches are outlined in the next two sections.

5.1.1 Natural Background

5.1.1.1 Exposure Rate Conversion Factor

A constant conversion factor is used to convert the gross count rate of ground origin to an exposure rate at one meter above the ground. The normal 500 ft, S.T.P. conversion factor of 683 ± 15% counts per second per micro-Roentgen per hour (μR/h) can be applied to the King Air gross counts after removal of the system background, cosmic rays, and the contribution from natural airborne radon and thoron daughters. The system background consists of natural radionuclides in the crystals and aircraft structure. The total contribution of all sources of background counts can be determined if a large body of water (greater than 500m wide) is present in the survey area. The water background data is subtracted from the gross counts measured over the survey area. The airborne background generally does not vary significantly over the survey area during the 3-4 hour flight.

The cosmic ray exposure rate, as determined from the air pressure data, is then added to exposure rate due to radionuclides of ground origin in order to obtain the total exposure rate at the 1m level.

5.1.1.2 Altitude Compensation

The normal King Air survey altitude is 152m (500 ft) above terrain. The aircraft can fly at this altitude with maximum field-of-view and sensitivity for the detector system, while retaining an adequate safety factor for an aircraft malfunction and for avoiding tall obstructions.

To compensate for count rate variations due to altitude changes, the gamma ray data are normalized to the nominal survey altitude on a second by-second-basis. The effective relaxation length* for the spectrum of gamma rays from normal background radioisotopes is approximately 177 meters, depending on the air density. The relaxation length in terms of air mass is 15.39 grams of air. All data are normalized to 16.0 grams of air using an attenuation coefficient of 0.065 cm^2/gram:

*The relaxation length is defined as the path length (or equivalent air blanket thickness, in grams) through which gamma rays would travel before being reduced to an intensity of 1/e, where e = 2.718 is the base of the natural logarithm.

$$C = Be^{-0.065(16.0 - \rho A)}$$

where

B = count rate at altitude A

ρ = air density

C = normalized count rate.

Altitude compensation coefficients have not yet been determined for the helicopter system.

5.1.1.3 Dead Time Correction

The analog-to-digital converter (ADC) dead time is recorded every second. The gross count and spectral data are corrected for counting losses due to dead time in the ADC.

Typical counting rates at 500 feet above terrain are between 4,000 and 6,000 counts per second. Dead time losses at these counting rates are less than 5%. The ADC can process counting rates up to 100,000 counts per second with reliable dead time correction, good spectral resolution and very little smearing due to pulse pile-up effects.

5.1.1.4 Comparison of Repeat Surveys

The surveillance capabilities of the older, less-sophisticated Twin Bonanza ARMS system have been demonstrated at numerous commercial nuclear power stations and ERDA sites. Reproducibility of the survey data is better than 1.0 μR/h in the exposure rate at one meter above terrain.[13] The computer software compares approximately 5000 data points acquired on each survey on a point-by-point basis. The computer locates data points from the two surveys that were acquired in the same area, within the field-of-view of the detector system (500m). The mean and standard deviation are computed for the observed differences in terrestrial exposure rates between the two surveys. Observed differences are plotted on an overlay map for the facility to expedite subsequent field measurements with ground-based instruments.

Figure 19 is an example of a repeat survey of a nuclear facility where the mean exposure rate difference between the two surveys was 0.15 ± 0.75 μR/h.

5.1.2 Man-Made Contaminants

5.1.2.1 Man-Made Gross Count Indicator

A sensitive method has been derived to detect man-made anomalies in the observed gamma ray data. The spectrum is divided into two time-resolved (1-sec or 3-sec) windows (see Figure 20). The lower energy window #1 (0.05 to 1.39 MeV) bounds the γ-ray energies of most common man-made isotopes. It also contains contributions from natural isotopes. The higher energy window #2 (1.40 to 3.05 MeV) is set above the energy of the γ-rays from the common man-made isotopes and thus has contributions primarily from the dominant natural radioelements (^{40}K, ^{214}Bi, ^{208}Tℓ).

The total gross count contributed by the man-made isotopes (MMGC) is the difference between the total counts in window #1 and the natural counts in window #2. Conceptually:

$$\text{MMGC} = \sum_{0.05}^{1.39} (\text{man-made} + \text{natural}) - \sum_{1.40}^{3.05} (\text{natural})$$

The natural γ-ray spectral shape is relatively insensitive to variation in flight altitude, concentraion of airborne radium and thorium daughters, and the mix and concentration of natural radioelements in the soil. This implies that for background spectra, the low energy

