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A SYSTEM FOR PREVENTING AIRCRAFT COLLISIONS

BY

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Graduate Aeronautical Engineering
August 1962

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A SYSTEM FOR PREVENTING AIRCRAFT COLLISIONS

THESIS

Presented to the Faculty of the School of Engineering of
the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

By
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Preface

As an Air Force pilot I have a special interest in the search for a method of preventing collisions between aircraft. My first "near miss" occurred in 1943 in Primary Flying School. More recent ones in B-36's and B-52's have sharpened my personal concern with the problem.

This report approaches the subject of collision prevention from the viewpoint of the pilot, and the proposed system is based the requirements I as a pilot would like to have met in such a system.

The bibliography by no means completely covers all that has been done or proposed in the field of aircraft collision prevention. New ideas and proposals are put forth almost weekly, so that a bibliography of the subject cannot be kept up to date. However, the sources listed have been helpful in my investigation, and should be useful to anyone interested in this subject.

In my investigation I did not try to design radio circuits for the system. My concern was to determine whether the ideas I propose can be applied using present knowledge of electronics. For this information I relied very heavily on my Faculty Thesis Adviser, Captain Matthew Kabrisky, of the Department of Electrical Engineering, Air Force Institute of Technology. To him I express my special thanks.

John F. Welch

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Abstract

A cooperative system for preventing aircraft collisions is possible. This report proposes one which requires the equipping of each aircraft with a radio tuned to a frequency varying with altitude, for the exchange of collision-prevention information. Warnings can be kept to a minimum without omitting valid ones by limiting the range of the radio. This can be done by adjustment of the power of the transmitter and of the sensitivity of the receiver. Minimum initial warning time of 80 seconds is recommended, to be maintained by varying actual range with airspeed.

Three or more levels of equipment complexity are possible, with all fitting into the same system. The most complex provides the pilot with bearing to the intruder, heading of the intruder and distance to the intruder. The next lower level omits the distance measurement. These two present their information on a Collision Avoidance Indicator (CAI). The least complex set of equipment omits the bearing and heading information as well as distance measurement, but has a sector indicator, called a Pilot Warning Instrument (PWI), to show the relative position of the intruder.

The Collision Avoidance Indicator eliminates unnecessary turns to avoid collision, and provides information to minimize the degree of turn made. Use of the Pilot Warning

Instrument will result in some unnecessary turns, but none of them more than 90°. The system provides for avoiding two or more intruders in close proximity or quick succession.

The primary rule for use of the system is as follows: Turn right to avoid a threat from ahead, and turn left to avoid a threat from behind.

The system can be used for ground control of air traffic, and for closer spacing of Instrument Flight Rules traffic. It can also be used to mark tall man-made obstructions to air traffic.

A SYSTEM FOR PREVENTING AIRCRAFT COLLISIONS

I. Introduction

The purpose of this investigation was to devise a system which could eliminate the growing problem of collisions between aircraft whose pilots are not aware of each other's presence. The problems of collision with other aircraft in the same formation and with terrain were not considered. Primary consideration was given to presenting to the pilot the information he needs to avoid collision, in a readily understood and easily used form.

When the word "intruder" is used in this report, it means another aircraft detected by one's own collision prevention equipment.

To solve the collision problem, it must be assumed that an intruder's path is to some extent predictable; it is expected to continue on the same heading or to turn only in a direction which will avoid collision. No attempt was made to provide for avoidance of aircraft performing acrobatics, turning at very high rates, or making extremely rapid climbs or descents.

As of early 1962, there were 111,580 aircraft using American airspace, of which about 40,000 are in flight over the United States each day (Ref 19). The number is greater when the weather is good, and less when there are large areas of bad flying weather. The large majority of near misses and mid-air collisions occurs in good weather, between small aircraft (Appendix A). Small aircraft must therefore be considered in any proposed system.

II. History of the Mid-Air Collision Problem

The first mid-air collision in the United States, between two JN-4's ("Jennies"), occurred on August 17, 1917, initiating what has been a problem of aviation ever since. There were 45 such accidents in 1918, causing 22 fatalities. The curtailment of flight training at the end of World War I resulted in a decreased rate, but the yearly total reached 45 again in 1941, and has continued at a high rate ever since (Ref 11).

In 118 major mid-air collision accidents between non-associated (not in formation) aircraft in the years 1950 to 1958, the Air Force lost 163 aircraft, and each of 88 of these accidents resulted in one or more fatalities (Ref 11). From 1938 through 1961, there have been 410 mid-air collisions in which at least one of the aircraft was not military. The average number has been about 18 per year. 834 deaths occurred in 214 of these collisions, with the years 1949, 1956, 1958 and 1960 accounting for more than half of them (Ref 4).

Efforts to Reduce Mid-Air Collisions

A large part of civil and military air regulations has grown out of the effort to avoid mid-air collisions. Traffic patterns at airports, rules establishing rights of way, minimum distance from clouds under visual flight rules, and altitude assignment according to course are all part of this endeavor.

Visual Aids. A very large effort has been devoted to making airplanes more conspicuous to the eye, based on the concept of avoiding collision visually. To this end, bright colors, reflective paints and various lighting systems have been tried (Ref 4). All these have been helpful, but depend upon the human eye, which must be aimed at and focused on its target (Ref 10).

Non-Visual Aids. Because human eyesight has proved to be inadequate to prevent mid-air collisions (Appendix B), many non-visual means of detecting other aircraft have been proposed. Adaptations of airborne radar have figured prominently in these proposals. Experimental work has been done with infra-red detectors, and with ultra-violet systems. Quite a number of proposals feature the use of radio (Ref 13). Some of the systems, such as those using radar and infra-red, are non-cooperative systems; that is, they depend on equipment installed on only the detecting aircraft. Most others, including all those using radio, are cooperative; they depend upon an exchange of information between aircraft. The Federal Aviation Agency's Research and Development Service, which is the governmental agency charged with development and testing of an anti-collision system, has "practically abandoned any hope of coming up with any self-contained (non-cooperative) type anti-collision or proximity warning system" (Ref 12).

III. Requirements for a Satisfactory System

The requirements described in the paragraphs which follow are based on pilot experience and on those given by other investigators (Refs 1, 11, and 15).

Information Required

The information needed by a pilot in order to determine whether a collision hazard exists, and how to avoid any that does exist, includes relative position of the intruder, at least an estimate of his distance, and if possible his heading (Ref 11). Knowing an intruder's heading can in many cases preclude an unnecessary avoiding turn, since its heading may be such that no threat of collision exists.

All Weather

Any system for preventing mid-air collisions must certainly be adaptable to all kinds of weather conditions, even though the majority of collisions and near misses does occur in good weather (Refs 4 and 16). Instrument flight rules do not always succeed in maintaining separation between aircraft, as was shown by the collision of two airliners over Staten Island, New York, on December 16, 1960 (Refs 12, 5 and 6).

All Aircraft

To be really effective, a collision prevention system must be applied to all aircraft. Since a cooperative system, in which all aircraft must carry some kind of equipment, offers the best hope of success (Ref 12), this requirement has special significance for light plane owners, and for the designer of the system, related to the weight and the cost of the equipment.

