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HELICOPTER CLOSE-ORDER
FORMATION KEEPING SYSTEM

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For
Division of Isotopes Development
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FINAL REPORT

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PREFACE

The work performed under this contract consisted of analytical and experimental studies to determine the feasibility and evaluation of the use of nuclear radiation and X-ray radiation in helicopter close-order formation keeping. The chief contributors to the program are listed below.

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ABSTRACT

Under Contract No. AT(11-1)-1471, with the United States Atomic Energy Commission, the Industrial Nucleonics Corporation has designed an isotopic gamma ray signaling system to permit close-order formation keeping in helicopters within a range of from 50 to 500 feet. The performance on this contract was from April 1965 to April 1966. During the contract, a successful ground demonstration of the Helicopter Formation Keeping System was performed. The system concept envisions a modulated gamma ray source and fixed gamma ray detector array on each helicopter. This feasibility demonstration proved that a fixed gamma ray detector array can differentiate between signals from two modulated gamma ray sources. The signals were processed to provide a display similar to a PPI-type display. The display indicated the proper bearing and spacing between the two sources and the detector array.

Phase II has been authorized to develop and demonstrate a flight model of the system with Navy participation through the Atomic Energy Commission.

1.0 SUMMARY

Under Phase I of Contract AT(11-1)-1471 between the United States Atomic Energy Commission and the Industrial Nucleonics Corporation, the utilization of nuclear or X-ray radiation in helicopter close-order formation keeping has been explored. The program was subdivided into an analytical study followed by an experimental feasibility demonstration of a ground system consisting of a detector and two sources.

Under the analytical study, consideration was given to the various sources and detector parameters suitable for operation at source-detector distances of 50 to 500 feet. Sources considered were Am-241, Cs-137, Kr-85-U brem, Sr-90-U brem, and X-ray. Co-60 was not considered because it is too difficult to shield and detect. This consideration was condensed into a matrix which permits an approach to be chosen for feasibility tests (see Table 2, page 4-36).

As shown in Appendix II, the information content (number of counts) required for the specified one-sigma accuracy of $\pm 10\%$ in range and angle sets a lower limit of 200 counts per resolving time. For a 3" x 6" detector with 100% detection efficiency, a resolving time of 1/3 second, and an air range of 500 feet (760 mm Hg), one requires a gamma ray source of the order of 30 curies at 60 keV, of the order of 20 curies at 100 keV, and 1 curie at 1.5 MeV (see Figure 3) to supply the desired signal. Detector efficiency and shielding efficiency strongly favor energy ranges below 100 keV (K-band absorption edge). The range of 60 keV to 100 keV is also quite suitable for air transmission.

Nature does not supply a suitable 100 keV source, but comes close for this application in Am-241 at 60 keV and in a Kr-85-U bremsstrahlung source. Concomitantly, any detector development for 60 to 100 keV gamma rays is ideal for use with an X-ray source. The belief that the desire to extend ranges beyond 500 feet in actual applications would require the use of X-ray sources in order to get adequate source strengths, also gave impetus to a low energy development. Consequently, because of the availability and efficiency of development, Phase I was planned around an Am-241 source. This approach provides a small compact light-weight detector and a source which is easily shielded be it nuclear or X-ray. Consequently, detector and electronic data processing equipment were developed under Phase I to be suitable for use with either an X-ray or a low energy γ source.

The X-ray source investigation revealed that no suitable X-ray tube is now available from vendors which emits X-rays in equal intensity over the desired solid angle. Preliminary estimates by vendors indicate that such a development is feasible and that it would require approximately one year at a cost of \$100,000.

During the planning of Phase II, which covers the design and demonstration of an airborne system, two factors arose which altered the course of the program. First was the decision to restrict Phase II to a nuclear source since no suitable X-ray source was readily available, and second was the directive by the Atomic Energy Commission to substitute another material, such as a Kr-85-U bremsstrahlung source for

Am-241 in airborne tests in order to decrease the operation hazard.

This latter decision results in the use of γ and bremsstrahlung rays of energy ranging up to .7 MeV, with a bremsstrahlung peak at 0.095 MeV and another peak at 0.54 MeV produced by the γ rays from Kr-85.

These high energies produce an appreciable increase in the source shield and detector weights over that required for energies of 100 keV and lower. One centimeter of NaI detects over 60% of the energy in a 200 keV gamma ray beam, so the 6" detector developed by Industrial Nucleonics still behaves as a surface detector for energies below this level. This property makes the detector developed suitable for use with a Kr-85-U brem source.

The datum of 200 counts per resolving time is for one sigma. If two-sigma accuracy is required, this count rate must be increased by a factor of four. There are other factors which tend to either increase or decrease the size of the source. The build-up factor tends to decrease the size of the source since the source size required varies inversely as the build-up factor for the distance considered. The measurements taken indicate that this factor does not rise above the value of 2 for the radiation considered. Chopping of nuclear radiation from a radioisotope for source identification purposes reduces the transmitted radiation to one-half its original intensity, and thereby doubles the source size required. All internal absorptions in source materials or source holders tend to increase the amount of radioactive source material required.

The discussion above has assumed digital data in principle from source to display. If analog techniques are used either in the data processing or in the method of display, there will be additional errors added over those produced by the statistical considerations given above. These errors always tend to increase the source strength required so that the statistical error will be only a portion of the total error. In summary, for nuclear sources it may be said that the factors other than source statistics tending to increase source size dominate those tending to decrease source size. Thus, one may take the limitation set by source statistics as a lower limit on source size required.

The study to date indicates that two approaches can be used to meet the specifications desired. One approach uses the Kr-85-U bremsstrahlung source and the other uses an X-ray source. Both approaches utilize the same type of stationary detector. The two approaches vary the weight between the source and detector, but tend to keep the overall weight equal.

The final choice for an operational helicopter formation keeping system between radioisotope sources and X-ray sources may well depend on logistic, operational, and political factors. For example: (1) modulated radioisotope sources need less maintenance and less space than X-ray sources, (2) on the other hand, radioisotopes may dictate more paperwork and inventory control than X-ray sources. Information is not presently available for considering the operational, logistic, or political factors.

2. INTRODUCTION

The work reported in this document was performed under contract with the Atomic Energy Commission (Contract No. AT(11-1)-1471) to develop an isotopic transmitting and receiving system which will permit close-order formation flight in helicopters.

Prior to the initiation of this contractual work, considerable work on the Helicopter Formation System had been carried out by the U. S. Naval Air Development Center (NADC), Johnsville, Pennsylvania, under the direction of Mr. George Wilcox. Concurrently with the work at NADC, Industrial Nucleonics Corporation also performed self-funded studies on several systems. In some of this work, an emphasis was placed on an operational concept of "follow-the-leader" type formation keeping. This concept used a single radioactive source on the lead helicopter with directional detectors on each other helicopter in formation, providing the following helicopters with information on their position relative to the leader and not relative to one another.

For this contract, Industrial Nucleonics Corporation proposes a different formation keeping concept in that each helicopter is equipped with a source and detector so that each helicopter in the formation knows the position of all the other helicopters. This concept is considered to be more versatile and advantageous than the first, namely, the "follow-the-leader" concept, in a number of respects. The contractual work performed deals solely with the second concept.

2.1 Purpose

The purpose of this contractual work was to conceive, develop, and demonstrate the feasibility of a nucleonic close-order helicopter formation keeping system.

2.2 Definition of Program

The program carried out under this contract covered the following tasks:

Task I -- Analytical Studies of System Approaches

In this task, various system approaches were conceived, analyzed, and evaluated in terms of desired performance requirements for the formation keeping system. One particular system considered to be the most optimum and promising was then selected to be pursued in the ensuing tasks.

Task II -- System Design Analysis and Fabrication

Based on the results of Task I, basic system components, consisting of a radioisotope source as a transmitter, a gamma ray detection system as a receiver, and an electronic information processing system, were designed and fabricated in breadboard form. Preliminary experimental measurements on several essential design parameters were carried out in this task.

Task 3--Experimental Studies

Task 3 involved the optimization and calibration of various system performance parameters, followed by a series of measurements on both range and direction of sources. The results of the measurements were then analyzed and evaluated.

Task 4--Feasibility Demonstration

The final task of this program was to demonstrate for representatives from various government agencies the feasibility of the helicopter close-order formation keeping system using a radioactive source.

3. OPERATIONAL CONSIDERATIONS

A meeting was held at the Atomic Energy Commission, Washington, D. C., on July 7, 1965, for the purpose of discussing the preferred method of operation and the desired performance specifications of the system. The meeting was attended by the personnel from the AEC, Army, Navy, and Air Force, as well as by those from Industrial Nucleonics Corporation.* At this meeting, a general agreement was reached as to the desired method of operation and also the overall operational considerations.

3.1 Requirements for the Formation Keeping System

The following operational method and requirements have been agreed upon as being desirable in the Helicopter Close-Order Formation Keeping System.

1. Each helicopter is to be equipped with a source (transmitter) and a detector (receiver) so that the other helicopters in formation flight may be located within the prescribed range.**

* The attendees from the government agencies were: J. C. Dempsey, AEC; Lt. M. J. Cole, Navy, BuWeps; G. E. Wilcox, Navy, USNADC; Maj. L. F. Baltzell, Army, US ADC AVNA; Capt. L. D. McIntoch, Air Force, SEG/RTD (SEAGN); T. E. Petriken, Army, Electronics Laboratory. Industrial Nucleonics Corporation was represented by C. O. Badgett, H. J. Evans, L. K. Hahn, and E. D. Jernigan.

** Thus, the method of "follow-the-leader" formation keeping is excluded from consideration in this program.

2. The range for the formation keeping system is from 50 to 500 feet.
3. The number of helicopters in the formation is restricted to four.
4. The formation of the four helicopters may vary in its configuration. The analysis of system performance must consider all the possible variations and their effect on the system.
5. The period of one scanning is to be so optimized as to be compatible with the average reaction time of the pilot and with the signal strength that can be practically maintained for the range from 50 to 500 feet.
6. A helicopter may, during a formation flight, tilt as much as $\pm 30^{\circ}$. The configuration of radiation patterns from a source and detector in the helicopter will be such that any error due to the tilt in this angular range may be kept at a tolerable minimum level.
7. An accuracy of $\pm 10\%$ in range measurements is to be required. Thus, all important design parameters are to be studied to determine the requirements to achieve this accuracy. Proper "trade-offs" are to be made between the desired performance characteristics and the inherent limitations found in the system.

8. The accuracy in direction measurement is to be compatible with the range accuracy of $\pm 10\%$.
9. The weight of the source and detector should be kept at a minimum, preferably not greater than ten pounds and 30 pounds, respectively.