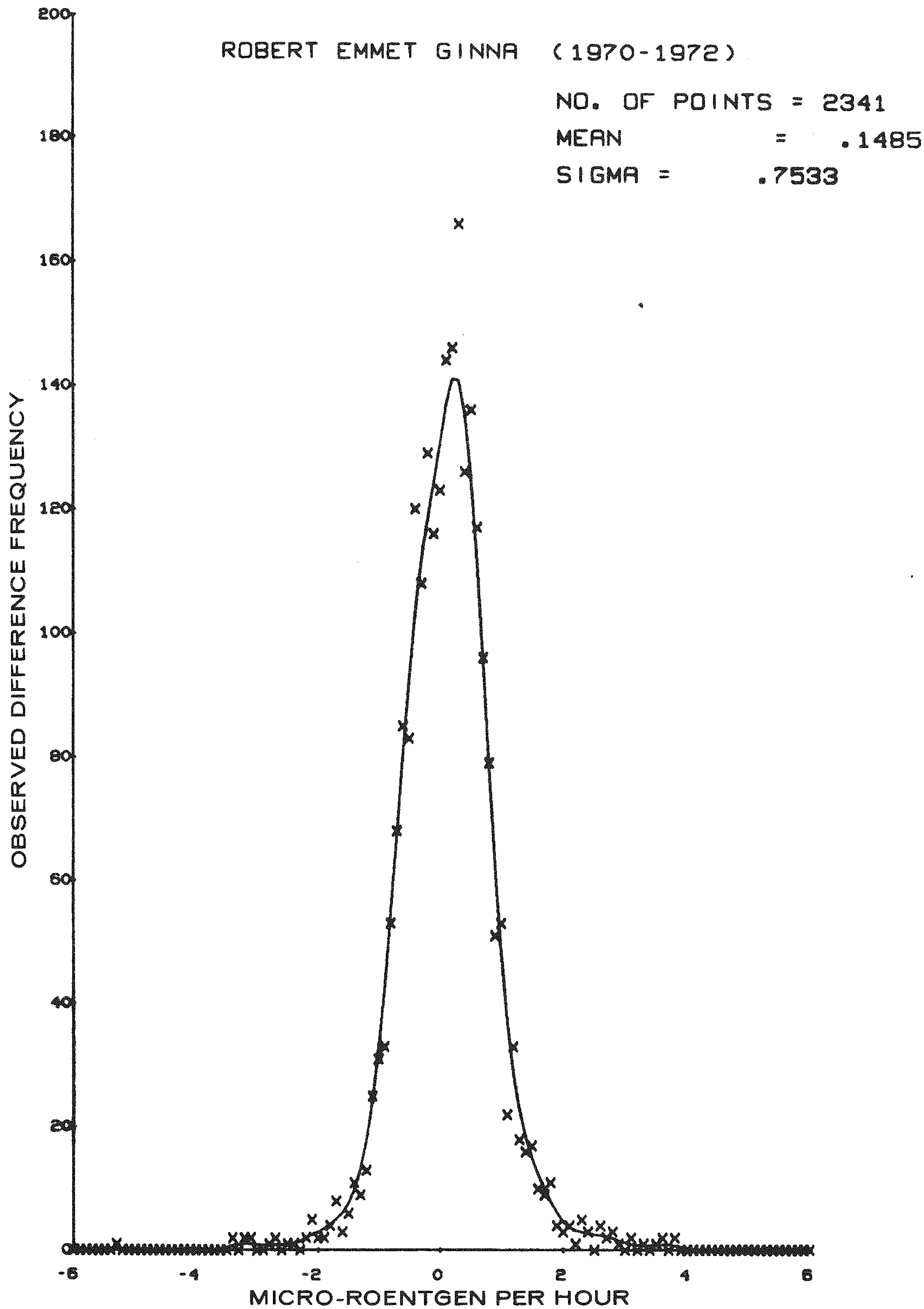

Figure 19. A comparison of the 1970 and 1972 Ginna surveys.

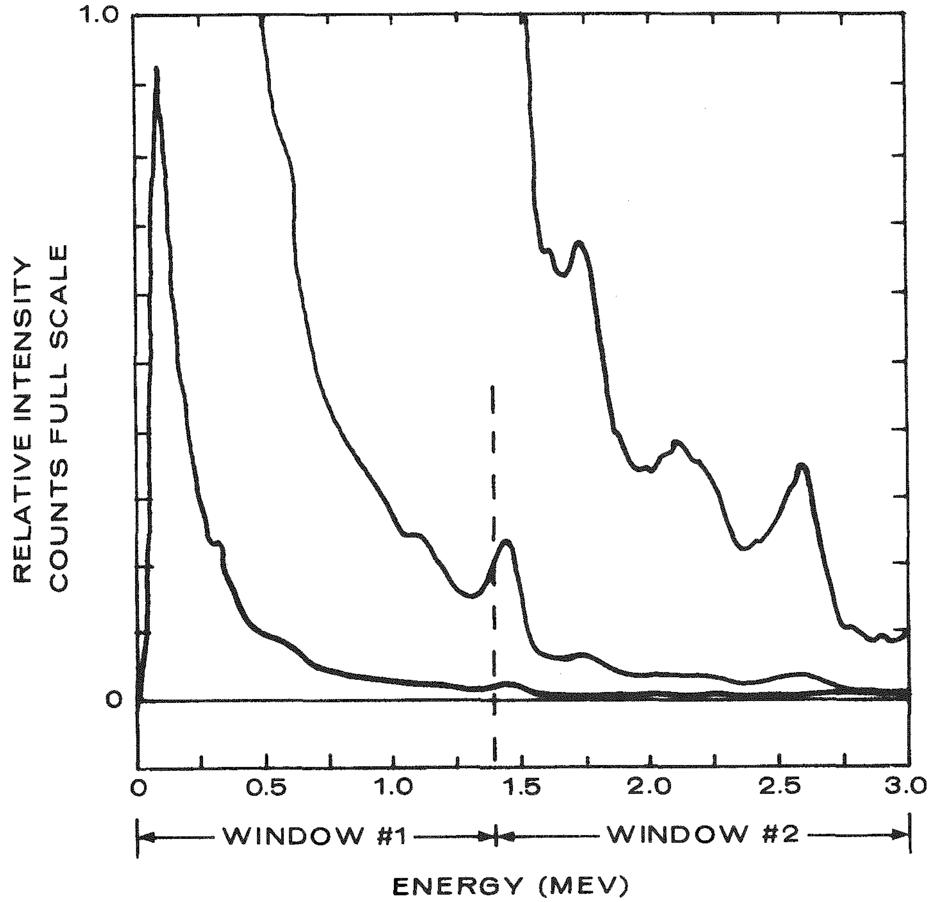

Figure 20. Window settings for the gamma pulse height spectra used to provide a normalizing factor to separate man-made radio-element contaminants from the natural background.

window counts are proportional to the high energy window counts.

$$\sum_{0.05}^{1.39} \text{(natural)} \approx C \sum_{1.40}^{3.05} \text{(natural)}$$

MMGC can then be written in terms of measurable quantities:

$$\text{MMGC} = \sum_{0.05}^{1.39} \text{(man-made + natural)} - C \sum_{1.40}^{3.05} \text{(natural)}$$

The mean value of MMGC is thus zero for uncontaminanted areas. For most areas, which have man-made isotopes whose energies are bounded by window #1, the value of MMGC is the true gross count due to man-made isotopes. In those rare instances where man-made isotope energies extend into window #2 or when very unusual natural anomalies occur, MMGC no longer indicates absolute man-made contribution. It is still an excellent indication that a significant spectral shape perturbation has occurred.

The MMGC stripping technique enhances the data analysts' capability to detect subtle changes in the surface terrestrial radiation due to man-made isotopes over a spatially-varying (in intensity) natural background radiation field. Figure 21 demonstrates the enhancement of signals from man-made isotopes using the method discussed above. (Notice the two man-made sources at the start of the flight line that were obscured by variations in the natural background level.) The gross count data, consisting of counts between 0.05 and 3.05 MeV, vary a factor of 2 or 3 or about an average of 4000 counts/sec, while the MMGC data are typically 0 ± 300 counts per second (at one standard deviation).