Weight. The light plane, as defined here, is capable of carrying no more than four or five people, or an equivalent amount of cargo. It cannot accommodate additional equipment weight which might seriously reduce its allowable load. The problem is even more critical in one-place and two-place airplanes. Collision prevention equipment for the light plane must be light in weight and small in size.

Cost. Many light plane owners have little more invested in their airplanes than in their automobiles. They would be financially unable to buy anti-collision equipment costong thousands of dollars. The cost of installing the minimum equipment to fit an airplane into the over all system must, therefore, be kept as low as possible consistent with required performance. There is the prospect that should such equipment be required on all aircraft, production runs would be long enough to bring the costs below those expected from current experience.

Limited Range

A device for detecting intruders for the purpose of avoiding collision with them should search only those areas from which a colliding aircraft can come. Detecting aircraft safely separated from the detector by altitude or by distance or by both would unnecessarily distract the pilot and overload the system.

Altitude Coverage. During normal cruise, a pilot generally maintains altitude at some multiple of 500 or 1,000 feet. 3,500 feet, 4,500 feet, 5,500 feet, et cetera, are used for visual flight rules under 29,000 feet, and multiples of 1,000 feet are used for instrument flight rules and for all flights above 29,000 feet. Because safe altitudes are located 500 feet apart vertically, the maximum vertical extent of search should not be more than from 300 feet below to 300 feet above the aircraft's flight level when in level flight. While climbing or descending, however, an aircraft should also search the levels it will penetrate within a reasonable warning time. A reasonable warning time is that length of time which will permit evaluation of the threat of collision followed by any necessary evasive maneuver.

Horizontal Range Coverage. In the horizontal plane, distance between two aircraft is most logically expressed in terms of the length of time it would take for the two to reach each other while maintaining their original headings. Distance thus expressed could be obtained from a computer supplied with bearings, headings, airspeeds and measured distances. Because such a system would immediately become too expensive for use on light planes, the requirement here established is that a basic warning time of one minute and twenty seconds be used. Based on this warning time, two airplanes approaching each other head-on at equal speeds would exchange warnings at a maximum horizontal distance equal to twice as far as one of them would travel in a minute and twenty seconds. A faster airplane thus should have greater horizontal search range than a slower one. Furthermore, for airplanes cruising faster than some basic speed, here chosen to be 180 knots, search and warning range should increase directly with increase in speed. These range considerations are based on a head-on approach; for any angle away from head-on the warning time would be correspondingly greater. This arrangement could be modified by having maximum range forward, less range to the sides, and least range to the rear, but such a feature is not here made a requirement.

Reliance on Pilot Judgment

Until flight becomes entirely automated, the pilot must continue to be in command of an airplane. Some proposals for Collision Avoidance Systems recommend that computers be given the task of detecting and evaluating threats of collision (Ref 15). If the computer should determine that a threat existed and that a maneuver was necessary, it would direct the pilot to make a specified maneuver, or accomplish it automatically through the autopilot (Ref 1). Even if this approach is taken, the pilot should still be able to monitor the equipment and intervene when his judgment indicates that he should. To be sure of maintaining pilot responsibility, the requirement here made is that the pilot be in full control of both the collision prevention system and the aircraft.

Easy to Use

A system for preventing mid-air collisions must present the necessary information to the pilot in a form which he can quickly interpret and from which he can readily determine what maneuver, if any, he must make.

IV. Proposed System

The system here proposed for preventing aircraft collisions uses radio as a means of communicating collision prevention information. The methods of establishing vertical and horizontal range will be discussed, then applications of the full equipment, partial equipment and minimum equipment of the system will be described.

Altitude Discrimination

The segment of altitude searched and broadcast into is limited by frequency tuning. Primary tuning of each transmitter and receiver is controlled by a sealed static pressure sensing unit, which varies frequency directly with altitude. No adjustments are made to compensate for changes in station barometric pressure. Each pressure sensor - tuning unit combination is periodically calibrated and adjusted if necessary, so that every set will tune to exactly the same frequency at any given static pressure.

Static Pressure Error. Properly located and maintained static pressure ports provide quite accurate readings at airspeeds below 250 knots. For aircraft flying at high subsonic speeds, however, the error may be several hundred feet, seriously affecting frequency tuning based on altitude. William Gracey and Virgil S. Ritchie, of the National Aeronautics and Space Administration, have designed a static pressure tube to compensate for these errors. It is mounted on a boom projecting at least 0.27 of the fuselage diameter forward from the nose. It compensates for static pressure measurement errors to within 1/2 percent at Mach numbers up to about 1.0 (Ref 9).

Altitude Overlap. Receiver frequency spread on both sides of the nominal frequency below 29,000 feet pressure altitude permits sufficient overlap to allow communication between sets within 300 feet vertically of each other. Above 29,000 feet the overlap zone increases to 600 feet.

Frequency Band. The frequency band, subject to relinquishment by a few present users and allocation by the Federal Communications Commission, is in the Ultra High Frequency range, from 370.0 to 399.9 megacycles. These frequencies are already allocated to aviation use, for air-to-air and air-to-ground communications (Ref 2).

Climb or Descent. For climb or descent, a secondary tuning control operated by a vertical speed sensor increases the frequency spread of the receiver to include the frequencies of all those altitudes which the aircraft will occupy within the ensuing minute and twenty seconds if it continues at the same vertical speed. The secondary tuning control does not operate for vertical rates less than 250 feet per minute. This eliminates false warnings which might occur because of moderate turbulence. A switch and related circuits permit the pilot to "look" above or below before starting climb or descent.

Maximum Range

Maximum range for exchange of information between aircraft is controlled by a combination of transmitter power and receiver sensitivity. Each aircraft has a detection "half-range" based on the air distance it covers in 80 seconds (Fig 1). Any two aircraft, except for those whose cruise speeds are slower than 120 knots, will detect each other at 80 seconds before meeting if their approach is head-on, or after some greater time period if it is not head-on. The distance between them at first detection is equal to the sum of their "half-ranges".

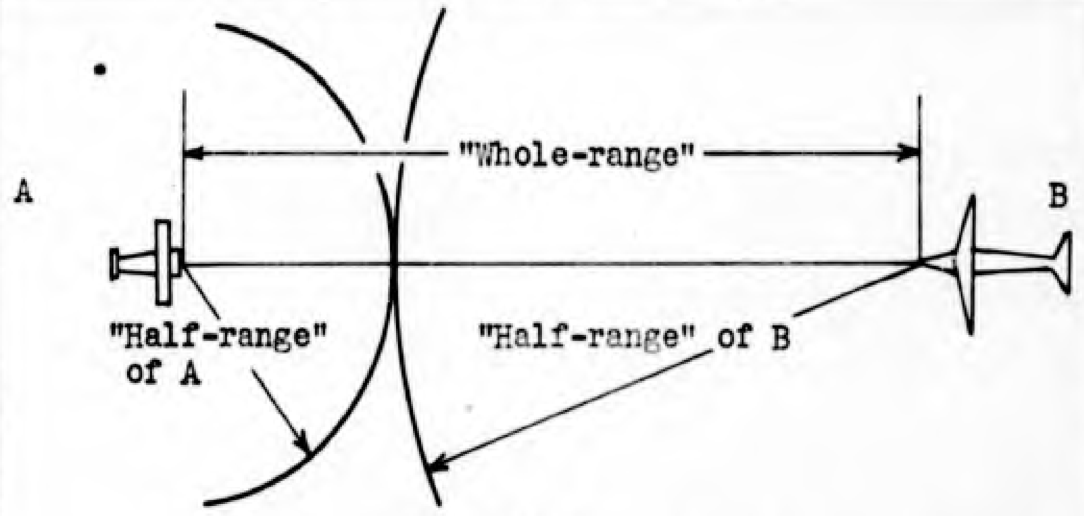

Fig. 1
Detection at the Sum of the "Half-ranges"

Fixed Range. Transmitter power and receiver sensitivity are maintained at fixed values for those aircraft with maximum cruise speeds less than 180 knots. For those capable of only 120 knots or less, the "half-range" is set at 2 2/3 nautical miles. For an airplane capable of a maximum speed between 120 and 180 knots, the "half-range" is set at the air distance it can travel at maximum cruise speed in 80 seconds.