3.2 Other Related Conditions and Characteristics

In addition to the above parameters to be considered in the development program, the following information is found pertinent to the analysis of the formation keeping problems:

1. The maximum speed of a helicopter in formation flight is approximately 150 knots.
2. The length of individual blades on helicopters range from 37 feet to 40 feet, approximately.
3. The normal altitude of helicopters in flight will be approximately 200 feet above vegetation.
4. No boom is to be used for the source and detector.
5. For the position of the source and detector in a certain helicopter, the tail pylon and the small radome under the passenger seats, respectively, are available and should be considered. The minimum distance between the tail pylon and the personnel will be between 15 and 23 feet during flight.

3.3 Effect of Requirements on System Parameters

It is clear that the foregoing operational requirements of the formation keeping system contain more facets than those treated in the proposal (Helicopter Close-Order Formation Keeping Instrumentation, dated May 6, 1964) and elsewhere. The program as now defined is more difficult and complex than the "follow-the-leader" formation keeping system. Instead of one source placed on the lead helicopter, the detector in each helicopter must respond to the range and direction of three different sources in all their different geometrical arrangements.

On the other hand, the desired method of operation as described above is certainly more versatile than the "follow-the-leader" method. It can be conveniently converted into the "follow-the-leader" mode of operation simply by "turning off" the transmitters (sources) except the one on the lead helicopter. In many cases, however, it is reported that pilots flying helicopters in formation under poor visibility conditions desire to know the location of all helicopters, including the lead helicopter. Finally, the formation flight can be maintained with the contemplated method of operation even when the lead helicopter is disabled and forced to leave the formation. Such is not the case for the "follow-the-leader" method of formation keeping.

3.3.1 Delineation of Measurement Accuracy

The accuracy of direction measurement equivalent to the range

accuracy of $\pm 10\%$ needs to be delineated. The range accuracy of $\pm 10\%$ is equivalent to a source at 500 feet from a detector measured with the uncertainty of ± 50 feet. Referring to Figure 1, the half angle, θ , of a right cone of which the diameter is 50 feet and the height is 500 feet is

$$\theta = \tan^{-1} 0.1 = 5.71^\circ \approx 0.1 \text{ radians} \quad (1)$$

That is to say, the accuracy of direction measurement equivalent to the range accuracy of $\pm 10\%$ is $\pm 5.71^\circ$. In terms of the accuracy as defined above, the maximum uncertainty in locating a source is given by a sector from a spherical shell whose half-thickness, half-width, and half-height are one-tenth the range, R , between the source and detector. It is sufficient to approximate this shell by a sphere of radius, $R/10$.

The tilt angle of $\pm 30^\circ$ in conjunction with the definition of accuracy implies that the center of the sphere of uncertainty makes a segment of a circle with radius, R (range), as shown in Figure 2. The significance of this tilt angle is that the overall efficiency of the detector for the incident radiation signals must not change by more than a certain tolerable amount when the direction of the incident radiation signals changes within this range of tilt angle. This is an important factor in detector design problems.

ACCURACY OF DIRECTION MEASUREMENT

FIGURE I

TILT ANGLE AND ACCURACY

FIGURE 2

4. SURVEY OF SYSTEM APPROACHES

There are essentially two basically different direction techniques suitable for the helicopter formation keeping system: one is the so-called rotational scanning detector, and the other is a new one that may be called the stationary array detector assembly. The latter differs from the former mainly in the complete absence of any moving parts. Both of these techniques can be used in combination with a number of different radiation sources. This section deals with the comparison of these two detection methods, evaluation of radiation sources usable in combination with each of the two detection methods, and finally, of the various system combinations.

4.1 Radiation Sources as System Transmitters

There are innumerable different radioactive sources that may be suitable in one sense or another for use in the helicopter formation keeping system. In order for a source to be practical, however, it must necessarily have a reasonably long half-life, and be not prohibitively expensive. It also must contain a minimum degree of hazard from the standpoint of personnel protection in the case of accident. Finally, it is necessary for the source to have certain energy characteristics in the emitted radiations so that the overall performance is optimum.

These four major parameters greatly diminish the number of possible sources to Cs-137, Am-241, bremsstrahlung from Kr-85 or

Sr-90, and a conventional X-ray generator. All other sources are regarded to be far from being desirable, for they are of too high energy, too short-lived isotopes, or too expensive.

The choice of energy is influenced by a number of different factors such as dynamic range of interest, detection technique to be employed, weight of radiation shielding allowed in the installation, and others.

If a point source emits S_0 per second of monoenergetic photons, and if a detector at a distance, R , from the source has an efficiency of η and sensitive area of A , then the number of primary rays, S , registered by the detector is given by

$$S = S_0 \eta A \frac{e^{-\mu \rho R}}{4 \pi R^2} \quad (\text{counts/second}) \quad (2)$$

where μ is the mass absorption coefficient for the photons and ρ is the density of air.

There exist, in general, photons of lower energy incident on the detector in addition to the primary rays. In the process of attenuation in air, some of the primary photons undergo one or more interactions with the transmitting medium. When the energy of the primary rays and the interacting medium are such that the Compton scattering is not negligibly small, then the low energy secondary rays incident on the detector become significant, generally increasing with distance as the primary radiation decreases.

It is to be noted that the intensity of secondary rays also contains

some useful information on the range, apart from the primary rays which are related to the range by Equation (2). The variation of the total intensity, S_t , with the range, R , from the point source, S_o , is

$$S_t = S_o \frac{\eta A e^{-\mu \rho R}}{4 \pi R^2} B(\mu \rho R) \quad (3)$$

where $B(\mu \rho R)$ is the so-called build-up factor due to scattered radiation. The function, $B(\mu \rho R)$ can be expressed empirically in a power series of the form

$$B(\mu \rho R) = 1 + a(\mu \rho R) + b(\mu \rho R)^2 + \dots \quad (4)$$

where a , b , etc., are constants determined mainly by the energy of the primary radiations, and also by the response characteristics of the detector medium.

Thus, when the constants, a , b , etc., are appreciably large, the second and third terms will become relatively important with increasing values of R , as the intensity of the primary radiation is reduced to a level where the statistical fluctuation may cause a large measurement error. It is, therefore, advantageous to utilize the scattered secondary radiation for range measurements together with the primary rays. A proper use of the secondary rays will result in the reduction of source strength for the range measurement with a given accuracy.

The characteristic length of photons as a function of their energy is computed for air and plotted in Figure 3. The lower curve represents

FIGURE 3 - CHARACTERISTIC LENGTH OF GAMMAS IN AIR VERSUS GAMMA ENERGY

the conventional characteristic length based on the total attenuation of the primary ray, whereas the upper curve represents another based on the total absorption.* The difference in the characteristic length between these two curves for a given energy is due to the Compton scattering which accounts for the build-up factor mentioned before. It is seen that the Compton scattering increases as the energy of primary photon decreases, reaching the maximum at about 80~100 kev region. Despite the relatively short characteristic length (in terms of the total attenuation coefficient) for low energy photons, an increase in its build-up factor usefully compensates, within a certain range, for the rapid attenuation of primary rays when the scattered secondary rays are properly utilized. Thus, the choice of the energy of the primary photon to be used depends on the range to be measured or the number of characteristic lengths involved in the measurement.

The scattering of primary rays in transmitting medium degrades the sharpness of a point source. When the detector viewing the source is made to measure the secondary as well as the primary rays, the source beyond a certain distance from the detector appears as a "smeared-out" one instead of a real point source. This may cause some degradation of the resolution in direction measurements.

* In this computation, the air density $\rho = 1.293 \text{ mg/cm}^3$ at 0°C and 760 mm Hg pressure is used.

Another important factor in the consideration of primary photon energy is the shielding required for the personnel protection. For a given activity of source, the thickness of the necessary shielding material increases with an increase in the energy of the primary photons. Since it is desirable to minimize the weight of the source housing and its shielding, the use of high energy photons is not to be preferred.

In particular, with the use of a rotational scanning detector, a source emitting high energy photons is found to be unsatisfactory because of the heavy shielding needed for the detector in order to have necessary signal-to-noise ratio. The signal-to-noise ratio must be maintained when one source is as close as 50 feet away from the detector, (contributing to the background level), while the other source is at approximately 500 feet. (It is presumed that there is sufficient shielding between the source and detector on each helicopter to keep the local background noise at a negligibly small level.) Simple straightforward calculations show that for high energy gamma rays such as those from Cs-137, the weight of necessary shielding to provide the required signal-to-noise ratio is prohibitively large.*

It is found that an isotopic source (and, for that matter, even a conventional X-ray source) emitting photons of around 80~100 kev is the most convenient for use with either a rotational scanning detector or stationary array detector assembly. The ratio of the attenuated primary ray at

* This will be discussed further in Section 5.2.

50 feet to that at 500 feet is about 390 for Cs-137, whereas it is about 1600 for 100 keV, 1900 for 80 keV, and 2700 for 60 keV photons.

As mentioned before, a proper use of scattered secondary rays will appreciably reduce the high attenuation ratio for low energy photons. The relative magnitude of constants, a and b , in Equation (4) generally increases with decreasing energy. Under certain measuring conditions,¹ the build-up factors for three different energies are obtained and shown in Table I.

Table I. Characteristics of Build-up Variations

Source	Energy (MeV)	$\frac{1}{\mu \rho}$ (ft) ($\rho = 1.057 \text{ mg cm}^{-3}$)	$B = 1 + a(\mu \rho R) + \dots$
Co-60	1.25	554	$1 + 1.4 (\mu \rho R) + \dots$
Cs-137	0.66	403	$1 + 2.7 (\mu \rho R) + \dots$
I-131	0.36	334	$1 + 5.5 (\mu \rho R) + \dots$

When considering suitable sources for helicopter formation keeping applications using digital counting, one is primarily interested in maximizing the number of photons detected (counts) by the detector and has only secondary interest in the energy of the individual photon as long as that energy is in a region of good air transmission and well above the detector threshold. The allowable number of γ -ray photons impinging on the human body in a given time is strongly dependent on the energy of the individual photon. This dependence is shown in Figure 4.² For instance, for equal dosage, the human body can accept an order of

FIGURE 4 - PHOTON FLUX TO GIVE 0.1 Rem/40 HOUR DOSE RATE

magnitude more photons at 60 keV than it can at 500 keV. The curves of Figure 3 indicate that photons whose energies lie between 50 keV and 200 keV fall within a favorable region as for total energy absorption. Thus, photon energies which are at or near 100 keV appear very favorable for this application.