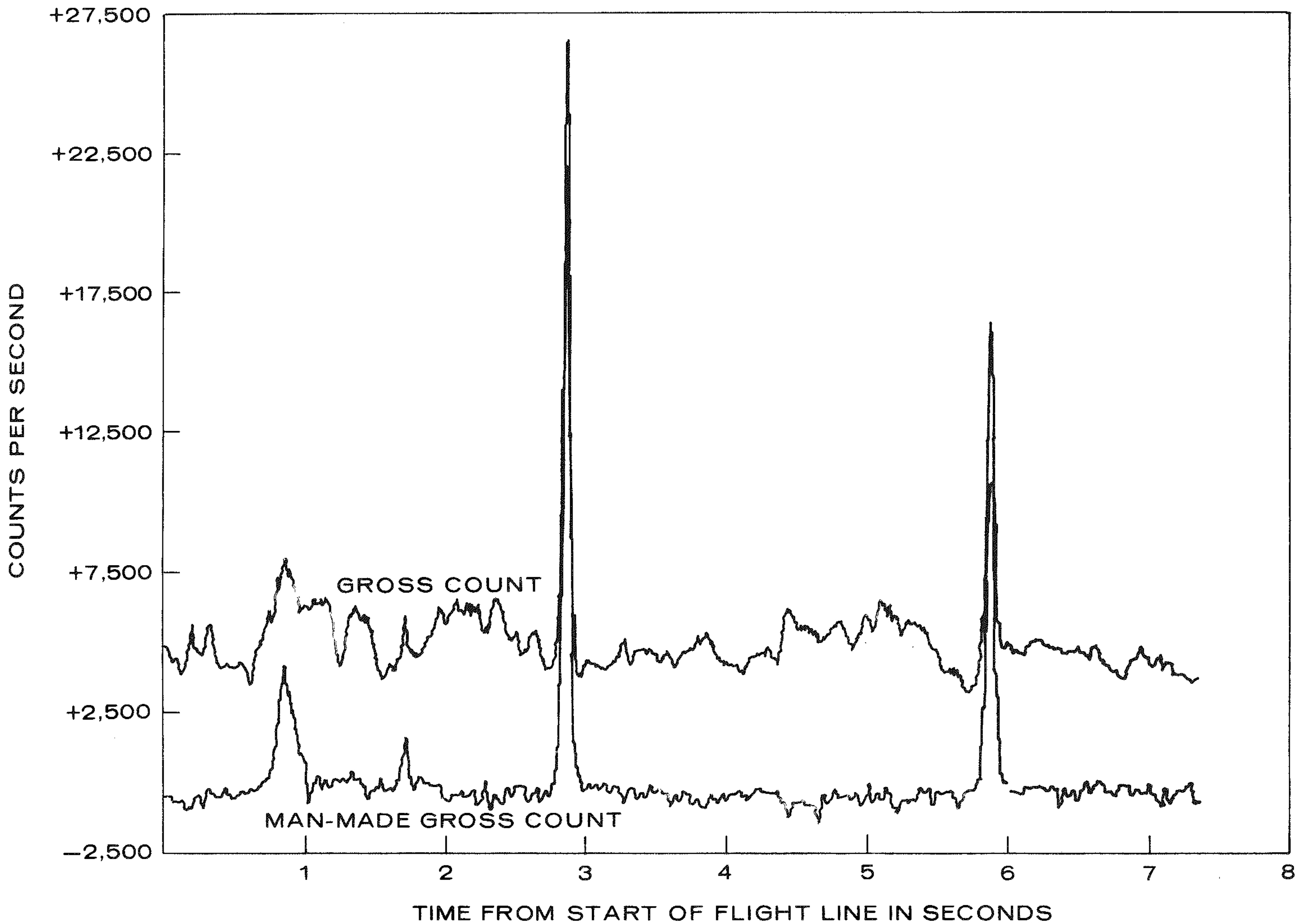

Figure 21. Example of the enhancement of the detectability of man-made contaminants over the fluctuating natural background radiation, employing the MMGC stripping technique.

The constant C can be determined in an area close to, or in, the survey area that is representative of normal background. Careful inspection of the spectral data in the background reference area is imperative to ensure that the area has not been contaminated, and that it is typical of the radiation from the naturally-occurring radioelements in the survey area. The minimum detectable level of man-made radioelements can be determined by the statistical variation of the MMGC in the background area. An example of the MMGC from the Savannah River Plant Survey[6] is shown in Figure 22. The data in the A region correspond to normal background intensity levels, while the minimum detectable activity (B level) is set at ±3 standard deviations (99 percent confidence level) for the MMGC measured over the background reference area. Less than one percent of the data, therefore, should yield erroneous B levels due to the statistical variation in the count rate. All spectral data for MMGC data points of B or greater are carefully analyzed. The C level is set a factor of two above the B, and the D level a factor of two above the C, etc. The levels generally indicate a positive MMGC attributable to man-made isotopes since the majority of the man-made isotopes observed in environmental surveys emit gammas with energies below 1.39 MeV. A "@" level on the plotted isopleths is set for negative values of the MMGC which indicates spectral distortion due to unusual isotopes, statistical variations, etc.

5.1.2.2 Exposure Rate Conversion Factor

Where man-made contaminants exist, a photopeak window count-rate approach is used to arrive at accurate conversion factors. Stripping procedures are used to remove all counts from this photopeak window except those from the contaminant of interest. This

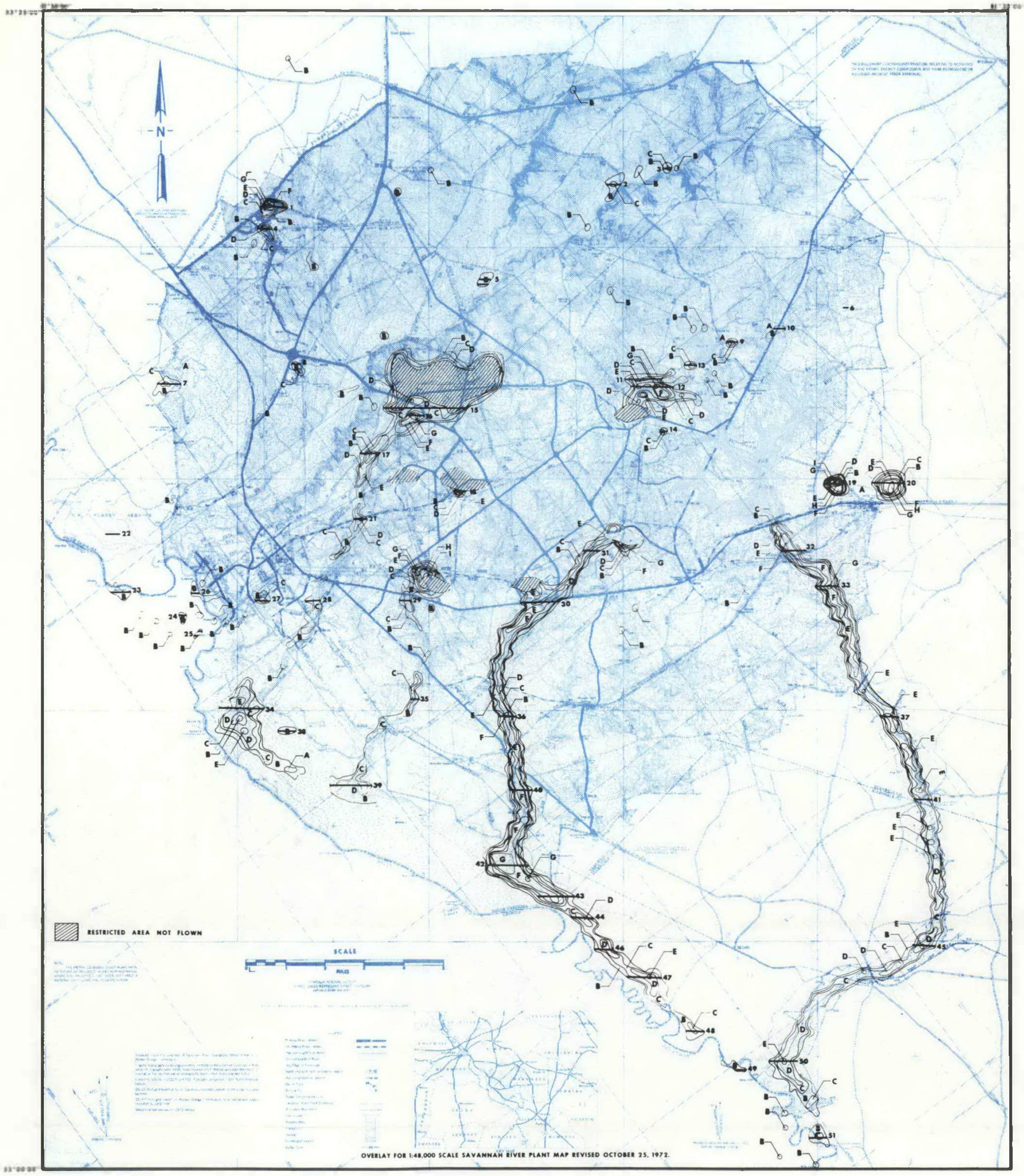

Figure 22. Map of the man-made gross count isopleths for the Savannah River Plant survey.

process, as applied to ^{60}Co and ^{137}Cs, is described in the next section. Section 5.1.2.2.2 describes the process by which the stripped photopeak count rates are converted to concentrations and exposure rates due to each specific contaminant. Stripping processes and conversion factors for ^{60}Co and ^{137}Cs are discussed here, but similar procedures can be applied to any mix of isotopes.