Variable Range. Airplanes which cruise faster than 180 knots have a minimum "half-range" of four nautical miles. A unit controlled by true airspeed increases transmitter power and receiver sensitivity, with increase of true airspeed above 180 knots, so that "half-range" is maintained equal to the air distance the airplane travels in 80 seconds. As an example, two jet airliners both cruising at 450 knots true airspeed would detect each other when 20 miles apart. One of them would detect, and be detected by, a Tripacer at a distance of 12 2/3 miles. Two Tripacers would detect each other when 5 1/3 miles apart.

Fully Equipped Aircraft

A large, costly aircraft, such as an airliner, a bomber or other fast military aircraft, is equipped with the complete set of collision avoidance equipment. This equipment broadcasts collision avoidance information, receives such information from other aircraft, and presents it to the pilot

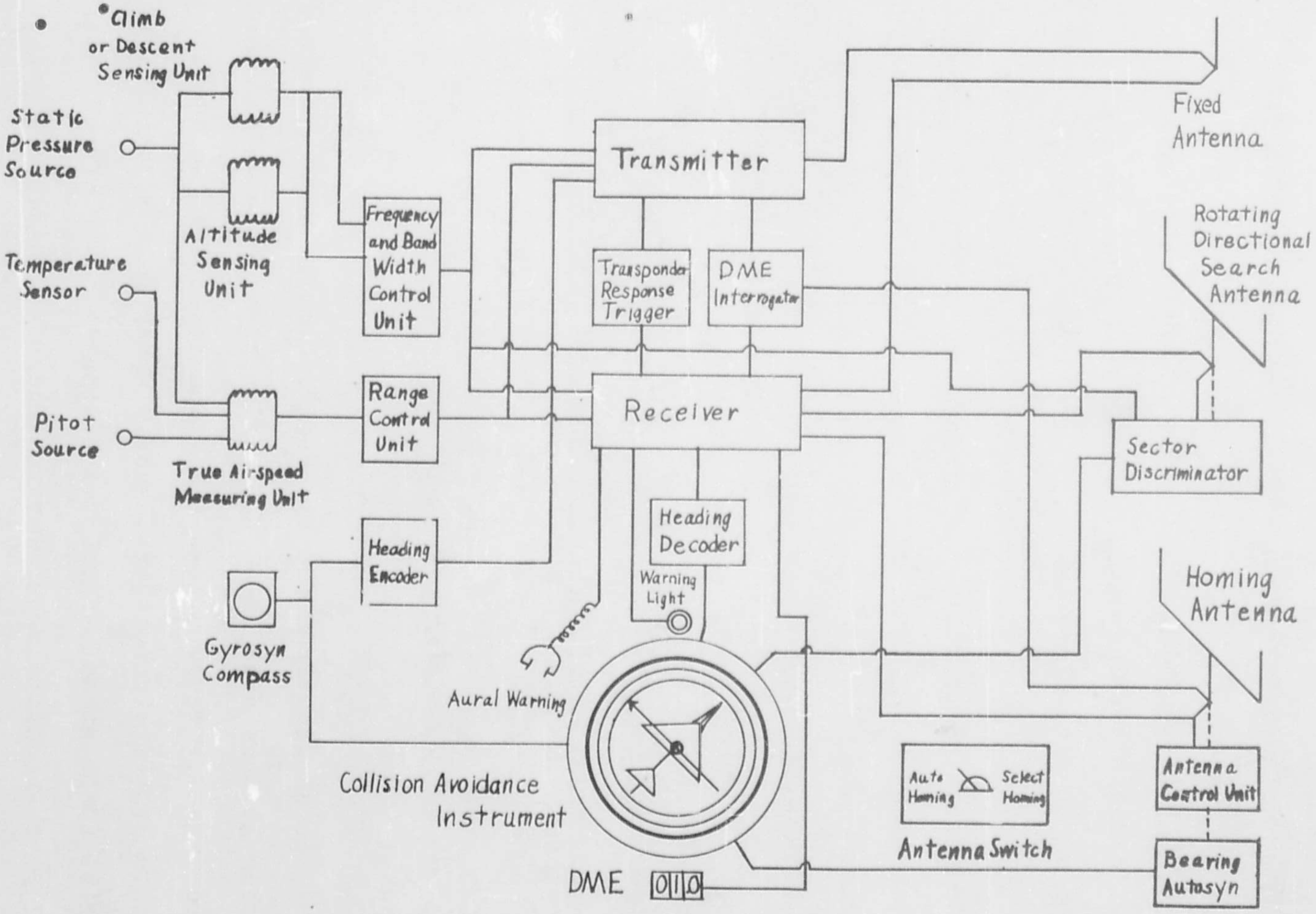

Fig. 2 Full Equipment, Collision Prevention System

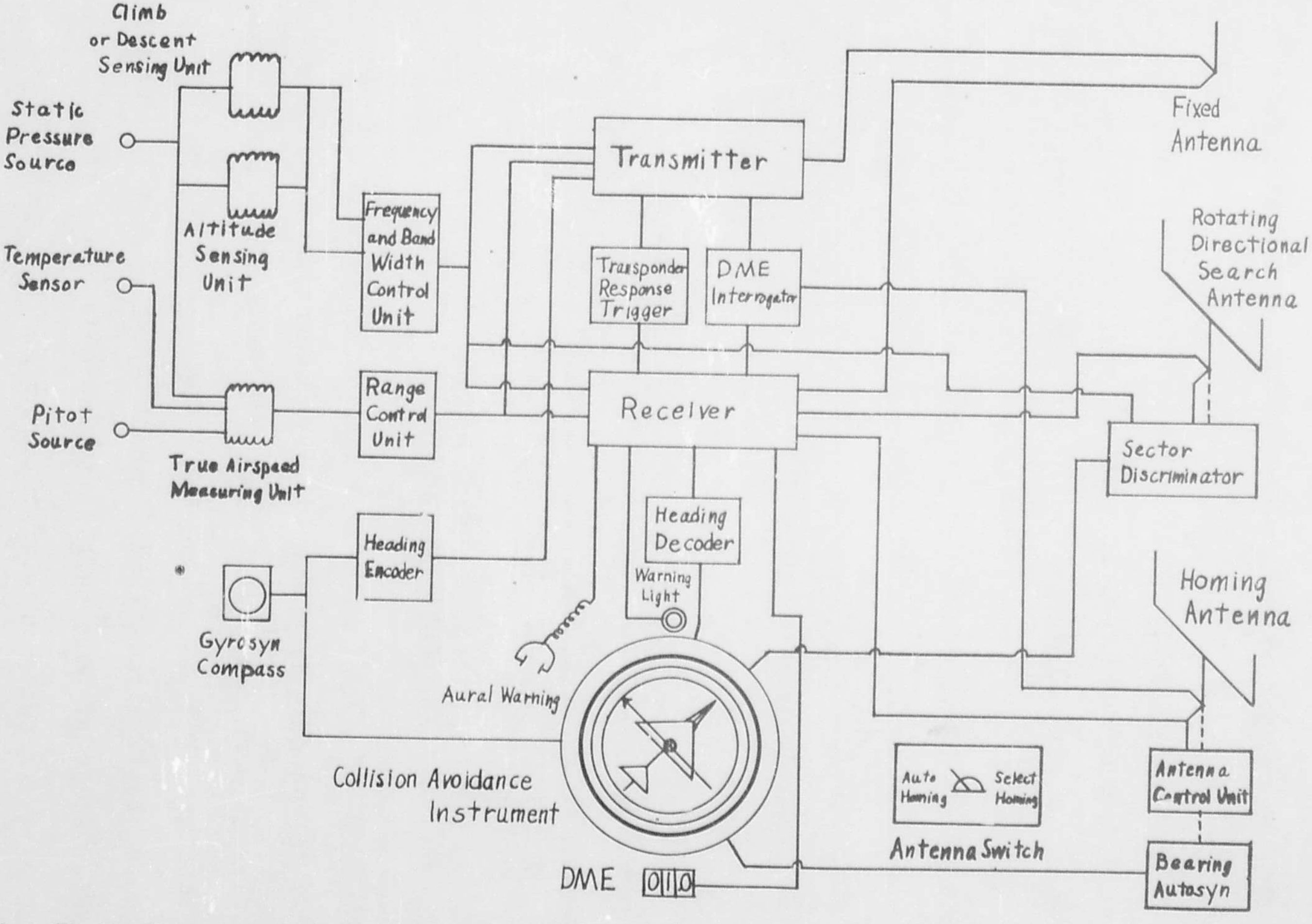

Fig. 2 Full Equipment, Collision Prevention System

in usable form. A block diagram of the full system is shown in Fig. 2.

Transmitted Data. Each radio of the system sends out a basic signal for approximately one millisecond, then listens for nine times as long. The times need not be exactly one millisecond and nine milliseconds, but their ratio should be maintained constant. On this basic signal are carried others (Fig. 3). A heading encoder (Fig. 2) takes the heading from the aircraft repeating compass system, encodes it, and adds it at the beginning and the end of the basic signal. Thus, unless the transmitted and received signals of two aircraft are exactly synchronized, each will receive at least some part of the other's basic signal, including its heading code. At the end of each basic signal, an interrogation pulse is sent, for distance measuring.

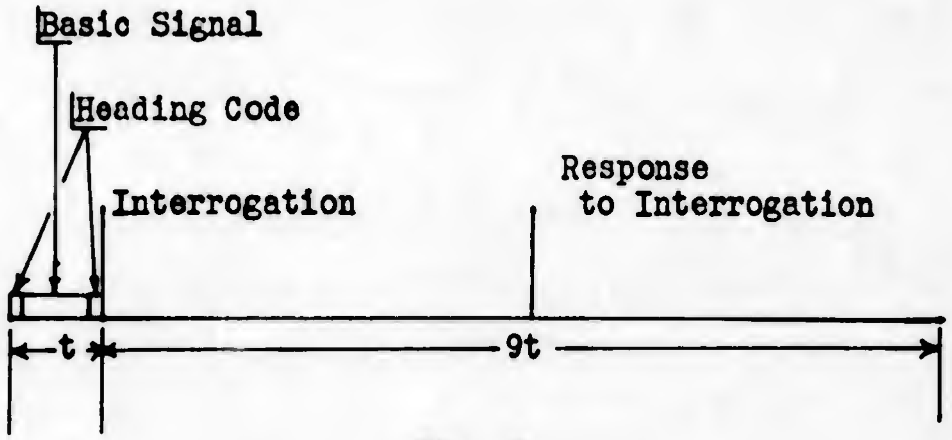

Fig. 3
Transmit-Receive Pattern
Transmissions

During its listening period of nine milliseconds, the receiver is listening on the fixed antenna for interrogations from other aircraft. An interrogation any time in the nine millisecond period triggers an instant response, transmitted on the fixed antenna. The basic signal and the coded heading are transmitted on the omnidirectional fixed antenna. Interrogation is sent out and response received on the homing antenna (Fig. 2).

Received Signals. When one or more aircraft are within range, the signals received are response to interrogation, basic signal with encoded heading, and interrogation pulses from another fully equipped aircraft.