The spectrum and also the intensity change of 60 keV (also 26 keV) gamma rays from Am-241 were measured as a function of range. Figures 5 and 6 are the result of the measurements. The source consisted of 3.3 curies of Am-241. The branching ratio in Am-241 for the 60 keV gamma ray represents only 36 to 40 per cent of the total integrations. This reduction plus internal absorption in the source, source shield, and detector shield reduced the effective curies to 0.67 curies of 60 keV gamma, where one curie is taken to mean 3.7×10^{10} gamma rays per second. The radiations were measured and analyzed with a NaI(Tl) scintillating crystal (3" x 3") coupled to a photomultiplier (EMI-60975), and 512-channel pulse-height analyzer (Nuclear Data - Model 130). The closure around the crystal was a 1/16" layer of aluminum oxide covered by a 0.015 inch thick aluminum can. The time taken for these measurements was 10 live minutes each. The range measurements, which are given by $N(E)dE$ for each spectrum, are expressed in terms of counts per second. In both cases, the natural background and noise were subtracted. Finally, the source and the detector were elevated from the ground level by 5 feet and 25 feet, respectively. The data of Figure 5, when compared with theory, indicate a small build-up factor (less than 2 at about 200 feet). This factor has decreased to one at a distance of 500 feet.

Beta-excited X-rays or bremsstrahlung using Kr-85 or Sr-90 with a high Z target are highly attractive for several reasons. It may be made into a source that can be "turned on and off" by changing the source housing by some suitable means from a high Z (target) material for radiation-on to a low Z (shielding) material for radiation-off.

Figures 7 and 8 are spectrum and range measurements with bremsstrahlung from Kr-85 at various distances. The source has an activity of 13.2 curies and is contained in a stainless steel cylinder one inch in radius and six inches in length, having four-mil thick uranium foil as a target. The detector and the pulse-height analyzer used and the conditions under which the measurements were carried out are similar to that for Am-241 measurements.

With Kr-85 emitting beta rays with the maximum energy of 0.695 MeV, the conversion efficiency for 90 keV X-rays using four-mil uranium as a target is approximately 0.52%.^{*} This is slightly greater than the efficiency of 0.54 MeV gamma rays also emitted from the source. The volume of Kr-85 necessitated by the low conversion efficiency can, however, be compensated for to some extent by compressing a high concentration of activity in a relatively small volume.^{**} Further, Kr-85 is a chemically inert gas, and thus provides an inherent safety from the standpoint of radiation hazard in the case of an accident.

^{*} A private communication with Robert Pressley, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

^{**} It is reported that the present concentration of about 4.2% Kr-85 could be enriched to about 50% in the near future.

In addition to the peak energy at 90 keV, there is appreciable bremsstrahlung radiation between 90 and 300 keV which may be used. The peak in Figure 7 at 0.540 MeV is due to the gamma ray emission from Kr-85 at this energy. This peak is undesirable for a system which seeks to use the lower energy since it adds to the health hazard as well as adding noise without contributing a useful signal.

The data shown are actual measurements after an average background has been subtracted. The degree of signal fluctuation will be greater than the square root of the signal at the lower count rate (large distance). The absolute fluctuation of course, is the square root of N where N is the total count received during the counting interval. This total count includes the background fluctuation as well as the fluctuation in the signal.

The bremsstrahlung from Sr-90/Y-90 used with a high Z target such as a uranium foil is also a possible source of radiation. It can also be "turned on and off" as in the case of Kr-85 bremsstrahlung. The main advantage of Sr-90/Y-90 over Kr-85 is that the former is a pure beta emitter with a high concentration, whereas the latter gives out 0.54 MeV gamma rays (0.42%) in addition to beta rays. The presence of 0.54 MeV gamma rays increases a radiation shielding problem for personnel protection, and therefore, necessarily introduces an increase in the shielding weight around the source. However, the consideration of safety against accidental hazard often makes the choice of Kr-85 preferable to Sr-90/Y-90.

Figure 9 shows spectrum measurements of bremsstrahlung from Sr-90/Y-90 with uranium foil as a target. These measurements were made at different times using a different detector and pulse-height analyzer.* Data was not taken on quanta above 750 keV. These quanta are few in number (about 1% of the total), and are neither modulated nor detected in sufficient degree to affect the operation. They must be considered in safety considerations since these rays are very difficult to shield.

Similar measurements were also made with a conventional X-ray generator. The generator is a Picker X-ray industrial unit (Andrex-200 kV-8 MA). As the X-ray output has 60 cps modulation, a gating circuit was used in the signal input to the pulse-height analyzer to measure the incident radiations only when the current was at peak value. The gating time was one-tenth of the full cycle, and the counting time was one live minute.

Figures 10 and 11 are the results of spectrum and range measurements using the X-ray generator. The same detector and pulse-height analyzer were used as before under almost identical conditions. The voltage and current applied to the X-ray generator was 120 kVP and about 0.01 MA.

* This data was obtained through private communication with Robert Pressley at Oak Ridge National Laboratory.

The conventional X-ray source is capable of producing a flux of large magnitude, as seen above. Further, the source can be turned on and off easily, eliminating the problem of continuously shielding the source as in the case of radioactive sources. The X-ray source must, however, have a uniform radiation field intensity over 360 degrees in azimuth angles and ± 30 degrees in elevation angles. Such an X-ray source could be developed in the future. At the present time, there is no known X-ray system available that can meet the desired performance specification for the Helicopter Formation Keeping System.

Some experimental tubes have been developed (see Aviation Week, April 8, 1966, p. 74) for X-ray studies. The receiver claims weights of 1 lb. for the tube and 8 lbs. for the power supply. No data is given on the ability of the tube to radiate uniformly over the desired solid angle. The design shown does not appear to be suitable for adequate solid angle coverage.

Finally, conventional X-ray sources have disadvantages in that they are invariably heavy as compared to isotopic sources and occupy a large space for power supplies and other electronic control instruments. They also suffer from the familiar drawbacks, such as lack of stability, short lifetime of tubes, etc. It is evident, therefore, that use of the conventional X-ray sources for the Helicopter Formation Keeping System should be preceded by an extensive development program to solve such technical problems as those mentioned above.

4.2 Rotational Scanning Detector

A rotational scanning detector consists of a single, fixed scintillating

phosphor optically coupled to a multiplier phototube and a collimator-shield rotating around the phosphor. This is a simple detection system in which different sources (i. e., helicopters in formation flight) and their relative locations are distinguished from one another and determined by a suitably designed collimator-shield. A simplified diagram of a rotational scanning detector is shown in Figure 12.

If the detector scans with a field of view of θ_o at the rate ω radians per second, the flux of photons from a single source registered during one scanning period is, from Equation (3),

$$I = I_o \frac{\eta A(\theta) \theta_o}{4 \pi \omega} \frac{e^{-\mu \rho R}}{R^2} B(\mu \rho R) \quad (5)$$

where η is detection efficiency and $A(\theta)$ is aperture. Equation 5 represents the general response function for the rotational scanning detector.

4. 2. 1 Range Measurement

In the range measurement, the aperture $A(\theta)$ can be replaced by the integrated sum aperture A_{st} , defined as

$$A_{st} = \int A_s d\theta = \int A_g \left[1 + \frac{A_p}{A_g} \right] d\theta \quad (6)$$

and

$$A_g = ab \left(\cos \theta - \frac{\sin \theta}{\tan \theta_o} \right) \quad (7)$$

where A_g and A_p stand for geometrical and penetrating apertures, respectively.*

* See Appendix I for the derivation of the geometrical and penetrating apertures and also the integrated sum aperture.

Figure 12

SCHEMATIC DIAGRAM OF ROTATIONAL SCANNING DETECTOR

The desired directional accuracy is $\pm 5.71^\circ$, which is equivalent to the range accuracy of $\pm 10\%$, (See Section 3.3). Since low energy gamma rays are preferably to be used, it is possible to make A_p/A_g negligibly small by using a high density material for the collimator. For $\theta_o = 5.71^\circ$, the integrated sum aperture A_{st} in Equation (6) is found to be

$$A_{st} \sim 0.1 \text{ a b} \quad (8)$$

Equation (5) can now be rewritten according to the preceding argument simply in the form

$$I = K(R) A_s(\theta) \quad (9)$$

where $K(R)$ may be regarded as an amplitude relating to the range R of one source; i. e. ,

$$K(R) = S_o \frac{\eta \theta_o}{4 \pi \omega} \frac{e^{-\mu \rho R}}{R^2} B(\mu \rho R) . \quad (10)$$

When the source of radiation is a conventional X-ray generator, the peak of the amplitude K at $\theta_o = 0$ may be used to measure the range (see Figure 27 in Appendix I). With the use of a conventional X-ray as a source, the source strength is not as critical a limiting factor as it is in the case of radioactive isotopes. On the other hand, the measurement of peak amplitude has an important advantage in that the range measurement of one source is not adversely affected by the presence of another source found in directional proximity of the former. This will be further discussed next in connection with the direction measurement.

In range measurement with a rotational scanning detector, it is important to keep the background level at a minimum through proper shielding and collimation of the detector. However, the background is expected to vary with the radiations received from two other "background" sources in a given formation. Since the background is not expected to be negligibly small, it may be necessary to continuously monitor its magnitude by means of a suitable electronic process, and then subtract the average noise from the total flux detected.

4. 2. 2 Direction Measurement

The direction of a source being measured by a rotational scanning detector can be determined from differentiation with respect to time of the number of photons registered per scan, as in Equation (9).

$$\begin{aligned} \frac{d}{dt} I &= \frac{\partial}{\partial \theta} K(R) A_s(\theta) \frac{d\theta}{dt} \\ &= S_o \frac{\eta \theta}{4 \pi} \frac{e^{-\mu \rho R}}{R^2} B(\mu \rho R) \frac{\partial}{\partial \theta} \left(A_g(\theta) + A_p(\theta) \right) \end{aligned} \quad (11)$$

If A_p / A_g is assumed to be negligibly small as before, Equation (11) can be expressed as

$$\frac{d}{dt} I = -S_o \frac{\eta \theta_o}{4 \pi} \frac{e^{-\mu \rho R}}{R^2} B(\mu \rho R) a b \left(\sin \theta + \frac{\cos \theta}{\tan \theta_o} \right) \quad (12)$$

where Equation (7) is substituted. Equation (12) has a discontinuity at $\theta = 0$; in other words, at the moment when the scanning collimator is aligned exactly with the source.

It is evident that the directional accuracy obtainable with this method is far greater than the one given by the collimating angle θ_0 . However, the collimating angle is still necessary in order to resolve two sources when the angle subtended by the two sources at the detector is close to θ_0 .

The rotational scanning detector, its principle and information processing, are all basically simple, especially when compared to the stationary array detector assembly to be discussed in the next section. The rotational scanning detector imposes no strict restriction on the number of sources, (i. e., helicopters) allowed in the formation. On the other hand, it requires an increase in source strength by as much as two orders of magnitude, depending on the scanning rate, because of the collimator-shield that limits the instantaneous field of view of the detector. This brings about an increased problem of radiation hazard and protection for personnel.