5.1.2.2.1 Stripping Procedures for ^{60}Co and ^{137}Cs

Equations can be formulated to extract the ^{60}Co and ^{137}Cs contributions to the measured spectrum. Three windows described below are used for this purpose. Figure 23 shows the position of these windows on the complete recorded spectrum.

Window	Energy Range (MeV)	Description
A	0.60-0.74	^{137}Cs
B	1.40-3.05	Natural background
C	1.10-1.39	^{60}Co

Again, the natural background contribution is removed from windows A and C by monitoring the counts above 1.40 MeV (window B). Shapes for ^{60}Co and ^{137}Cs pulse height spectra and resulting stripping coefficients are obtained by comparing natural background spectra with spectra gathered over areas containing predominantly one or the other contaminant.

The pulse height energy window encompassing each photopeak generally contain contributions from the Compton tails of higher energy gammas from other isotopes. A constant α can be determined for the particular survey area for the counts from higher energy natural isotopes which appear in the ^{60}Co photopeak window.

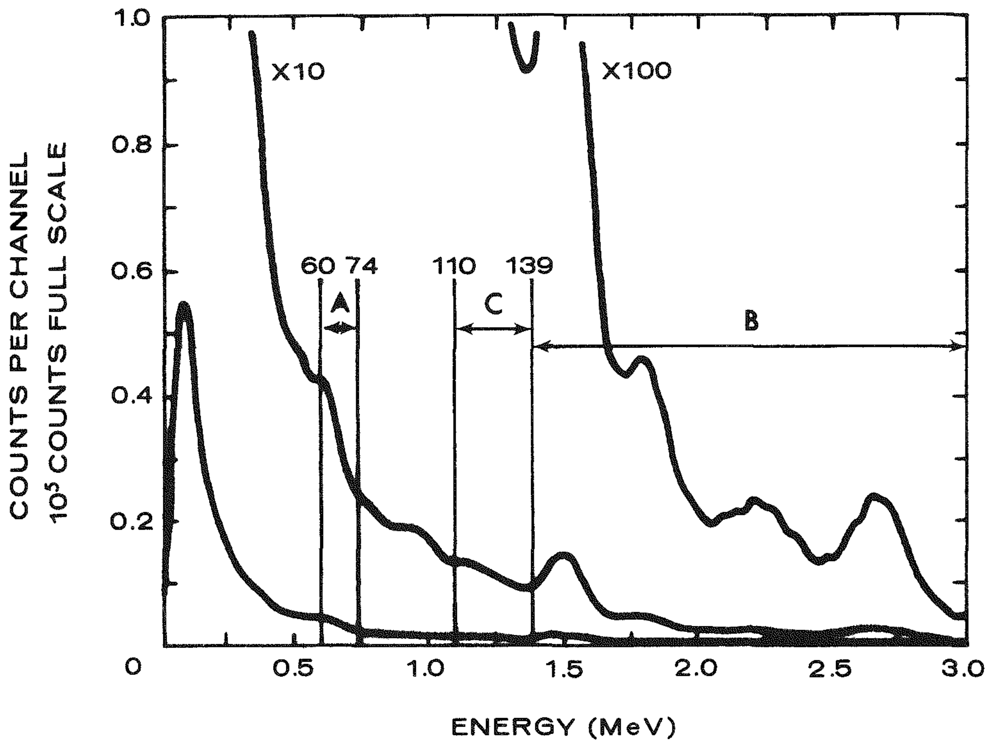

Figure 23. Energy windows superimposed on a "typical" background spectrum. The windows are for CS-137(A), Co-60(C), and background (B). The channel numbers indicated have an energy coefficient of 10 keV per channel.

The ^{60}Co extraction is simply the removal of the background counts due to window B that appear in window C. The net counts due to ^{60}Co can be written as:

$$Co = C - \alpha B \tag{5-1}$$

The ^{137}Cs extraction has to take into account the possible presence of ^{60}Co. The ^{137}Cs window A contains counts from the Compton tails of photopeaks in the natural background and of any ^{60}Co that is present. Using β for the ratio of the natural background counts from window B that appear in the ^{137}Cs window A and γ for the number of counts from window C due only to ^{60}Co, the net counts due to ^{137}Cs can be written as:

$$Cs = A - \beta B - \gamma C \tag{5-2}$$

Substituting the counts due to ^{60}Co from Equation (5-1) for C, the ^{137}Cs extraction is:

$$Cs = A - \beta B - \gamma(C - \alpha B)$$

or

$$Cs = A - \gamma C + B(\alpha\gamma - \beta)$$

The extraction coefficients α and β must be computed for each survey area and detector system.

5.1.2.2.2 Calibrations

In order to convert the aerial measurement of the number of gamma photopeak counts to an exposure rate one meter above the ground, it is necessary to consider two important factors:

(a) the response of the NaI detectors to photons versus the angle of incidence (θ) from the vertical (see Figure 24), and
(b) the distribution of radionuclides in the soil.