Bearing Presentation. The relative bearing of another aircraft within range is shown approximately by the lighting of one of the 36 sector lights around the outer rim of the Collision Avoidance Indicator (CAI) (Fig. 4). The top index represents the nose of the aircraft at all times. The rotating directional search antenna rotates continuously at ten revolutions per minute. As it turns it picks up any signal, within range, on frequency, which it sweeps past.

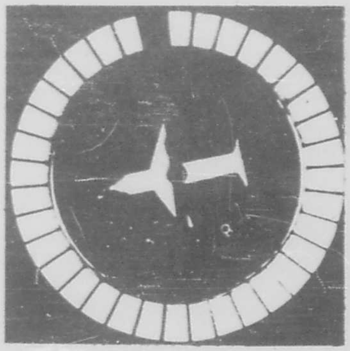

Fig. 4
Collision Avoidance Indicator

A signal received is translated by the sector discriminator (Fig. 2) into a sector light on at the relative bearing of the intruder. At the instant the rotating antenna sweeps past an intruder, turning on the sector light, a warning light above the CAI flashes, and a warning signal sounds in the pilot's headphones or speaker. Once a sector light is turned on, a hold down circuit keeps it on for two antenna rotations or twelve seconds after the last signal received in the sector. At any given time, there is a sector light on in each sector in which one or more intruders were detected within the last twelve seconds.

The bearing to an intruder is given more accurately by the bearing needle of the CAI (the narrow needle in Fig. 4). Its position corresponds exactly with that of the homing antenna (Fig. 2). The homing antenna is brought to within ten degrees of the bearing of a selected intruder by means of the antenna control switch and the control unit, then the control unit automatically aligns it on the bearing to the intruder. The bearing needle of the CAI then shows, in degrees measured from the top index, the relative bearing of the intruder. The rotating card of the CAI is synchronized with the repeater compass system of the aircraft, so that magnetic bearing to the intruder is read at the point of the needle.

Heading. The magnetic heading of the aircraft is shown by the reading on the rotating card under the top index of the CAI, just as it is on any compass repeater with a rotating card. The heading decoder of the receiver (Fig. 2) decodes the heading of the intruder from the incoming basic signal received on the homing antenna. It is presented on the heading needle of the CAI (the miniature airplane, Fig. 4). The magnetic heading of the intruder is read in degrees under the point of the heading needle. Relative heading is measured by the angle between the heading needle and the top index. If the intruder has minimum equipment, it will not be broadcasting heading. In this case the receiver rotates the heading needle counterclockwise at three revolutions per minute.