Clearly, high energy gamma rays are not desirable for use here with the rotational scanning detector. Thus, Cs-137 which emits 662 keV gamma rays is not found to be suitable for use in place of a lower energy source. The additional weight in the collimator-shield and personnel shield around the source is too large to be practical. As will be seen later, in the case of the stationary array detector assembly, this problem of heavy shielding is diminished considerably.

Low energy gamma rays in the energy region of 90 - 100 keV appear to be the most suitable when using the rotational scanning detector type system. In view of the relatively large source strength required by the rotational scanning detector, it is believed that only an X-ray generator is potentially capable of meeting the requirements, despite the drawbacks and limitations, as mentioned before. Section 5.4 will present more specific discussions on the subject in connection with the evaluation of various system approaches.

4.3 Stationary Array Detector Assembly

4.3.1 General Description

The alternate method conceived for use in the helicopter formation keeping system in terms of four helicopters in formation consists of four intensity-modulated radiation sources, one placed on each helicopter, and four stationary array detector assemblies, one on each helicopter. The intensity is modulated in time at four different frequencies, a different frequency for each helicopter.

Each stationary array detector assembly is made of four (or three) identical scintillator-photomultiplier units arranged in a certain symmetrical cluster to give both range and direction information without the necessity of any moving parts.

On each helicopter, the range and bearing information for each of the other helicopters in formation is separated electronically on a frequency basis. Three receiving frequency channels are provided on each helicopter (or four channels including its own for calibration purposes). Although this alternate method is described in terms of four helicopters in formation keeping, there is no reason why additional channels could not be provided.

4.3.2 Concept of Detector Array

The stationary array detector assembly consists of four identical scintillation crystals, each optically coupled to a photomultiplier. The four scintillator-photomultiplier units are arranged in a certain symmetrical manner with suitable partition shields between them. A possible stationary array detector assembly is shown in Figure 13.

The following equations are true for surface detection and provide a unique means of obtaining range and azimuth.

$$C_1 + C_2 = 1/2 B(1 + \sin \theta) + \alpha B + B_o \quad (13)$$

$$C_3 + C_4 = 1/2 B(1 - \sin \theta) + \alpha B + B_o \quad (14)$$

$$C_4 + C_1 = 1/2 B(1 + \cos \theta) + \alpha B + B_o \quad (15)$$

$$C_2 + C_3 = 1/2 B(1 - \cos \theta) + \alpha B + B_o \quad (16)$$

FIGURE 13

where

B_o is the total background quanta striking the detectors. B is directly related to Equation (13) when saturation and pile-up effects at short distances are properly taken into account. A sketch of Equation (13) is helpful and is shown in Figure 14.

B is the total direct quanta intercepted by the detector array, C_1, C_2, C_3, C_4 are the counts for detectors $D_1 - D_4$, respectively, a is a contrast factor which depends on the detector efficiency and effectiveness of partition shield,

and

θ is the angle shown in Figure 13.

Equations (13), (14), (15), and (16) can be satisfactorily realized if the energy of incident radiation is low, preferably below 100 keV, and the density of the scintillator is large. Then, the detection of the incident radiations takes place predominantly in a region close to the surface of the crystal. A scintillating phosphor such as NaI(Tl) or CsI(Tl) is the most suitable for this purpose.

From Equations (13), (14), (15), and (16), the following relations hold:

SINUSOIDAL ANGULAR RESPONSE OF STATIONARY ARRAY
DETECTOR ASSEMBLY

FIGURE 14

$$C_1 + C_2 + C_3 + C_4 = B(1 + \alpha) + B_0 \quad (17)$$

$$(C_1 - C_3) + (C_2 - C_4) = B \sin \theta \quad (18)$$

$$(C_1 - C_3) + (C_2 - C_4) = B \cos \theta \quad (19)$$

It is noted that a decrease in the source range R causes a corresponding increase in αB . However, α can be made a very small number by virtue of the low energy of radiation and the high density of detector used.

Equation (17) and Equations (18) and (19) provide the range and the bearing of a single source, respectively, placed at angle θ from a fixed reference axis of the detector. It is interesting to note that the most important functional property required of the stationary array detector assembly is that angular response of a signal exhibits a periodic antisymmetry with respect to the average value of the signal amplitude. It is experimentally found that the required antisymmetry is obtained even from high energy gamma rays such as those from Cs-137. However, the characteristics of the antisymmetry property with high energy gamma rays is not the most convenient and simple form from the standpoint of information processing. As discussed above, a sinusoidal response is desirable. Another response form is a straight line connecting the adjacent peaks (i. e., maximum and minimum of $C_1 + C_2$, etc.), as shown in curve (b) of Figure 14.

In the case of a single source, Equations (17), (18), and (19) can be used to obtain direction and range. Since α is a constant measurable

design parameter, B_o can then be determined from Equation (17) continuously, even in the presence of the source, provided B_o is isotropic.

The statistical fluctuation and its effect on the range and direction measurements has been analyzed and is presented in Appendix II of this report.

4.3.3 Modulated Source

The source on each helicopter is modulated at a characteristic frequency so that the individual source may be identified. The modulation can be accomplished by rotating a source collimator-shield, by displacing the source periodically within the collimator-shield, or by electrically modulating (or turning on and off) the beam in the case of a conventional X-ray generator.

If a single source is modulated in its intensity at frequency f so that B is the peak amplitude of modulation of the radiation, the actual source strength must be greater by at least a factor of two. Since the source is not completely turned off in the modulation process, the average flux level can be given by $B(1 + \gamma)$, where γ is the contrast factor associated with the modulation of the beam intensity. The value of γ may not necessarily be a constant; as the range between the source and the detector changes, γ may take on a slightly different value. Figure 15 is a sketch of this intensity modulation. The percentage modulation is given by $M = 100 / (1 + \gamma)$. For low energy radiation, it is easy to make the value of γ very small without using a thick collimator-shield.

INTENSITY

INTENSITY- MODULATED RADIATIONS

FIGURE 15

Equations (13), (14), (15), and (16) take the same form with B multiplied by the factor $(1 + \gamma)$, as do Equations (17), (18), and (19).

It may be said that the stationary array detector assembly has the following advantageous features:

- (1) The complete absence of any moving part in the detector operation.
- (2) The virtual absence of heavy shielding or collimating material at the detector.
- (3) The significant reduction in the source strength necessary for desired system performance.
- (4) Continuous and simultaneous information processing for all different sources.*

4. 4 Evaluation of Various System Combinations

For the purpose of selecting one final source-detector combination that is the most promising and practical in demonstrating the feasibility of the Helicopter Formation Keeping System, various system combinations were surveyed. Both the rotational scanning detector and stationary array detector assembly were considered in combination with the conventional X-ray generator, Am-241, Cs-137, Kr-85 (bremsstrahlung), and Sr-90 (bremsstrahlung). The various system combinations were compared in terms of minimum source strength, source weight and size, detector size and weight, availability and cost, information processing electronics, etc.

* In Section 5. 3, a method of processing information will be discussed.

Table 2 shows the summary of the survey. The computations carried out in the survey were based on presently available information. Since the most stringent requirement on source strength occurs at the distance of 500 feet, it was decided to choose the size of detector which is suitable for this range without requiring excessive source strength. At the same time, the detector size chosen was considered to be of practical size allowed from the standpoint of actual installation of the formation keeping system.

The first line considers a conventional X-ray generator combined with a rotational scanning detector. It is assumed that the scanning rate is 2 revolutions per second. A practical X-ray generator for use in this application appears to be one with 150 kVP with a power consumption of 20 watts. For this voltage, the efficiency of the X-ray generator is taken to be approximately 25 curies/watt input with one-fifth of the radiation taken as useful number for calculation purposes. As mentioned in the preceding sections of this report, an X-ray tube which will meet the beam pattern requirements will have to be developed.*

The second data line indicates that, if a stationary array detector assembly is used instead of the rotational scanning detector, an X-ray source of 5 watts would be sufficient to meet the range requirement.

* It is estimated that a development program of this type will cost about \$100,000.

PRELIMINARY SURVEY OF SYSTEM COMBINATIONS
FOR HELICOPTER FORMATION KEEPING

50 - 500 Ft.

TABLE 2

Type of Detector and Source	Minimum Source Strength	Source Weight	Source Package	Detector Package	Detector Weight	Source Availability and Cost	Information Processing Electronics
150 kVP X-ray with scan detector	20 watt (25-5) c/watt	25 lbs.	15" x 10" x 10"	12" x 7" x 7"	10 lbs.	\$10 ⁵ Dev. Program	Simple
150 kVP X-ray with stationary detector	5 watt 25 c	"	"	12" x 8" x 8"	12 lbs.	"	Complex
Americium-241 with scan detector	>2000 c	8 lbs.	6" x 3" x 3"	12" x 7" x 7"	10 lbs.	Very Expensive	Simple
Americium-241 with stationary detector	30 c	6 lbs.	8" x 4" x 4"	12" x 8" x 8"	12 lbs.	Expensive	Complex
Cesium-137 with scan detector	> 20 c	12 lbs.	6" x 3" x 3"	12" x 9" x 9"	60 lbs.	Inexpensive	Simple
Cesium-137 with stationary detector	(6-9) c	10 lbs.	7" x 4" x 4"	12" x 8" x 8"	30 lbs.	"	Very Complex
Krypton-85 (1000 c) with stationary detector	30 c * γ equivalent	10 lbs.	8" x 5" x 5"	12" x 8" x 8"	25 lbs.	\$15/curie Kr	Complex
Sr ⁹⁰ - Y ⁹⁰ (1000 c) with stationary detector	30 c * γ equivalent	8 lbs.	8" x 4" x 4"	12" x 8" x 8"	30 lbs.	Inexpensive	Complex

* Assumes an efficiency of 3 per cent.

Obviously, the large difference in the power (or source strength) requirement arises from the fact that the rotational scanning detector with a resolution of $\pm 5^\circ$ will receive only 1/36th of the total radiation per unit time incident over the area intercepted by the detector, whereas the stationary array detector assembly receives the entire radiation continuously incident on it. It is seen that the combination of a suitable X-ray source and stationary array detector assembly could be used to extend the formation range beyond 500 feet.

The combination of Am-241 with the rotational scanning detector is considered in line 3. The source strength required for the range of 500 feet is seen to be prohibitively large in terms of the cost for the source.* Despite the favorable energy of gamma rays from Am-241 (26 and 60 keV), its possible use must take into consideration the potential hazard and also appreciable self-absorption inherent with the nature of the source.