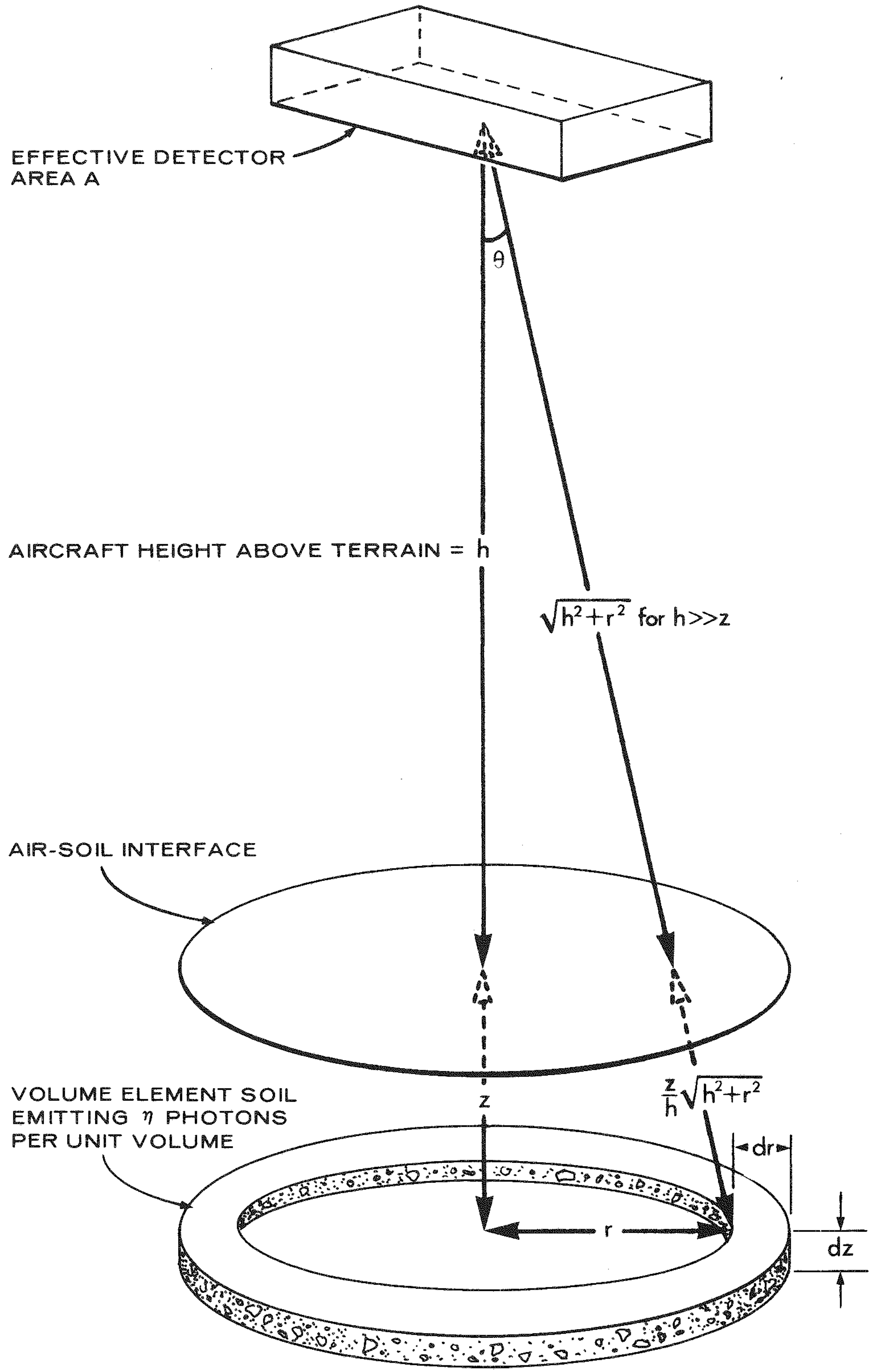

Figure 24. Definition of geometric parameters relating to the exposure rate conversion factors.

Two limiting cases of detector response will be considered: isotropic (uniform response for $0 \leq \theta \leq 90°$) and cosine response (decreases to zero at $\theta = 90°$). Similarly, two limiting cases of source distribution in the ground will be considered: uniform (isotopes are uniformly distributed, both horizontally and vertically) and planar (isotopes are uniformly distributed on the surface of the ground). Four conversion factors are calculated with these assumptions, which can be combined to yield an approximate exposure rate conversion factor.

The counting efficiency of the airborne sodium iodide crystal detector package was determined by measuring the signal minus background count rates while flying over calibration sources of known strength. The photopeak window count rate, N_c, when flying directly over a calibration source, can be written as

$$N_c = \frac{sA}{4\pi d^2} e^{-d/\lambda_a} \qquad (5\text{-}3)$$

where

d = distance between the point source and the detector (cm),

s = calibration source strength (photons/sec),

λ_a = photon mean free path in air (cm),

A = effective detector area (cm^2). This term includes an efficiency factor.

Case I. If we now assume a flux η_s (photons/sec-cm^2) at the ground surface level from an infinite planar radioactive source uniformly distributed over a ring of width dr on the ground and we assume an isotropic detector response, we can calculate $N_{s\,I}$ (the number of photons per second in the photopeak window detected by the isotropic detector at an altitude h over a planar surface source).

$$dN_{s1} = \frac{\eta_s A e^{-\sqrt{h^2 + r^2}/\lambda_a}}{4\pi(h^2 + r^2)} 2\pi r\, dr \qquad (5\text{-}4)$$

where

r = radius of the ring of differential area.

Integrating over $0 \le r \le \infty$ we obtain:

$$N_{s1} = \frac{\eta_s A}{2} E_1 (h/\lambda_a), \qquad (5\text{-}5)$$

where $E_1 (h/\lambda_a)$ is an exponential integral of the first kind. By eliminating A between Equations (5-3) and (5-5) we obtain the gamma flux η_s at the ground surface.

$$\eta_s = \left[\frac{s\, e^{-d/\lambda_a}}{2\pi d^2 N_c E_1 (h/\lambda_a)}\right] N_{s1} \qquad (5\text{-}6)$$

The expression in brackets contains known parameters, for the conversion of counts measured by the detector to an infinite planar source distribution (photons/cm^2-sec).

Case II. If the detector response is a function of the cosine of the angle θ between the source direction from the detector and the vertical, and additional factor of $\left(h/\sqrt{h^2 + r^2}\right)$ is included in the expression corresponding to Equation (5-4). For this second case, we write the expression for N_{sc} (the total number of photons per second detected in the photopeak window).

$$dN_{sc} = \frac{\eta_s A h e^{-\sqrt{h^2 + r^2}/\lambda_a}}{4\pi(h^2 + r^2)^{3/2}} 2\pi r\, dr \qquad (5\text{-}7)$$

Hence the count rate for a cosine-response detector is

$$N_{sc} = \frac{\eta_s A}{2} E_2 (h/\lambda_a), \tag{5-8}$$

where E_2 is an exponential integral of the second kind.

By eliminating A between Equations (5-3) and (5-8) we obtain:

$$\eta_s = \left[\frac{s\, e^{-d/\lambda a}}{2\pi d^2 E_2(h/\lambda a) N_c}\right] N_{sc} \tag{5-9}$$

Case III. Now let us consider a third case where the gamma flux η_U is from a source uniformly distributed both on the surface and in the vertical z direction, from ground level to infinite depth. For this third case, we assume that the detector has isotropic response. The number of gamma rays detected in the photopeak window N_{Ui} is

$$d^2 N_{UI} = \frac{\rho \eta_U \; A\, e^{-\sqrt{h^2 + r^2}/\lambda a} \; e^{-z\sqrt{h^2 + r^2}/\lambda_s h}}{4\pi (h^2 + r^2)} \, 2\pi r \, dr \, dz \tag{5-10}$$

where

ρ = soil density (g/cm^3)

η_U = source strength $\left(\frac{\text{photons}}{\text{sec} \cdot \text{g}}\right)$

λ_s = mean free path of the gamma rays in soil (cm)

h = height of the detector above the ground (cm)

λ_a = mean free path of the gamma rays in air (cm).

r = radius of the ring of differential volume.

Integrating over r and z we obtain:

$$N_{U\,I} = \frac{\rho \eta_U \lambda_s A}{2} E_2 (h/\lambda_a), \qquad (5\text{-}11)$$

where E_2 is again an exponential integral of the second kind.