Distance. Each radio of the system contains a transponder which responds on the tuned frequency when triggered by the proper interrogating impulse, also on the tuned frequency. Each fully equipped radio of the system contains the interrogator and the circuitry for measuring distance by the time delay between interrogation and response. The distance measured is presented to the nearest tenth of a mile on a mileage dial located below the CAI. Interrogation is sent and response is received on the homing antenna, which limits them to the sector being checked by it at the moment.

Warning Light. The warning light above the CAI flashes a dash once every three seconds whenever one sector light is on, with a dot each time a sector signal is received. The dash is not given if more than two sector signals are being received.

Aural Signal. Dashes and dots with a distinctive pitch are fed into the pilot's earphones or speaker, in synchronization with the warning light.

Intermediate Equipped Aircraft

The complete equipment described above may prove more expensive than many business aircraft owners and small feeder line operators can afford. A somewhat less elaborate set which fits into the system is shown in Fig. 5. Simplification has been achieved by omitting interrogation, distance measuring circuits, the mileage dial, and the homing antenna. The number of sector lights is reduced from 36 to 18, reducing the cost and complexity of the CAI and of the sector discriminator.

Bearing. The rotating directional antenna rotates at ten rpm in the search mode. Whenever it sweeps past an intruder within range, the corresponding sector light comes on and the warning light and the aural signal operate. By means of the antenna control switch, the pilot stops antenna rotation in the desired lighted sector, and the antenna homes on the intruder automatically. The intruder's bearing

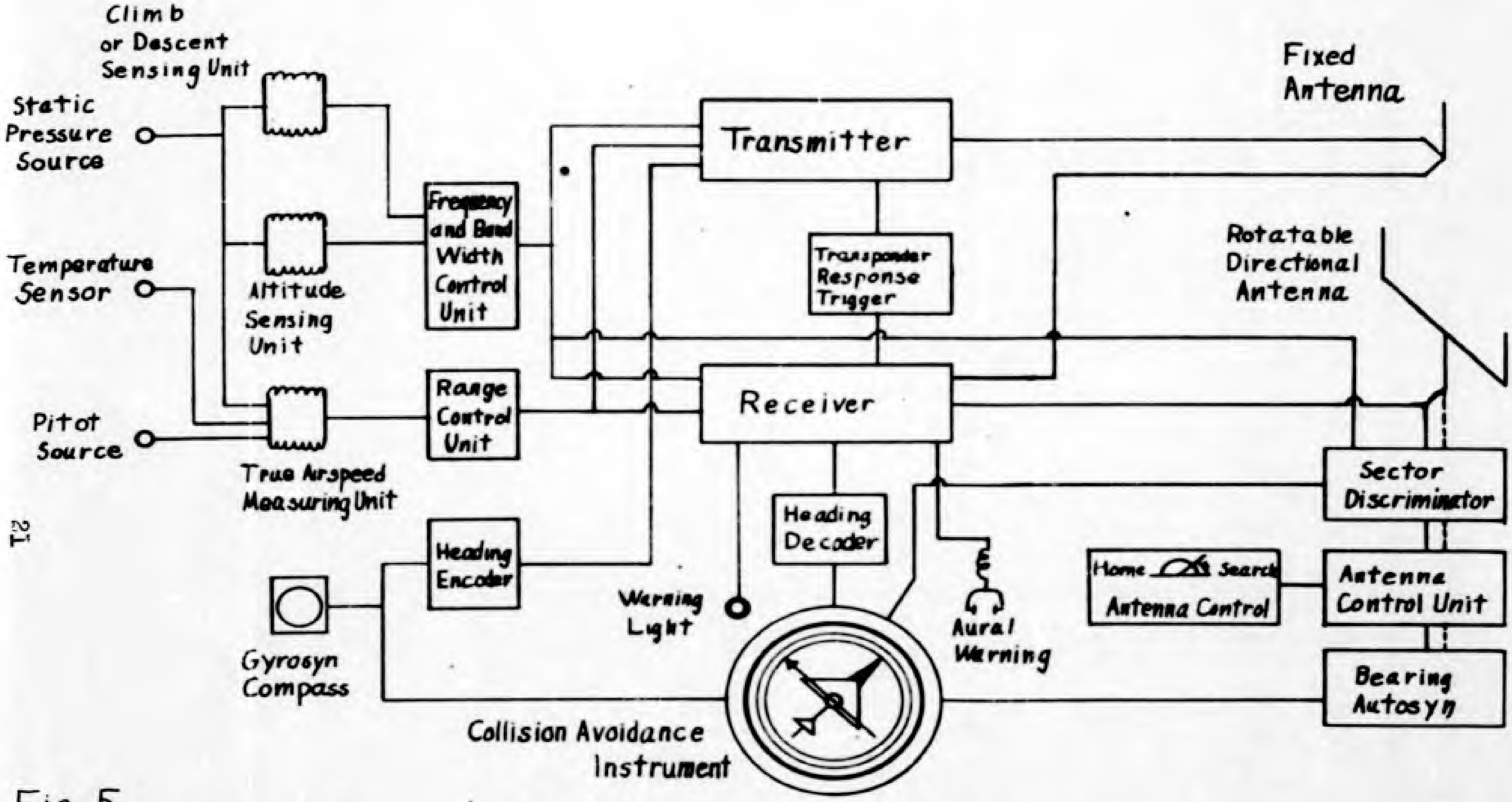

Fig. 5
Intermediate Equipment, Collision Prevention System

and heading are then read the same as described above. Search operation is resumed by returning the antenna control switch to the search position.

Minimum Equipped Aircraft

For the typical light plane, both cost and weight of the collision avoidance equipment must be kept as low as possible, as was pointed out in the preceding section. The proposed minimum equipment is shown in Fig. 6. It has no rotating antenna to obtain accurate bearing, and neither transmits nor receives heading information. It broadcasts the basic signal, and responds to interrogation of its transponder by fully equipped sets. The receiver flashes the warning light and sounds an aural warning in the same manner as with the more elaborate sets. The sector lights in the Pilot Warning Instrument come on to indicate in which ninety degree quadrants there are intruders within range.