It is believed that the combination of Am-241 with the stationary array detector presented in line 4 was the most attractive choice for the purpose of the ground feasibility demonstration in all factors. The combination entails an important advantage in that Am-241 as a source may be easily replaced with another type such as an X-ray generator or bremsstrahlung source from Kr-85-U. As will be shown more clearly in sections to follow, the soft gamma rays emitted make it possible to satisfactorily

* The current cost of Am-241 is reported to be about \$500 per curie.

approximate the ideal sinusoidal function in the angular response characteristics of the stationary array detector assembly.*

In the next line, the combination of Cs-137 and the rotational scanning detector is considered. This combination is seen to be impractical because of the source strength required and also the weight of the detector collimator-shield necessary to have the desired signal-to-noise ratio.

On the other hand, Cs-137 looks promising when used with the stationary array detector assembly. As line 6 shows, the minimum source strength required is not prohibitively large. The weight of the detector is seen to be high due to the shields required in the detector. One important disadvantage in this combination is the difficulty in obtaining the desired sinusoidal property in the angular response function. The required antisymmetry of the stationary array detector assembly is obtainable with Cs-137. However, a significant deviation from a simple sinusoidal function makes the information processing for bearing measurement much more complex than it is otherwise. This system is rejected on the basis of the complex electronics and detector weight. Of course, the deviation is caused by the relatively high energy of gamma rays from the source.

The bremsstrahlung from Kr-85 with a target of high atomic number has a unique possibility with the stationary array detector assembly for several reasons. It can be made into a source of radiation that may be

* A 30-curie Am-241 source was originally deemed permissible. This value has now been lowered more than one order of magnitude, so Am-241 can no longer be considered for helicopter formation keeping purposes.

modulated in its intensity by changing the source housing by some suitable means from a high Z (target) material to a low Z (shielding) material.

The efficiency for generating the bremsstrahlung is generally small of the order of 3 to 4 per cent for the total radiation emitted. For instance, with a uranium foil as a target, the efficiency of generating 90 keV bremsstrahlung with Kr-85 is experimentally found to be about 0.52%. A typical spectrum of the bremsstrahlung from Kr-85 and Sr-90-Y-90 is shown in Figures 7 and 9, respectively. In Table 2, we have assumed an overall efficiency of 3 per cent.

Kr-85 emits 520 keV gamma rays (0.42%), in addition to the beta rays. This will bring about some deviations from the desired sinusoidal angular response similar to the case of Cs-137. However, the bremsstrahlung in the energy range of 70 - 120 keV is expected to play a dominant role as it may be deduced from Figure 7. Further, a proper design of the scintillating phosphors used in the stationary array detector assembly would minimize the magnitude of the undesirable deviation by preferentially reducing the detection efficiency for 520 keV gamma rays. The shielding problem of the source is increased by 520 keV gamma rays. Thus, the usefulness of Kr-85 bremsstrahlung as a source in the Helicopter Formation Keeping System is somewhat limited by the presence of the relatively hard gamma rays. It is important to note, however, that the inherent safety found in the use of Kr-85 due to its being chemically inert gas, seems to overshadow the above disadvantage, namely, increased weight in source shielding. With the possibility of enrichment of Kr-85

from the present 5% to about 50% in the near future, its attractiveness as a radiation source for use with the stationary array detector assembly is expected to increase.

Sr-90 - Y-90 is a pure β emitter with the maximum energy of 2.18 MeV. The efficiency of generating bremsstrahlung with this source is greater than with Kr-85 for a given target. The high concentration of activity will result in a relatively compact source housing. It appears that these two advantages over Kr-85 are, however, balanced out, to a large extent, by the inherent safety aspect of Kr-85. The last line in Table 2 shows the close comparison with Kr-85. The detector weight for Sr-90 is higher than that for Kr-85 due to the small amount of radiation between .7 MeV and 2.27 MeV which must be shielded. The weight of health shields must be added to the weight of the high energy sources if one is to come into contact with the source housing. These weights are not included in Table 2. They would be needed for Cs-137, Kr-85, and Sr-90 sources.

The foregoing discussions lead to the conclusion that, for the purpose of a laboratory demonstration of the feasibility of the Helicopter Formation Keeping System, the combination of the stationary array detector assembly with Am-241 was the most attractive choice for all factors considered. Thus, in keeping with this decision on the system approach, experimental efforts were restricted to investigations of problems found in this approach.

Safety considerations during actual operations appear to limit the number of source contenders to either a Kr-85 bremsstrahlung radioactive

source or an X-ray source. Other sources such as Cs-137 and Co-60 provide reasonably small sources, but require very heavy shielding on the partition shields in the detectors. In principle, one loses all of the advantages of a surface detector and must rely on shadow effects for angular resolution. A NaI(Tl) crystal detector 3" long by 6" in diameter retains the surface detection principle for a Kr-85-U bremsstrahlung source to a large degree since a large percentage of the radiation is detected within a distance of 1 cm, so the detector can actually be made into a cylindrical shell. This provides surface detection and also reduces the detector weight.

5.0 DESIGN ANALYSIS OF PROPOSED FORMATION KEEPING SYSTEM

The surface detection principle outlined under Section 43 was mostly easily demonstrated in principle by use of Am-241 sources. Safety considerations in operations, however, demand that some other source such as a Kr-85-U bremsstrahlung source be used.

The following discussions on principles of modulation and detection which deal with tests on Am-241 are quite applicable for a Kr-85 bremsstrahlung source. The main difference is in the thickness of chopper blades and partition shields.

5.1 Intensity-Modulated Radiation Source

The intensity of gamma radiations from Am-241 can be modulated with relative ease by virtue of its low energy. There are several different ways by which the intensity can be modulated. One is to rotate a source in the form of a plate with a bisecting line as the axis. In this case, the radiation must be emitted from both sides of the plate with equal intensity. Although Am-241 is very difficult and expensive to be fabricated in such a form at the present time, this method of modulation would give a sinusoidal variation in intensity. Another method will be to move by some suitable means either a source or shielding relative to each other. In this method, the source may form a cylindrical shell in order to make sure the radiation field covers the entire 360° of horizontal plane.

For the present purpose of the feasibility demonstration on the ground, however, a far simpler method of modulation was chosen. A circular disc source was prepared with a proper backing material. This is of

high integrity and mechanical ruggedness sufficient to stand environmental conditions that may be encountered on the mount of the modulating mechanism. The modulation was achieved by means of a chopper wheel driven by a synchronous motor. The chopper wheel was made of brass plate having 0.156 inches in thickness. The contrast factor given by the chopper wheel (i. e., the value of γ in Section 5.3.3) was found to be approximately 1/200. The amplitude ratio of this magnitude in the modulated radiation beam is quite adequate from the standpoint of signal processing for range and bearing information.

It was decided, for the sake of simplicity and convenience without changing the original purpose of this program, that only two sources operating at modulation frequencies of 60 cps and 90 cps would be used. These two frequencies were easily obtained by using a chopper wheel having two blades and three blades, respectively, each driven by an identical synchronous (1800 rpm) motor. In this manner, both sources of equal strength produced the same intensity but at different frequencies. Figure 16 is a picture of the modulating mechanism used in the demonstration.

The source strength used in the program was limited by the availability and cost of Am-241. Two Am-241 sources, with actual activity of 2.3 curies each, were purchased for the purpose. The source is in the form of a circular disc 2.3 inches in diameter. Despite the large area used and the minimum practical window thickness allowed, the

Modulating Mechanisms for Radiation Intensity

Figure 16

effective useful source strength was experimentally determined to be approximately 1.8 curie "point source equivalent", due to the absorption by the source material itself and also by the window of the source housing. In addition to this 2.3 curie source, two other Am-241 sources readily available at Industrial Nucleonics Corporation were used in order to increase the useful source strength. These two are also in the shape of a circular disc, each having the actual source strength of 1 curie and the effective useful strength of about 0.6 curie. Thus, the combination of one large and one small source for each modulating mechanism gave an effective source strength of 2.4 curie before the modulation and about 1.2 curie after modulation.

The 1.2 curie effective strength necessitated a significant limitation in range to be covered in the feasibility demonstration. Furthermore, some degradation in the accuracy of measurement was to be expected within the reduced range because of the small source strength. These shortcomings were superficial, however, in that they could be eventually overcome by the use of a larger source strength.

It is not expected that the intensity of radiation modulated by this manner would have a sinusoidal variation with time. Although such a variation may be desirable, it is not necessary so far as the acquisition of information by the detector and later by the signal processor are concerned. The filters in the signal processing electronics pass only the sine wave component at the fundamental chopping frequency. Thus,

information contained at any other frequencies (harmonic) due to a non-sinusoidal time variation contains no additional information other than that contained in the fundamental component. Scattering by the chopper wheel blades may presumably cause some distortion in the intensity modulation. It is believed, however, that the distortion would be insignificant and that the modulated radiation beam would maintain a well-behaving periodic function for all practical purposes. As the discussion of the experimental work will show in the following section, the intensity-modulated radiation as described above was satisfactory, meeting the essential design purpose.

5.2 Stationary Array Detector Assembly

The desired configuration of the stationary array detector assembly is a cylinder composed of four identical segments as shown in Figure 17. If the scintillating phosphor used is of a high density material such as NaI(Tl) or CsI(Tl), then the assembly may be in the form of a cylindrical shell with the thickness sufficient for high detection efficiency. On account of budgetary reasons, we used four cylinders for detectors instead of four sectors. This design permitted the use of readily available scintillating phosphor-photomultiplier units.*

* When the detectors were to be purchased, the survey on radiation sources was not completed. Thus, the scintillation phosphor chosen was of such kind (namely, NaI(Tl)) and shape as to be commonly useful for the several different sources listed in Section 5.

SCHEMATIC DIAGRAM OF STATIONARY ARRAY
DETECTOR ASSEMBLY USED IN FEASIBILITY
DEMONSTRATION OF FORMATION KEEPING SYSTEM

FIGURE 17

Figure 17 shows a schematic diagram of the stationary array detector assembly fabricated and used in the feasibility demonstration of the Helicopter Formation Keeping System. It consists of four identical NaI(Tl) crystals each in the shape of a cylinder 3 inches in diameter and 3 inches in length, coupled to an individual multiplier phototube (EMI-6097 S). In order to minimize the absorption of incident radiation by the detector window, the thickness of aluminum housing for the crystal was reduced to a practical minimum of 15 mil. With this thickness, the rigidity of the housing was found to be satisfactory.

Because of the deviation in the configuration of this assembly, from that shown in Figure 13, a certain corrective shield, made of a thin lead sheet (1/16 inch thick) was devised and used between the adjacent crystal housings in order to obtain the desired sinusoidal response mentioned before. The shape of this corrective shield is found to be critical as far as obtaining the desired sinusoidal function is concerned. The dimensions of the shield that would give the most satisfactory results were experimentally determined.