We note that $\lambda_s = 1/\mu$, where μ is the linear attenuation coefficient. We eliminate the effective area A using Equations (5-3) and (5-11) to obtain:

$$\eta_U = \left[\frac{\mu}{\rho} \frac{s\, e^{-d/\lambda_a}}{2\pi d^2 N_c E_2 (h/\lambda_a)} \right] N_{\mu I} \qquad (5\text{-}12)$$

Case IV. Finally, if we assume that the detector response is a function of the cosine of the angle between the source and the normal to the detector surface area, an additional factor of $(h/\sqrt{h^2 + r^2})$ is included in the expression corresponding to Equation (5-10):

$$d^2 N_{\mu c} = \frac{\rho \eta_U \, Ahe^{-\sqrt{h^2 + r^2}/\lambda_a} \; e^{-z\sqrt{h^2 + r^2}/\lambda_s h}}{4\pi (h^2 + r^2)^{3/2}} \, 2\pi r\, dr\, dz, \qquad (5\text{-}13)$$

where again:

η_U = gamma source strength $\left(\frac{\text{photons}}{\text{sec} \cdot \text{g}}\right)$.

By integrating and eliminating A we obtain:

$$\eta_U = \left[\frac{\mu}{\rho} \frac{s\, e^{-d/\lambda_a}}{2\pi d^2 N_c E_3 (h/\lambda_a)} \right] N_{\mu I}, \qquad (5\text{-}14)$$

where E_3 is an exponential integral of the third kind.

The expressions derived in these sections convert photopeak count rates to ground concentrations. The data of Beck, et al,[14] can be used to convert ground concentrations to exposure rate at the 1m level. Their computations included the contributions from gamma rays scattered in both the soil and air and were determined from a polynominal solution to the gamma ray transport equation. The composition by weight of the soil used in the calculations is shown in Table 3.

Table 4 lists Beck's conversion factors (J column), gamma ray mean free path through air (λ_a column) and soil mass attenuation coefficients (μ/ρ column) for the source geometries of interest and the two radionuclides previously discussed. These values can be combined with measurements and calculations using the previously derived equations to arrive at the King Air system exposure rate conversion factors (CF) at 500 ft altitude (Table 5). An average value between an isotropic and cosine response has been assumed, introducing errors of ±15 percent. Note that these King Air system conversion factors are sensitive to source distribution in the soil, making soil sampling measurements an attractive support function where man-made contaminants exist.

Conversion factors for the H-500 system at the same altitude should not differ from these by more than 20%. Conversion factors for lower altitudes, where the helicopter normally flies, are less sensitive to source distribution.

The previous discussions are based on the two limiting cases of source distributions. Beck, et al have also calculated exposure rates due to source distributions that decrease with selected exponential relaxation depths in the soil. These data can be combined with calculations using an HP65 computer program[16] to obtain exposure rate conversion factors for source distributions between the two limiting cases.

Table 3. Composition by Weight of Soil Used in Beck, et al's Calculations

Al_2O_3	13.5%
Fe_2O_3	4.5%
SiO_2	67.5%
CO_2	4.5%
H_2O	10.0%

Table 4. Constants Used for Exposure Rate Conversions

Isotope	Distribution	J	λ_a (cm)	μ/ρ for soil[15] (cm^2/g)
^{137}Cs	surface	3.4(μR/h)/ (photons/cm^2-sec)	13,000	---
	volume	19.6(μR/h)/ (photons/gm-sec)	13,000	0.078
^{60}Co	surface	5.8(μR/h)/ (photons/cm^2-sec)	17,000	---
	volume	38.4(μR/h)/ (photons/gm-sec)	17,000	0.057*

*An average mass attenuation coefficient, μ/ρ = 0.057 cm^2/g, was obtained for photons of energy E_{γ_1} = 1.333 MeV and E_{γ_2} = 1.172.

Table 5. A-100 Conversion Factors at 152m Altitude and and a Velocity of 77m/sec

CONVERSION SCALE				
Distribution cm	^{137}Cs		^{60}Co	
	CF	MDA	CF	MDA
Surface	0.0416	3.2	0.0732	4.6
0.1	0.0374	2.9	0.0665	4.2
1.0	0.0288	2.2	0.0503	3.2
2.0	0.0269	2.1	0.0455	2.9
3.0	0.0260	2.0	0.0443	2.8
10.0	0.0251	2.0	0.0402	2.5
Volume	0.0251	2.0	0.0389	2.5

CF – Conversion Factor (counts per second per μR/h)

MDA – In units of μR/h at the 99% confidence level

Surface – Infinite planar source with no vertical distribution

Volume – Source is uniformly distributed from the surface to infinity

Other distributions are expressed in terms of relaxation depths for an exponentially distributed source

The Minimum Detectable Activity (MDA) for a detector system depends on its ability to sense subtle changes in the terrestrial radiation due to man-made isotopes in the presence of a spatially-varying natural background radiation field. The MDA for the King Air system was calculated by measuring the statistical variation of the stripped data for ^{60}Co and ^{137}Cs while flying over a typical area of varying concentrations of natural isotopes producing exposure rates between 4 and 6 μR/h. The MDA was set at ±3 standard deviations (the 99% confidence level) for a positive identification of these isotopes. Less than 1% of the data, therefore, should yield erroneous indications.

The MDA's for the King Air system (columns 3 and 5 in Table 5) were assumed to be the product of three standard deviations times the conversion factors shown in columns 2 and 4 of the same table. The MDA's were calculated using three-second multichannel data. A weighted, moving average can be applied to smooth the survey data, reduce statistical variations, and thereby reduce the MDA. Generally, a seven second filter is used for the King Air data, which integrates the data over 540 meters, the field-of-view of the detector system. Longer time filters can be applied to eliminate spurious level changes due to statistics; however, this procedure can reduce spatial resolution if carried too far.

5.1.2.3 Comparison of Aerial and Ground Surveys

Considerations for relating airborne results to ground based measurements are discussed below. At 150 meters above terrain, the airborne detectors measure radiation from an area on the ground about 300 to 500 meters in diameter. The situation can be illustrated by visualizing that over 10^4 tons of surface soil are sampled in a single one-second airborne measurement. The airborne survey results, then, represent a pseudo-average over a large area of investigation. To obtain such an average by ground sampling requires a multitude of individual measurements. In attempting to compare aerial radiometric data with ground-based measurements, one must also consider the isotope's vertical distribution in the soil, the spatial distribution contamination and terrain effects, such as ground roughness or ground cover. The airborne detector cannot readily distinguish between a point source and a source distributed over an area whose linear dimensions are comparable to the spatial resolution as controlled by the aircraft altitude. Lower altitude flights and closer spaced lines can provide better resolution of localized "hot spots." Previous surveys have shown that a significant improvement in revealing detailed information of an area can be obtained by flying at lower altitudes (50 m) and closer line spacing (50 m) with the H-500 helicopter.

5.2 AIRBORNE SOURCES

Stripping procedures similar to those described previously are used for airborne sources. Conversion factors that relate the stripped photopeak count rates to airborne concentrations are calculated on the assumption that the aircraft is surrounded by a cloud of activity that is terminated by the surface of the ground. Thus, conversion factors will depend on altitude. Point source calibrations are made with the source both above and below the detectors, so that corrections can be made for shielding by P. M. tubes in the upward direction. The proper conversion factor is assumed to be an average between a cosine and an isotropic response for sources both above and below the detectors. Uncertainty due to the use of the average value decreases with altitude and is about 30% at 500 feet.