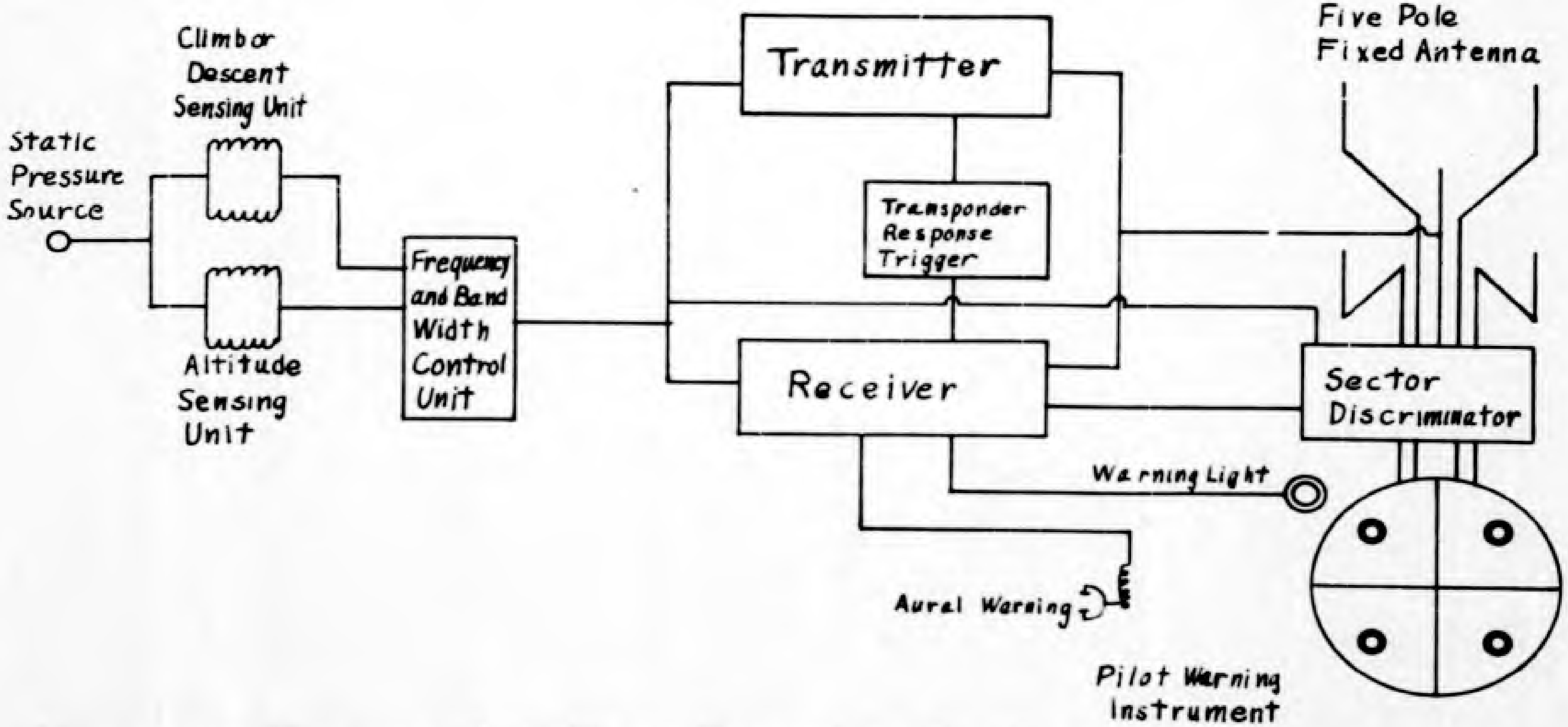

Fig 6. Minimum Equipment, Collision Prevention System

V. Operation of the System

The components described in the last section fit together to form the over all system. The method of operation is governed by the degree of sophistication of the equipment installed on the aircraft, but the basic principles and rules are the same for all aircraft.

Fully Equipped Aircraft

When a fully equipped aircraft comes within detection range of another fully equipped or an intermediate equipped aircraft, it makes use of the full system. If the intruder is a minimum equipped aircraft, it does not broadcast heading, consequently no heading information is received, and the heading needle of the CAI rotates counterclockwise at three rpm. This rotation is an immediate indication that the intruder is a light, slow airplane.

Warning. The first indication of an intruder is the initial flash of the warning light accompanied by the sounding of the aural signal, as the sector light comes on.

Selecting and Checking the Target. Upon hearing and seeing the warning signal, the pilot looks at the CAI to see which sector light is on, and with the antenna control switch turns the homing antenna to select the sector. He then switches back to automatic homing. The homing antenna swings to the bearing to the intruder, and the bearing needle shows its relative and magnetic bearings. The incoming signal is decoded and the heading of the intruder is indicated by the heading needle. The time delay between the interrogation signal and response on the homing antenna is converted into distance and is read in nautical miles under the CAI. Fig. 7 shows two aircraft approaching a collision point, and the indications on the instrument panel of the bottom one. The CAI shows an intruder 10° to the right of aircraft heading, on a bearing of 11°. The intruder's heading is 201°, and its distance is 6.2 nautical miles.

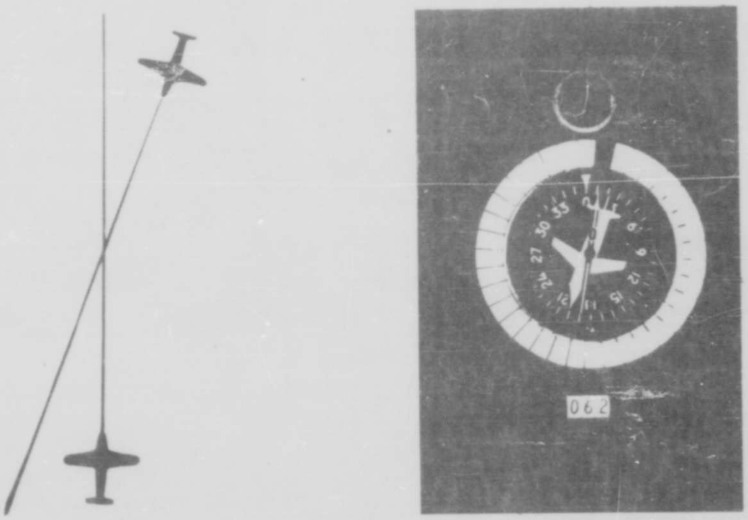

Fig. 7
Impending Collision

<u>Determining the Hazard</u>. A possibility of getting into

a position to collide exists whenever the heading of the aircraft lies within the angle less than 180° formed by the points of the two needles of the CAI; or put in another way, whenever the bearing of the intruder lies between the aircraft heading and the tail of the heading needle, collision is possible. These both say the same thing, that the paths of the two aircraft will cross somewhere ahead of both aircraft. However, in order to collide, their relative bearings to each other must be constant (Ref 14), if they maintain straight headings. No hazard exists unless the paths cross ahead of both aircraft and the relative bearings are not changing. Fig. 7 shows collision is probable if bearing remains steady. It also shows another fact; for two aircraft at the same speed, the steady bearing for collision lies half way between the aircraft heading and the recipro-

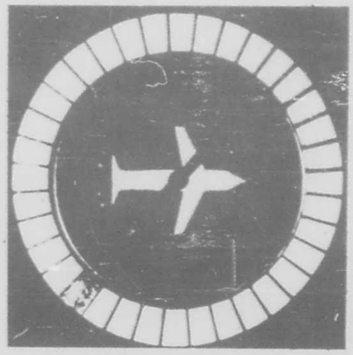

Fig. 8
Crossing Behind

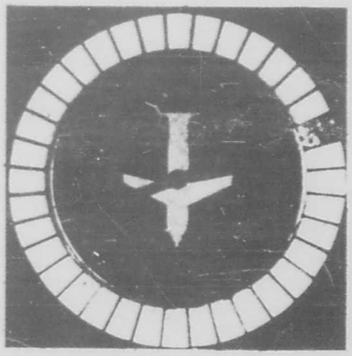

Fig. 9
Passing Parallel

cal of the intruder's heading. Fig. 8 and Fig. 9 indicate that no hazard exists. Fig. 10 shows the special case of head-on approach.