Figure 18 represents data taken with a 3.3 curie Am-241 source placed at 59' from the stationary detector. The detector was rotated through 360° , and the output voltages measured. No effort was made to trim the detector for balance. Likewise, the results are outputs of the conventional electronics without attempting to balance the various amplifiers. A calculated cosine curve is superimposed on the data for the first 180° of rotation. This curve shows that the errors at the worst points approach $\pm 10\%$. In view of the improvement in the circuits which will be used in Phase II, it is believed that the system developed should be able to meet the accuracy

FIGURE 18 ANGULAR RESPONSE OF
 STATIONARY ARRAY DETECTOR SYSTEM
 (60~CHOPPED 3.3 CURIE Am 241 SOURCE AT 59°)

specifications in range and angle.

Since individual sources are identified by their modulation frequency, there is no formation problem even when two sources are in line. This capability was demonstrated in the ground demonstration. The system does, of course, suffer from the shadow effect produced by two helicopters in line. The limitations imposed by this effect can be determined only by airborne tests. The effect will depend on the source position on the helicopter and on the particular helicopter used. The most important property of antisymmetry with respect to the average value of the amplitude variation is observed in this figure.

It is anticipated that when the configuration of the detector assembly is properly designed, having a horizontal cross section of a true circle and also when a high density scintillating phosphor is used here, the angular response of the stationary array detector assembly will be closer to the theoretical sinusoidal function than the one shown in Figure 18.

Figure 19 shows that a cylindrical detector yields a relative response which varies from 1.075 to 1.035 as the angle varies $\pm 30^\circ$ about a horizontal plane through the detector. Since this variation represents only $\pm 2\%$ about the mean, no further experimental effort was made to adapt the detector for variations in tilt of the detector. Actual measurements of tilt can be done by adding two individual detectors with a horizontal plane shadow partition between them. Since azimuth is given by the standard detector, tilt can be obtained by comparing the count rate from each detector. The actual tests performed will now be described.

Preliminary measurements were made to determine the variation of detection efficiency of a cylindrical crystal as a function of the crystal orientation. In the measurement, an Am-241 source was placed at about 30 feet from an NaI(Tl) crystal that was two inches in diameter and two

inches in length, and both 26 keV and 60 keV peaks were integrated from a multichannel pulse-height analyzer. Figure 19 is one result of the measurement. In the graphic presentation, the efficiencies of detection were normalized to that value for radiations in the direction of the detector axis. The result seems to indicate that the detector assembly could be designed so as to have the desired uniform detection efficiency over the elevation angle of $\pm 30^\circ$.

5.3 Information Processing

5.3.1 General

The electronic system was designed to demonstrate the feasibility of helicopter formation keeping. It was completed within the available time and funds, and is not necessarily a final system design. It does, however, successfully demonstrate feasibility and if necessary, could be further developed into a flyable system.

The electronic system must process and display information contained in the detector output signals. This information is essentially: range R contained in the signal $(C_1 + C_2) + (C_3 + C_4)$, azimuth component $R \cos \theta$ contained in $(C_1 - C_3) - (C_2 - C_4)$, azimuth component $R \sin \theta$ contained in $(C_1 - C_3) + (C_2 - C_4)$.

Two simulated helicopters (sources) were used in the demonstration. In order to identify the signals from the different helicopters, each helicopter source is chopped (turned on and off) at its own distinctive modulation frequency. The signals from the different sources are then separated by filters in the electronics. Although several simulated helicopters (sources) could have been used, it was believed that two sources would be sufficient to demonstrate the absence of any interactions.

For the feasibility study, a laboratory oscilloscope was used as a display device. To make the display easy to interpret, range is displayed from the center of the scope outward with the observer's position represented

by the center of the scope. Azimuth is measured from some fixed reference line (e. g., straight ahead), which corresponds to the positive y - axis of the scope. The surrounding helicopters are represented by bright spots on the scope.

The electronics system is all solid state, except for the MPT, and contains no moving or mechanically rotating parts other than the source chopper.

5. 3. 2 Functional Diagram

5. 3. 2. 1 Simplified Diagram

Figure 20 shows a simplified functional diagram of the signal processing and display system in which the positions of helicopters (sources) are displayed on a conventional oscilloscope. The observing helicopter's position corresponds to the center of the scope and the positions of surrounding helicopters are represented by bright spots on the scope whose distance from the center indicates range. The angular position of a bright spot from some reference line (e. g., y-axis) indicates the angular bearing from the observer's reference line (e. g., straight ahead).

The four detectors comprise a stationary array detector system located on the observer's helicopter.

Any system must perform the functions indicated in Figure 20, or their equivalent. For each helicopter, the system must process the signals from the detector array, compute range R , compute vertical oscilloscope deflection $y = R \sin \theta$, and compute horizontal oscilloscope deflection

SIMPLIFIED FUNCTIONAL DIAGRAM

HELICOPTER FORMATION KEEPING (HFK 0562-01)

FIGURE 20

$x = R \cos \theta$, where θ is the angle measured from the fixed reference line. The cartesian, or x-y coordinate system, suitable for a conventional oscilloscope, is used. If a polar coordinate display device were used, it would be necessary to compute R and θ rather than $R \sin \theta$ and $R \cos \theta$.

5.3.2.2 Complete Block Diagram

Figure 21 is a complete system block diagram as used for the feasibility study. The system displays the positions of two sources (helicopters) on the oscilloscope. Source #1 is chopped at a frequency $f_1 = 60$ cps, and source #2 is chopped at $f_2 = 90$ cps. Figure 21 shows the complete detector system excluding the sources.

D_1 through D_4 are multiplier phototubes. These tubes form a stationary array detector system. The four signal processor blocks shown in Figure 21 shape the output pulses from the detectors and convert the pulse count rates to slowly varying signals. These signals, which we call C_1, C_2, C_3, C_4 , are voltages proportional to the count rate of pulses as received by the associated detector and vary in time in accordance with the source modulation frequency. If both #1 and #2 sources are present, the C signals will contain information representative of each of the source frequencies f_1 and f_2 . At a later stage in the circuitry, these different frequency components are separated by appropriate filtering.

Omitting constant gain factors, these processed C signals follow relations 1-4 given on the following page due to the symmetrical design

SYSTEM BLOCK DIAGRAM
HELICOPTER FORMATION KEEPING
FEASIBILITY DEMONSTRATION MODEL

FIGURE 21. COMPLETE BLOCK DIAGRAM

of the detector array. A sinusoidal variation in θ is assumed.

$$C_1 + C_2 = 1/2 [B(1 + \sin \theta) + \alpha B] \sin 2\pi ft \quad (20)$$

$$C_3 + C_4 = 1/2 [B(1 - \sin \theta) + \alpha B] \sin 2\pi ft \quad (21)$$

$$C_4 + C_1 = 1/2 [B(1 + \cos \theta) + \alpha B] \sin 2\pi ft \quad (22)$$

$$C_2 + C_3 = 1/2 [B(1 - \cos \theta) + \alpha B] \sin 2\pi ft \quad (23)$$

The $\sin 2\pi ft$ factor in Equations 20-23 represents the variation in time of the signals as received from a source due to being chopped at frequency f . The angle θ is the bearing to the source from a fixed reference line at the detector. The design parameter, α , is a contrast factor determined by the detector partition shielding.

The B factor in Equations 20-23 is the count rate intensity of the source as measured at the detectors, and is a function of the range to the source according to

$$B = K \frac{\epsilon^{-R/\lambda}}{R^2} \quad (24)$$

where R = the range from the source to the detector. K and λ = constants determined by source material and strength, amplitude of the modulated signal at the source, etc. In practice, K may be a function of R .

The C_1 through C_4 signals are algebraically combined in three different ways to provide range and directional information to the source.

The three signals, S_1 , S_2 , and S_3 shown in Equations (25), (26), and (27) are formed by the summing circuits in Figure 21. Note that each of these S signals is a voltage varying in time in accordance with the source modulation frequency f . Again, if more than one source is present, there will be additional frequency components of Equations (25), (26), and (27), each with its own particular modulation frequency f . From Equations (20) through (23), it is seen that these three signals may be written as Equations (25), (26), and (27) (assuming the presence of a single source).

$$S_1 = (C_1 + C_2 + C_3 + C_4) = B(1 + \alpha) \sin 2\pi ft \quad (25)$$

$$S_2 = (C_1 - C_3) - (C_2 - C_4) = B \cos \theta \sin 2\pi ft \quad (26)$$

$$S_3 = (C_1 - C_3) + (C_2 - C_4) = B \sin \theta \sin 2\pi ft \quad (27)$$

Note that Equation (25) is independent of the bearing θ , whereas Equations (26) and (27) include bearing information. Thus, the amplitude of the S_1 signal, $B(1 + \alpha)$ in Equation (25) can be used to determine range R and is used in conjunction with Equations (26) and (27) to determine bearing information.

The amplitude of the S_2 signal, $B \cos \theta$ in Equation (26), yields the horizontal range component to the source. The amplitude of the S_3 signal, $B \sin \theta$ in Equation (27), yields the vertical range component to the source. Since $\cos \theta \leq 1$ and $\sin \theta \leq 1$, the maximum amplitude of S_2 or S_3 is B , which is less than the amplitude $B(1 + \alpha)$ of S_1 .

The band pass filters in Figure 21 separate the different source signals from each other. The outputs of the band pass filters are fed to phase detectors shown in Figure 21. The output of the phase detector, e. g., A_1 in Figure 21, is a dc voltage proportional to the peak-to-peak value of the input ac signal, f_1 . The polarity of the A_1 signal (i. e., positive or negative) is determined by the phase relationship between the ac f_1 and the ac f_1 reference input signals to the phase detector. Both inputs are sine waves, with f_1 reference being a constant amplitude signal phase locked to the f_1 source chopper motor signal. For example, if the f_1 input is 180° out of phase with the f_1 reference input, the output A_1 will be a positive dc voltage. Similarly, if f_1 and f_1 reference are in phase, A_1 will be a negative dc voltage. These polarities are arbitrary and may be reversed by reversing the transformer input leads shown in the phase detector.

The components $A_1 \cos \theta_1$ and $A_1 \sin \theta_1$ are determined in a similar manner through the filter and phase detector channels for S_2 and S_3 , respectively.

The components for the other source at frequency f_2 are similarly determined.

For the purpose of demonstrating feasibility, the chopper motors for the sources were driven synchronously from the 60 cps commercial power source. The commercial power source was used as the reference signal at the detector location. The purpose of this approach was to

simplify the feasibility studies as well as to minimize cost and effort leading to the feasibility demonstration. The method by which the 90 cps reference signal was derived from the 60 cps commercial source was to form the third harmonic (180 cps) and divide by 2 in a flip-flop.