As with terrestrial sources, MDA's for airborne distributions are controlled by (1) counting statistics in the windows selected for monitoring contaminants and background, and (2) the effectiveness of the stripping technique in suppression of unwanted signals. As an example, the MDA for ^{41}Ar at 1000 ft altitude is a few tens of pCi/m^3 when windows must be set to suppress not only natural terrestrial background changes but also contributions from ^{60}Co, which has a photopeak near the 1.29 MeV photopeak from ^{41}Ar.

5.3 DISCRETE SOURCES

A background compensation technique is also advantageous when processing data taken in searches for discrete sources. One approach is to use the same photopeak window used in the measurement of terrestrial distributions, although this technique may be more specific than necessary and not give maximum sensitivity for shielded sources. Figure 25, which shows peak to total ratios for buried sources, illustrates the fact that a portion of the photopeak photons lost by attenuation due to shielding can be recovered by sensing the lower energy scattered photons. However, it should be borne in mind that wide energy windows also accept more background photons and increase statistical fluctuations on which the source signal is superimposed. Optimum windows for discrete source searches are still being investigated.

The minimum-detectable, unshielded point source activity of ^{60}Co and ^{137}Cs was determined for the windows described in Section 5.1.2.2.1 by comparing source signals with measured variations in background signals over "typical" areas flown at 500 ft with the King Air system. The detector efficiently in the photopeak

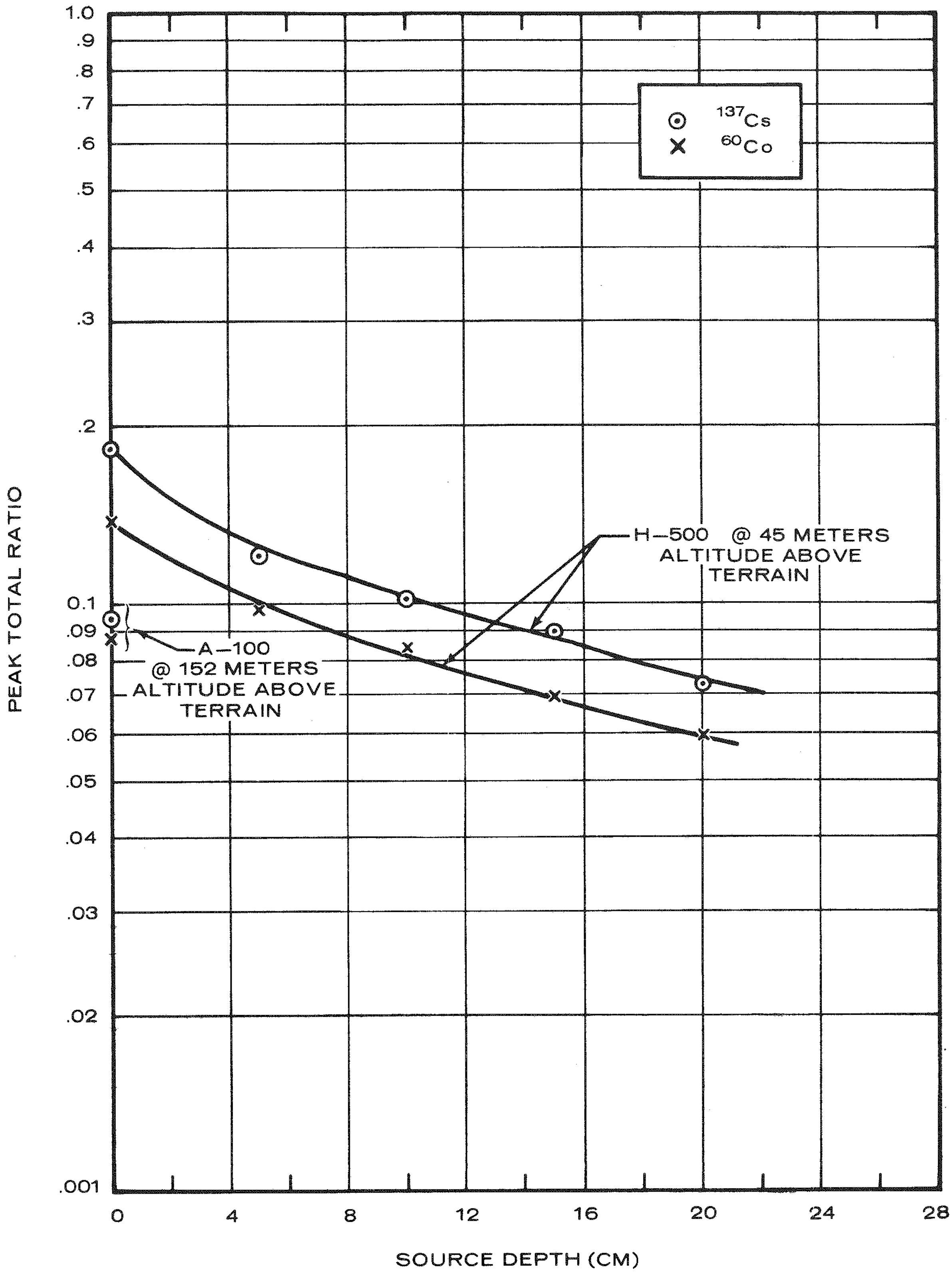

Figure 25. Peak-to-total ratio versus point source depth in soil from experimental data.

window was determined by flying directly over calibrated sources. Peak counting rates for lateral displacements were calculated on the basis of a response proportional to $\left(1 + \alpha \frac{d}{h}\right) \frac{he^{-r/\lambda}}{r^3}$ where r = distance of closest approach, d = lateral displacement, λ = gamma ray mean free path through air, and α = ratio of the side area to bottom area of the crystal arrays. Use of this expression assumes that the peak signal is proportional to the cosine of the angle of incidence on the crystal faces. The side area of the detectors is estimated to be 50% of the bottom area from the geometrical arrangement of the crystals in the detector packages. The source activity giving a peak signal equal to three times the standard deviation of the stripped "typical" background signal was assumed to be detectable. Results from these measurements and calculations are shown in Figure 26.

All measurements were made with one-second data accumulation time, which is not optimum for these velocities and distances of closest approach. Optimum data accumulation times are approximately equal to the full width at half maximum of the signal profile, representative ones of which are shown in Figure 27. These profiles were calculated for unshielded sources overflown at typical King Air velocities.

Sources not detectable with the King Air system may be detectable with the H-500 system, since distances of closest approach can never be less than the search altitude, which is 500 ft for the King Air and may be 100 ft for the helicopter. The helicopter also has the advantage of slower speed with longer "time over target" to accumulate source data. The price paid for increased detectability is a slower search rate. Theoretical minimum detectable activities can be calculated for both systems according to procedures outlined in Reference 16.