Fig. 10
Head-on Approach

Checking the Bearing. If the CAI indicates that the paths of the two airplanes will cross ahead of both, the relative bearing is observed closely for a short period, not over 15 seconds for a near head-on approach. If it is not changing, a probability of collision exists and an avoiding turn must be made.

Climb or Descent. When the aircraft is climbing or descending, its receiver frequency band is expanded from its normal 600 feet of vertical coverage, in the direction of altitude change. The basic signal with encoded heading is then received from each intruder within horizontal detection range at an altitude the aircraft will pass through or reach within the next 80 seconds. (The heading code will not be received from a minimum equipped aircraft.) The intruder flying level does not receive the signals of a climbing or descending aircraft not within 300 feet of its own level. The climbing or descending aircraft does not trigger the transponder of an intruder unless they are within 300 feet vertically of each other, hence gets no distance measurement from an intruder outside the 600 foot altitude segment centered on it. The pilot of the climbing or descending aircraft is responsible for avoiding collision with an intruder flying straight and level, and must make avoiding turns based on the expectation of no turns by the intruder.

Turning to Avoid Collision. For minimum maneuvering and least interference with other traffic, a normal turn is used to avoid a threatened collision. When a turn is necessary, as indicated by the CAI, it is made to the right for an intruder anywhere ahead of the aircraft, and to the left for an intruder anywhere behind. This is slightly different from visual rules, which do not require the overtaken aircraft to turn. The amount of turn necessary is determined from the CAI. The turn must be great enough to turn past one of the needle points or to start the bearing to changing. If the intruder is noted to be changing heading also, the required amount of turn is lessened.

A turn left by a CAI equipped aircraft being overtaken is used because it assures the pilot of collision avoidance even if the overtaking intruder does not make an avoiding turn, and because a less drastic manouver may then be required of the intruder.

Avoiding a Minimum Equipped Intruder. In the absence of heading information from an intruder, a changing bearing still indicates there is no hazard. However, the intruder may be expected to turn up to 90° to his right if he is being met. He does not turn if his Pilot Warning Indicator shows an intruder behind him. The greater burden of avoidance rests with the larger, better equipped aircraft. If it has a much higher airspeed than the small intruder, the intruder becomes almost like a fixed point to be avoided, and its heading is not of very large consequence to the pilot of the fast airplane.

Intermediate Equipped Aircraft

The intermediate equipped aircraft does not obtain a distance measurement, and cannot simultaneously search for intruders and check an individual target. Otherwise the equipment is used exactly as is the more complete set, and the principles and rules are the same.

Selecting and Checking the Target. When the pilot notes the visual and aural warnings, he looks at the CAI to determine the sector, then switches the rotating directional antenna to the homing mode as the bearing needle enters the sector. The antenna aligns with the bearing to the intruder. Bearing and intruder heading are read on the CAI just as with the full equipment. After he has obtained the required information, the pilot returns the antenna control switch to the search position, in order to search for other intruders. The sector light will change as relative bearing changes, indicating no hazard from that particular intruder.

Minimum Equipped Aircraft

A minimum equipped aircraft receives identical information from all other aircraft, and has no way of distinguishing one type of equipment from another. The pilot must therefore treat all intruders alike.

Information Displayed. The visual and aural warnings are exactly like those for more completely equipped aircraft. A Pilot Warning Instrument (Fig. 11) shows which quadrant relative to aircraft heading the intruder is in, the top of the instrument representing the nose of the

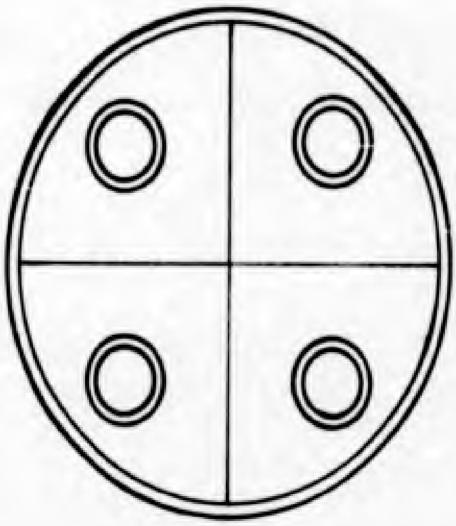

Fig. 11
Pilot Warning Instrument
Minimum Equipped Aircraft

aircraft.

Using the Information. Upon noting the aural and visual warnings, the pilot looks at the Pilot Warning Instrument (PWI) to ascertain which sector the intruder is in. If visual conditions prevail, he can look in the quadrant indicated to see if he can locate the intruder visually. However, judging relative altitudes is tricky, especially at night, and an airplane he spots visually may not be the indicated intruder. He again looks at his PWI. If the original sector light went out and an adjacent one came on in the few seconds he was looking out, but maintaining heading, the relative bearing with the intruder is changing, and no collision threat exists. For an aft sector light on, the pilot maintains heading, exercising his right-of-way as an overtaken aircraft, because he does not have precise information for a turn. But if the same forward sector light is still on after 20 seconds from initial warning, and he has not positively located the intruder visually, he must turn.

Turning to Avoid Collision. If the left forward sector light is on, the pilot turns right up to 45°, stopping the turn sooner if the sector light changes to the left aft sector before he has turned 45°. He then holds the new heading until the sector light changes either clockwise or counterclockwise, after which he returns to course.

If the right forward sector light is on, the pilot turns right up to 90°, stopping the turn sooner if the sector light changes to the left forward sector before he has turned 90°. He then maintains the new heading until the sector light shifts either clockwise or counterclockwise, after which he returns to course.

Multiple Intruders

The aircraft cruising fast at low altitudes and the one climbing or descending rapidly may often detect more than one intruder at a time, particularly in terminal areas. The pilot of a slower aircraft will do so less frequently because of the lesser range of his collision avoidance radio.

Fully Equipped Aircraft. When more than one sector light is on, the pilot checks each sector individually to evaluate the threat from each. Should two or more sectors light up at about the same time, the most forward ones are checked first. Those intruders which are no threat are quickly eliminated from further immediate concern. The most immediate remaining threat is avoided first, being careful not to increase the hazard with other intruders.

Intermediate Equipped Aircraft. Checking of multiple intruders with an intermediate equipped aircraft is not as rapid as with the fully equipped one, because the rotating directional antenna must be switched back and forth between search and homing use. The lack of distance indication is also a slight disadvantage. Otherwise, operation with multiple intruders is as safe as for the fully equipped aircraft.

Minimum Equipped Aircraft. If both forward sector lights of the PWI are on, the pilot may try to locate one or both intruders by eyesight and avoid them visually. If he is unable to locate them visually, or is uncertain, he turns right 90°, holds the new heading until at least one sector light goes out, then uses normal procedures. If both intruders are behind, he holds heading, exercising his right-of-way as an overtaken aircraft, while clearing visually the best he can. If one intuder is behind and the other ahead, he uses the normal procedure to avoid the one ahead.