The f_1 - ref and f_2 - ref signals are sinusoidal signals which are phase-locked (and frequency-locked) to the f_1 and f_2 source frequencies, respectively. The reference signals are generated and controlled by the f_2 - ref generator block and the f_2 - ref and f_1 - ref reference phase control blocks shown in Figure 21.

In a flyable system, these reference signals will be generated by phase-locked oscillators. The frequency and phase of a phase-locked oscillator may be controlled through the use of a separate phase detector. If the f_1 and f_1 - ref inputs to a phase detector are 90° out of phase, known as in quadrature, the output of the phase detector will be zero volts. The phase detector output may be fed back to the oscillator to "force" the oscillator to provide an output frequency f_1 which will cause the phase detector output to remain nearly at zero volts. The use of the commercial power source eliminates the requirement of phase-locked loops in the feasibility model.

The phase detection scheme yields the proper positive or negative sign of the cosine and sine components so that the proper quadrant for the angle may be determined. Also, the phase detection scheme adds additional selectivity to the channel due to the fact that a detector yields,

on the average, zero output for frequencies other than the exact frequency of the reference signal applied to the phase detector. Thus, the phase detectors yield an additional amount of "filtering" above that which the bandpass filters provide. The phase detectors include a time constant for attenuating statistical fluctuations in the signals.

A common computer is used to compute range, horizontal deflection, and vertical deflection. An electronic switch is used (shown in Figure 21) to alternately switch the computer to source #1 signals and then to source #2 signals. Notice that the signal processor circuits and the summing circuits in Figure 21 also use common circuits. Only through the bandpass filter and phase detector channels are the signals from the two sources processed separately.

The channel selector blocks in Figure 21 along with the flip-flops and the clock, determine which source's signals are switched to the common computer during a given time interval.

The range computer in Figure 21 takes the A signal, which is essentially the B of Equation (24), and computes the range R from this signal. The three integrators in Figure 21 generate a voltage ramp whose slope is directly proportional to the magnitude of the dc voltage of its input. For example, the integrator whose output is fed to the horizontal input of the oscilloscope generates a sweep voltage $(A_1 \cos \theta)kt$, where k is a constant and t is the time. This signal sweeps the beam of the oscilloscope horizontally for a time period proportional to R/A. Similarly, the vertical

integrator sweeps the beam of the oscilloscope vertically for the same time period. The oscilloscope combines the horizontal and vertical sweep components vectorially, causing the beam to actually sweep out on a radius at the angle θ . When the beam is swept a distance proportional to R_1 , the comparator circuit shown in Figure 21 pulses the intensity modulation input, or Z axis input, causing a bright spot to appear on the scope at that point. The description thus given was for source #1. Then, alternately, the channel selector through the electronic switch, switches to the signals representing source #2, and the process repeats for source #2 producing a bright spot on the scope representing a distance proportional to R_2 . Only a bright spot caused when the intensity modulation input is pulsed is seen on the scope. The method just described, that is, the action of the sweep integrators and the comparator circuit, is essentially an electronic multiplication and division process. The information processing of the S_2 (and S_3) signals yields, for example for source #1, $A_1 \cos \theta_1$ and $A_1 \sin \theta_1$. Thus, we must divide by A_1 and multiply by R_1 to get $R_1 \cos \theta_1$ (and $R_1 \sin \theta_1$). The circuit arrangement produces this computation.

5.3.2.3 Display

For the feasibility model, a conventional laboratory oscilloscope was used as a display device. This type of oscilloscope is naturally suited to the cartesian coordinate system, and was used to provide a display means requiring no development time. The type of display used in the

design of flight hardware may be of different design; for example, it might use polar coordinates R and θ instead of x-y coordinates, or it might use x-y coordinates in digital form. The type of display or the design of a display device is a factor that will be given more attention during the next phase of this work.

5.3.2.4 Power

Regulated dc power supplies used in the feasibility model were as follows:

<u>dc Voltage</u>	<u>dc Current</u>	<u>(Power) Watts</u>
+ 22 V	100 MA	2.2 w
- 22 V	27 MA	0.6 w
+ 15 V	132 MA	2.0 w
- 15 V	132 MA	2.0 w
+ 1100 V (MPT's)		

In addition, the two chopper motors each draw about 0.5 A rms, 55 watts, from the 115 V 60 cps line.

Breadboard Electronics System and Oscilloscope Display

Figure 22

6.0 SYSTEM EXPERIMENTS AND FEASIBILITY OF DEMONSTRATION

The objective of this program was to conduct experiments and to provide a feasibility demonstration of an actual working piece of equipment.

After design, fabrication, and testing, the subassemblies were interconnected to form a complete operating system. Various calibration tests, experiments, and measurements were performed to experimentally verify the system concept. The breadboard system verified the feasibility of the system concept. Valuable practical experience was obtained which will speed the development of an operational flyable formation keeping system. Figure 22 is a photograph of the breadboard electronics system and the oscilloscope display (excluding the stationary array detector).

Since there is little build up in air for the ranges considered, it is expected that the range and angle accuracy will remain within the specified limits as the distance is increased, until the count rate falls below the figure of 2000 counts per second. The dynamic range in counts for a distance change from 100 feet to 500 feet is about 100:1. The electronics developed can cover this range. It is expected that any installation will provide adequate shielding between the source and detector on the same aircraft.

6.1 Optimization and Calibration of System

The sources were designed with "gun sights" so they could be accurately "pointed" toward the detector. In a flyable system, omnidirectional sources will be used. Tests showed that irregularities in the field caused the movable source to tilt up or down as it was moved about. This caused insignificant changes in the signal received at the detector.

Individual electronics units were designed to be independent of one another. Individual gain adjustments were provided in each unit for calibration purposes.

The stationary array detector assembly and the four MPT's and four signal processing channels were calibrated. All four channels were matched as closely as possible. The gain of each MPT was individually adjusted to "match" noise count rates (total background plus noise) from each tube. Also, a threshold amplitude adjustment in each processing channel was adjusted to discriminate the signal from the tube noise. All four channels were matched at a range of 50 feet. Matching was accomplished with adjustable gain amplifiers (C_1, C_2, C_3, C_4), so that the resulting output voltage of all channels may be identical. Minor final adjustments to the position and shape of the corrective lead shield on the detector were performed where necessary to obtain an angular detector response shape as close as possible to a sinusoidal response to azimuth changes.

Input e_{in} and output e_{out} voltage of the range computer were calibrated to fit the equation

$$e_{in} = \frac{K_1 e^{-\frac{e_{out}}{\lambda}}}{e_{out}^2}$$

where K_1 is a factor for proper conversion of units. This equation is the electrical analog of the range equation

$$A = \frac{k e^{-R/\lambda}}{R^2}$$

where A represents the detected count rate, R , the range in feet, and λ , the characteristic length for the gamma radiation in the air. Calibration points were $e_{out} = 10$ V for $R = 200$ feet and $e_{in} = 10$ V for $R = 50$ feet.

6.2 Range Measurements

The source was moved along a radial line over the range from 50 feet to 200 feet, and the corresponding movement on the oscilloscope display was observed. * When the source intensity was not modulated, the total count rate from two detector units varied from 17,000 counts/sec at 50 feet to 4,950 counts/sec at 100 feet, approximately, when the two detector units were "facing" the source so as to receive the equal maximum count rate. Of course, the count rate is reduced, as expected, to about half the above value when the source intensity is modulated.

Vertical and horizontal deflection amplifiers of the oscilloscope were calibrated so that a one centimeter deflection of the beam on the scope represented 50 feet of range.

The gain of the range filter and phase detector channels was calibrated to provide a 10 volt signal input to the range computer when the source was placed at a fifty foot range. The $\cos \theta$ filter and phase detector channel was adjusted to provide a 10 volt signal when the source was

* It was found that actually 150 feet was the maximum usable range because of the small source strength used.

placed at $\theta = 0^\circ$ and $R = 50$ feet. The $\sin \theta$ filter and phase detector channel was calibrated to provide a 10 volt signal when $\theta = 90^\circ$ and $R = 50$ feet. Instead of moving the source in the field for the above calibration, it was left at $R = 50$ feet and $\theta = 0^\circ$ and the detector was rotated to simulate $\theta = 90^\circ$. In this manner, precision angular settings could be obtained and the range was always a constant at 50 feet as initially set. After calibration (with $R = 50$ feet), the detector was rotated to various angles (e.g., $\theta = 0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ$, etc.), and the range $A \cos \theta$ and $A \sin \theta$ channel outputs were measured to assure proper calibration.

6.3 Direction Measurements

Direction measurements were performed both by moving the source along a circular path about the detector and also by rotating the detector assembly. By leaving the source fixed and rotating the detectors through a full revolution, the full 360° geometry of the system was verified by observing the path traversed by the spot on the oscilloscope. Slight deviation from a perfect circle, as the detector assembly was rotated a full revolution, was more or less expected from the slight deviation of the detector angular response from pure sinusoidal response.

The signal processing electronics design was greatly simplified by assuming sinusoidal detector angular response since the oscilloscope effectively performs a vector addition to produce the R and θ coordinates

from x-y coordinate inputs to the scope.

A final detector design would improve this angular response deviation. It is also possible that the signal processing electronics be redesigned to handle detector angular response other than sinusoidal responses.

6.4 Identification of Different Sources

To prove from a practical viewpoint that the system can operate with more than one source, two sources were used simultaneously; one was located at a fixed point on the field and one was moved about on the field. The two sources were modulated in intensity by 60 and 90 cps, respectively. This arrangement was chosen for convenience only and both sources could have been moved if desired. The position of the movable source was varied about the field, and its movement relative to the fixed source (and to the detectors) was observed on the scope. Figure 23 is a photograph of the oscilloscope display when the two sources were within one foot of each other and both at a range of 100 feet and $\theta = 30^\circ$ from the detector assembly. Figure 24 is a close-up photo of the same condition, while Figure 25 is a photo of the two sources on the field (source and its housing removed) for this condition. The exceptional resolution of the system is apparent in these photographs. The system has the ability to distinguish between two sources located very close to each other.

Oscilloscope Display of Two Sources Close Together

6-7

Figure 23

Close-Up View of Oscilloscope Display
with Two Sources Close Together

6-8

Figure 24 ·

Actual View of Two Sources in the Field

Figure 25

6.5 Feasibility Demonstration

In December 1965, Industrial Nucleonics Corporation held a feasibility demonstration of the breadboard formation keeping system. All major operational aspects of the system were demonstrated, including most of the measurement observations discussed above. The demonstration was quite successful and proved the objective of the program.