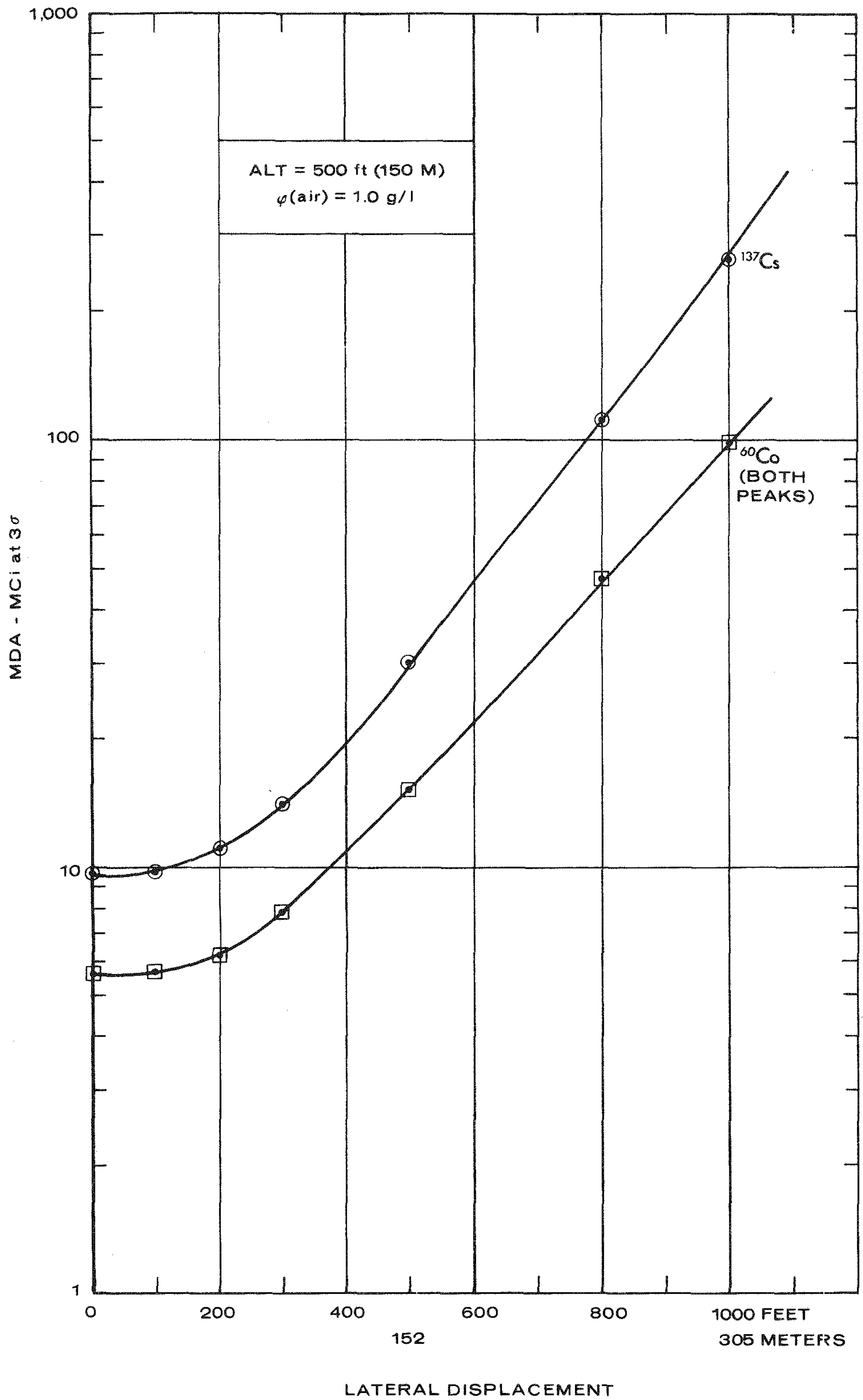

Figure 26. Minimum detectable activity versus lateral displacement of source from distance of closest approach.

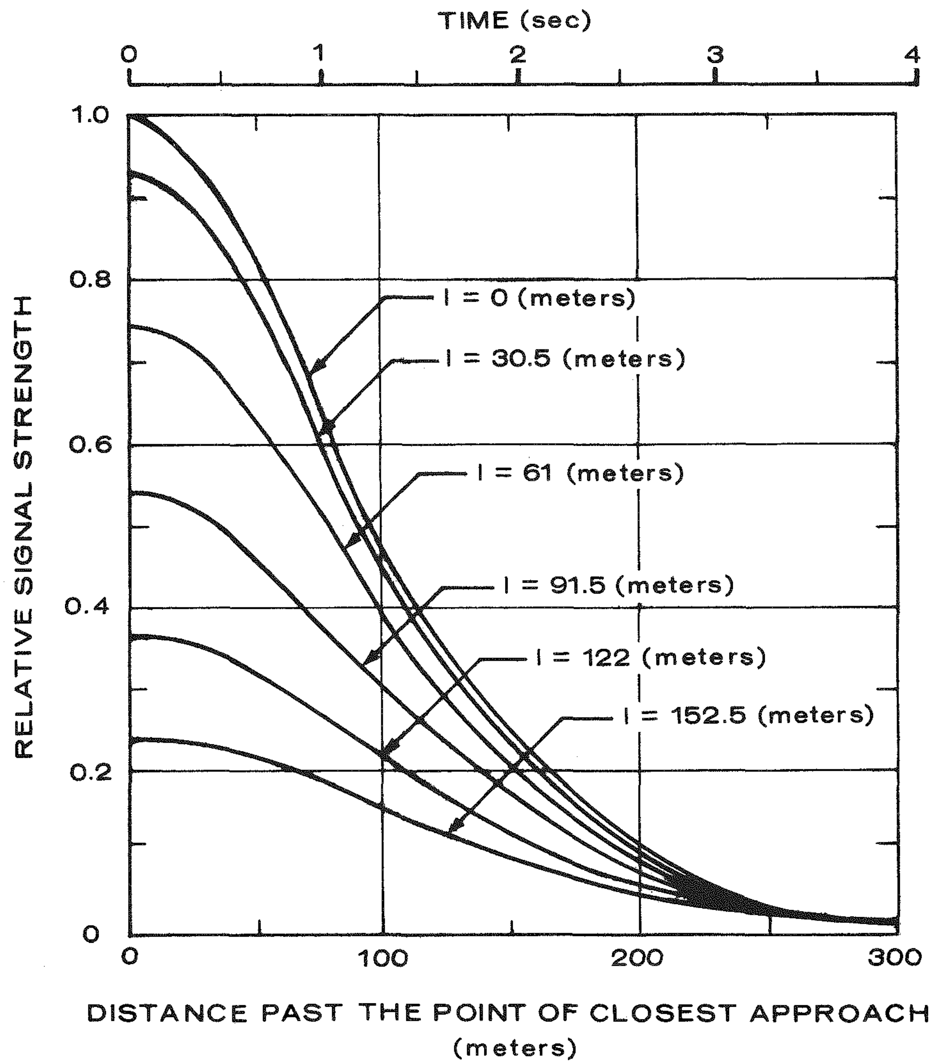

Figure 27. Theoretical calculations of the relative signal strength from a point Cs-137 source at various lateral displacements (l) versus the distance past the point of closest approach.

6. SUMMARY

An integral part of the ARMS program is continuous effort to improve electronic design of data acquisition equipment, data analysis techniques and the navigation instruments used for the precision flying required during aerial surveys.

The latest micro-processers are being integrated into a new REDAR system to reduce the physical size, weight and power required.

The computer software is updated as better methods of filtering, smoothing and stripping the gamma ray spectral data are developed. In the near future, the spectral shape of the aircraft background, airborne radon, cosmic rays and the individual natural isotopes (^{40}K, ^{214}Bi and ^{208}Tl) will be established. The removal of the aforementioned spectra will enhance the detection of man-made isotopes and provide a quantitative measurement of the individual natural isotopes.

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