VI. Possible Additional Uses of the System

This system can also be used as an aid in ground control of air traffic. A ground station sweeping the frequency range of the system, using a more sophisticated receiver with increased sensitivity, and interrogating for distance measurement with greater power, could maintain a complete plot of the position and pressure altitude of every aircraft within 30 or 40 miles, plus the headings of all but the light, slow ones.

Spacing of IFR Traffic

The system can be used in three ways to increase the flow of Instrument Flight Rules traffic. One is to use the more accurate position plotting capability of the system as outlined in the preceding paragraph, to maintain a reduced but still safe separation. Another is to allow the pilot of an airliner, for instance, to maintain his own safe distance behind the airplane in front of him on the same course; perhaps as little as two miles could be used. The third way is to allow the faster aircraft to pass slower ones at the same altitude going in the same direction.

Marking Man-Made Obstructions

Many television transmitter towers and some buildings are so high as to be a threat to aircraft at what otherwise is a safe flight altitude. The towers particularly are not easy to see, especially in reduced daytime visibility. They can be equipped with this system to broadcast the basic signal on all the pressure tuned frequencies between their tops and ground level. The heading code of the transmitted basic signal can be replaced by a special code to identify them as fixed obstructions.

VII. Conclusions

A system for preventing collisions by the use of radio is feasible. The system proposed in this report supplies the necessary information, in a form which the pilot can apply to avoid collision. In order to minimize cost, the minimum equipment was simplified more than is actually desirable. As a consequence, the pilot of the better equipped airplane bears the greater share of the burden of avoiding collision with the less well equipped.

The proposed system would certainly reduce the present rates of near misses and mid-air collisions, and is therefore recommended for further study by persons qualified in electronics.

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Appendix A

Some Data on the Air Collision Problem

There is an average of 1,600 aircraft airborne in the United States each hour (Ref 19). There are times when several times that number are flying.

> FAA towers handle 25.7 million operations a year. There are some 13,000 air traffic controllers operating in 36 Air Route Traffic Control Centers, 229 air traffic control towers, and 425 flight service stations (Ref 19).

The percentage of Air Force accidents that are mid-air collisions doubled from 1947 to 1958, while the overall accident rate went down (Ref 11).

Of collisions not strictly between military aircraft:

80% are between general aviation;

10% are between general aviation and military;

5% are between general aviation and air carrier (Ref 4).

Of air carrier collisions, 78% occur in daylight, 85% are below 10,000 feet; 3% are head-on, 16% are converging courses from opposite directions, 78% are going in the same direction, converging or overtaking (Ref 4).

More than 1,000 near misses are reported each year. 84% are in daylight, 74% are below 10,000 feet, 34% are head-on (Ref 4).

There is not much time in which to see the other aircraft in a head-on approach. For example, the time to close a distance of six miles between airplanes for head-on approach is for a Tripacer and a Bonanza, 1 minute, 15 seconds;

for a Constellation and a Convair, 41 seconds;

for a Viscount and an Electra, 25 seconds; and

for two Boeing 707's, 19 seconds (Ref 4).

In spite of the spectacular speeds of head-on approaches, near misses occur most often at relatively slow rates of closure, and the aircraft which collide are flying straight and level below 3500 feet, in a terminal area (Ref 16).

Appendix B

Some Limitations of Vision in Flight

An object filling a small visual angle against a non-contrasting background is very difficult to see. For instance, an aircraft filling one minute of visual angle at seven miles can be seen only if it is daylight, the pilot's eyes are focused for distant vision, there is high brightness contrast between the aircraft and the background, and the pilot is looking directly at the other aircraft. Should the pilot be looking 30° to the right or left of the other aircraft, he could not see it more than 3/10 of a mile away (Ref 10).

When the limitations of the eye are coupled to the time lags of human and machine reaction, the problem of avoiding collision by visual means becomes apparent. For example, suppose two aircraft are approaching head-on at 600 mph each. Their closing rate is 1760 feet per second. The time factors, starting with the aircraft in focus in the visual field, are as follows:

a.	Perception lag	0.1 sec
b.	Recognition	0.5 sec
c.	Making decision	1.0 sec
d.	Reaction	0.4 sec
e.	Machine reaction and path deviation	2.0 sec

The total time is four seconds. In four seconds the two aircraft reduce their separation by 7,040 feet. If the pilots see each other 7,040 feet apart, no time margin is available (Ref 20).

> When the basic acuity limitations of the eye are considered, together with factors such as the position of the sun, haze, and aircraft color, it is apparent that an aircraft is inside the "point of no return" before it is seen. A clear recognition of this fact leads to the clear formulation of the philosophy that the days of "see and be seen" in flight are at an end (Ref 11).

Appendix C

Some Suggested Non-Visual Means of Collision Avoidance

Bendix Aviation has proposed and built a ground bounce ranging system which uses the ratio of intruder range to closing rate to determine whether a collision hazard exists. It is a Collision Avoidance System (CAS), which by definition uses a computer to solve the problem of collision avoidance and presents instructions to the pilot or to the autopilot.

Sperry Gyroscope Company is working on a system using a flush mounted scanning antenna and an omnidirectional transponder antenna in a single package, similar to Sperry's AN/APN-121 equipment used in USAF aircraft to locate aerial tankers for refueling. It would use frequencies around 15,700 megacycles. The first model will be a Proximity Warning Indicator (PWI), with a CAS model to follow later. A PWI warns the pilot of the presence of another aircraft, and may give information on heading, bearing, distance, altitude and/or airspeed. The pilot must do the computing, if any is done (Ref 13).

Minneapolis-Honeywell has developed an infrared proximity warning indicator using an infrared scanner and a rotating infrared beacon. This is expected to be an improvement over a self-contained system, which must depend upon natural infrared radiation from aircraft engines and has proved unsatisfactory (Ref 13).

The National Company, of Malden, Massachusetts, has proposed an airborne time reference technique requiring each aircraft to transmit signals at precise times measured to the microsecond. There would be no interference because only one aircraft would be assigned a given time. The set would listen for other signals and measure their displacement from their assigned times in microseconds. Since radio waves travel approximately 1,000 feet per microsecond, an aircraft would be distant by 1,000 feet times the difference of its signal from its assigned time. The required time accuracy would be obtained by the use of extremely stable crystal oscillators periodically resynchronized from ground stations (Ref 13).

Many other proposals for PWI and CAS have been made, including the use of radar, and a large variety of radios. For further information, see Refs 3, 7, and 17 of the Bibliography.

Vita

John Francis Welch was born [redacted], on a farm near [redacted], the son of Patrick Thomas Welch and Mary Cecilia [redacted] Welch. He attended rural schools and graduated from Corning Rural High School in 1937. In 1938-39 he took a fifth year of High School to qualify for a Teacher's Certificate, and taught a rural grade school in 1939-40. In 1941 he enrolled in Mechanical Engineering at Kansas State University. He became an Aviation Cadet in 1943 and served as an Army Air Force pilot to the end of 1946. He returned to Kansas State in 1947 and graduated in 1950 with two Bachelor of Science degrees, one in Mechanical Engineering and one in Business Administration. He worked as a technical writer for Beech Aircraft for eight months, then was recalled to active duty with the Air Force in 1951. He served ten years in Strategic Air Command, as Maintenance Officer and as Pilot and Aircraft Commander of B-36's and B-52's, before coming to Air Force Institute of Technology in January, 1961.

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