7.0 CONCLUSION AND RECOMMENDATIONS

On the basis of the discussions presented in the preceding sections of this report, it can be concluded that the nucleonic Helicopter Close-Order Formation Keeping System as conceived and developed by Industrial Nucleonics Corporation is definitely feasible. The principles of the stationary array detector assembly for continuous range and direction measurements and of the intensity-modulated radiation signal for the simultaneous separation of information from different helicopters are all proved to be sound.

The development of a flight model and the actual demonstration of the system aboard helicopters is deemed feasible.

In the work to be continued, several areas will require special consideration. Some of these are: (1) a phase-locked loop must be developed, (2) interactions in the signal processing between two different intensity-modulated radiations must be minimized, (3) drift in the range computer must be minimized, (4) a much larger source strength of a kind other than Am-241 will be used to cover the range of interest, (5) a new intensity-modulating mechanism will be designed and tested, (6) an improved stationary array detector assembly will be designed and tested, and (7) small, reliable filters will have to be developed.

The detailed discussions on the second phase of the Helicopter Formation Keeping System are presented in the proposal submitted by Industrial

Nucleonics Corporation on October 18, 1965, to the Bureau of Naval
Weapons, Department of Navy, Washington, D. C.

8.0 APPENDIXES

8.1 Appendix I - Angular Dependence of Detector Aperture

The effect of a collimator on the radiation detection may, in general, be divided into three different parts: (1) geometrical aperture, A_g , (2) penetrating aperture, A_p , and (3) scattering aperture, A_s . Aperture is defined as the difference between the flux of unidirectional radiation passing through a shielding material of finite thickness with and without a collimator hole, divided by the incident flux per unit area found at the center of the collimator hole.

A rigorous treatment of collimator effect on radiation detection is difficult due to complex geometrical relations among such parameters as the angle of incidence, the shape of collimator, detector and source configurations, distance between the source and the detector, etc. The problem is further complicated by various interactions that the incident radiation undergoes in the collimator material.

Calculations using the geometrical aperture alone do not usually give a satisfactory result since they are based on the assumption that the collimator material is completely opaque and non-scattering. The deviation becomes especially significant when the energy of gamma radiation is highly penetrating. The deviation is corrected for by addition of the penetrating aperture and the scattering aperture to the geometrical aperture.

However, when the energy of radiation is low and the collimator material is of a high Z element, the geometrical aperture is often found to be a reasonable approximation for many practical engineering problems. In particular, the scattering aperture is relatively small because of relatively small cross sections for the Compton scattering. Thus, the penetrating aperture is the only useful correction if it is needed. The sum aperture is, then,

$$A_s = A_g \left(1 + \frac{A_p}{A_g} \right) \quad (28)$$

8.1.1 Geometrical Aperture

It is assumed that the collimator is made of a non-scattering, perfectly opaque material. If the source emitting monoenergetic gamma rays (or X-ray) is placed at a great distance from the detector, then the incident radiation may be taken to be a parallel beam for all practical purposes.

The collimator under discussion is in the form of a slit having the width a , length b , and depth c , as shown in Figure 26. When the source is located along the z -axis, the maximum aperture of the detector is obtained. As the collimator rotates on y -axis, the detector area exposed to the incoming beam decreases, becoming finally nil when the angle of rotation reaches θ_0 .

The geometrical aperture A_g is found to be related to the angle of rotation by

$$A_g(\theta) = 2b(a - c \tan \theta) \cos \theta \quad (29)$$

APERTURE OF A SLIT COLLIMATOR

FIGURE 26

The angle θ_o subtended at the center 0 by the width a of collimator is simply

$$\tan \theta_o = \frac{a}{c} \quad (30)$$

Finally, substitution of Equation (13) into Equation (12) gives

$$A_g(\theta) = ab \left(\cos \theta - \frac{\sin \theta}{\tan \theta_o} \right) \quad (31)$$

Equation (14) shows that as θ_o decreases, i. e., as the slit becomes narrower for a given depth c , the slope also decreases. It means that the directional accuracy increases proportionally with the decrease in the geometrical aperture, as obviously expected. It has been discovered, however, that a substantially higher directional accuracy is obtained by a certain signal process rather than merely by the geometrical aperture.

Integrated geometrical aperture is

$$A_{gt} = 2ab \int_0^{\tan^{-1} a/c} \left(\cos \theta - \frac{\sin \theta}{\tan \theta_o} \right) d\theta = \frac{2ab}{\sin \theta_o} (1 - \cos \theta_o) \quad (32)$$

Finally, differentiation of Equation (9) with respect to θ gives

$$\frac{dA_g(\theta)}{d\theta} = -ab \left(\sin \theta + \frac{\cos \theta}{\tan \theta_o} \right) \quad (33)$$

Equations (14) and (16) are plotted for $\theta_o = 5.71^\circ$ and shown in Figures 27 and 28, respectively.

APERTURE FUNCTION
FOR $\theta_0 = 5.71^\circ$

———— GEOMETRICAL APERTURE (A_g)
----- APPROXIMATE SUM APERTURE ($A_g + A_p$)

FIGURE 27

DERIVATIVE OF APERTURE FUNCTION
FOR $\theta_0 = 5.71^\circ$

FIGURE 28

8.1.2 Penetrating Aperture

Only one collimator is analyzed for penetrating aperture. The analysis can be extended, when necessary to the case of multiple parallel slits comprising the final collimator aperture.

The slit collimator has the width a , the length b , and the depth c , as before. The two identical slabs forming the slit have the thickness d and are made of a high density material to act as a radiation shield. The collimator is attached by some mechanical means to a rotating platform of which the center coincides with the axis of a fixed detector. The detector may be in the form of a cylinder or even a section of sphere, whose side is properly shielded with the exception of the collimator-aperture. The radius r of the rotating platform may be taken to be approximately equal to that of the detector.

It is assumed that the source is placed on the (x, z) plane, and that the distance between the source and detector is so large that the radiation incident on the detector is virtually a parallel beam.

The problem is to determine the path length ℓ as a function of rotating angle θ' that a ray takes in traversing the slab. The primary ray of a given energy is then attenuated by a factor $e^{-\mu_c \rho_c \ell(\theta)}$, where μ_c and ρ_c are the mass absorption coefficient and the density of the slab material, respectively. Only the attenuated primary rays are considered to contribute to the penetrating aperture. With reference to Figure 26 and the symbols designated therein, it can be shown that the following geometrical relations hold for rays passing through the center.

$$(\theta') = \frac{c + r}{\cos \theta'} - \frac{a}{2 \tan \theta' \cos \theta'} \quad (\theta_1' \leq \theta' \leq \theta_2') \quad (34)$$

$$(\theta') = \frac{d}{\sin \theta'} \quad (\theta_2' \leq \theta' \leq \theta_3') \quad (35)$$

$$(\theta') = \frac{a + 2d}{2 \tan \theta' \cos \theta'} - \frac{r}{\cos \theta'} \quad (\theta_3' \leq \theta' \leq \theta_4') \quad (36)$$

and also,

$$\tan \theta_1' = \frac{a}{2(c + r)}, \quad \tan \theta_2' = \frac{a + 2d}{2(c + r)} \quad (37) \text{ \& } (38)$$

$$\tan \theta_3' = \frac{a}{2r}, \quad \tan \theta_4' = \frac{a + 2d}{2r} \quad (39) \text{ \& } (40)$$

For given constants a , c , and d , the path length (θ') can be computed using the above relations. The path length for a given angle θ' is then used as the magnitude of penetrating aperture in terms of $e^{-\mu_c \rho_c}$.

If a beam of parallel rays is incident on the detector at an angle θ , the slab casts a shadow on the detector window. The area that remains exposed comprises the geometrical aperture; the shadowed area becomes the penetrating aperture by virtue of the rays partially transmitted through the slab. The penetrating aperture will not, in general, be uniform even for a given angle of incidence because of the peculiar shape of the slab. It should be expected that that portion of the shadow cast by the upper edge of the slab will contribute more to the penetrating aperture than the other.

When the penetrating aperture is added to the geometrical aperture, it will result in the decrease of a slope of the aperture curves. This is approximately represented by a dotted line in Figure 27. The degree of

this change depends on the energy of gamma rays, the mass absorption coefficient and the density of the slab material. Clearly, the larger the product $\mu_c \rho_c \mathcal{L}(\theta)$, the greater the degree of collimation, for it will then depend mainly on the geometrical aperture. It is believed that $A_p A_g$ in Equation (28) could be made smaller than 0.1 by using a low energy photon of the order of 100 keV or less and a proper high density material for the slabs.

8.2 Appendix II - Analysis of Statistical Fluctuation in Measurements

From Equations (13) thru (16), one can write

$$\tan \theta = \frac{C_1 - C_3 + C_2 - C_4}{C_1 - C_3 - C_2 + C_4} = \frac{G}{H} = U \quad (41)$$

where G = numerator and H = the denominator of the fraction.

To find the variance in the angle θ measurement, we write,

$$\theta = \tan^{-1} U \quad (42)$$

and

$$\sigma_\theta = \frac{d}{dU} \left[\tan^{-1} U \right] \sigma_U = \frac{\sigma_U}{1 + U^2} \quad (43)$$

where the symbol σ is used for the standard deviation.

From statistical theory for variables of the type under consideration,

$$\left(\frac{\sigma_U}{U} \right)^2 = \left(\frac{\sigma_G}{G} \right)^2 + \left(\frac{\sigma_H}{H} \right)^2 \quad (44)$$

For nuclear radiations,

$$(\sigma_G)^2 = C_1 + C_3 + C_2 + C_4 = (\sigma_H)^2 = B \quad (45)$$

where B is the total direct count received by the detectors for some distance R .

From (45) and (44),

$$\sigma_U = U B^{1/2} \left(\frac{1}{G^2} + \frac{1}{H^2} \right)^{1/2} = \frac{B^{1/2}}{H^2} (H^2 + G^2)^{1/2} \quad (46)$$

Therefore, from (46) and (43),

$$\sigma_{\theta} = \frac{B^{1/2}}{(H^2 + G^2)^{1/2}} = \left\{ \frac{C_1 + C_2 + C_3 + C_4}{2 [(C_1 - C_3)^2 + (C_2 - C_4)^2]} \right\}^{1/2} \quad (47)$$

If $\theta = 45^\circ$ and $B = 200$ counts, then $C_4 \approx C_2$, $C_3 \approx 0$, and

$C_1 \approx 141$, and

$$\sigma_{\theta} \approx \left[\frac{200}{2 \times (141)^2} \right]^{1/2} = \frac{1}{14} \text{ radian} = 4.1^\circ$$

Similarly, for $\theta = 0^\circ$ and $B = 200$ counts, $\sigma_{\theta} = 5.7^\circ$. This indicates that the system must always receive more than 200 counts per resolving time interval to meet the one σ accuracy of $\pm 10\%$ on range and angle.

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