U. S. AIR FORCE
PROJECT RAND

RESEARCH MEMORANDUM

SURVEY OF SELF-CONTAINED NAVIGATION SYSTEMS

W. E. Frye
E. V. Stearns

RM-756-1

26 December 1951
Revised 20 May 1952

The RAND Corporation
1700 MAIN ST. • SANTA MONICA • CALIFORNIA

SURVEY OF SELF-CONTAINED NAVIGATION SYSTEMS

I. Scope

This survey of self-contained navigation systems has been prepared to summarize the state of the art, to estimate the probable time of availability for operational use of various systems and components now under development, and to suggest a program which will provide for the earliest integration of the component developments into systems for more immediate use.

The term "self-contained" is interpreted to include all systems in which the mechanization is contained solely within the aircraft. This includes systems that employ radiation interaction with the earth (such as doppler) and with celestial bodies (by means of optical sensing devices) in addition to those using "black boxes" e.g., inertial and magnetic navigation. Excluded from this category are all systems employing ground-based installations such as Shoran and Loran.

Applications of the navigation systems are made to the various types of aircraft (including missiles), and conclusions are drawn with regard to the suitability and availability of equipments now under development.

RAND is presently conducting a study to ascertain the relative operational utility of guided missiles and manned aircraft for strategic bombardment. It is apparent that the results of this study may affect the requirements for navigation and bombing equipment to some degree. Since the missiles aircraft study will not be completed for some time, the present work does not attempt to anticipate its results but assumes continuation of the present operational requirements.

II. Conclusions

As a result of this study we are able to make a number of critical comments regarding the present Air Force development program for self-contained navigation systems. The development philosophy has shown a recent trend toward "weaponeering," representing a desire to lower our sights in order to provide usable hardware at the earliest possible date. In the field of self-contained navigation systems this trend should be tempered by the realization that certain developments have progressed for about five years, and it is doubtful that any new, reduced objective, development programs could be initiated now and expected to yield prototypes appreciably sooner than some of the existing programs. Although the production requirements of these systems (e.g., APN-66, SIBS, and MX-1688B) may call for some re-orientation of their development programs, it does not necessarily follow that a down grading of objectives is desirable to shorten the time to completion of the type-testing phase.

All of the present projects lean heavily on the assumption that adequate ground reconnaissance and mapping information is available. We have not made a study of this, but feel a reasonable doubt that astronomical or terrestrial coordinates of many targets are defined within approximately a mile. This doubt should be resolved.

It has been suggested that the SAC bomber of the post 1955 era will be a small, high speed airplane. As soon as this requirement is established, work should be initiated to satisfy the resulting requirements for small navigation and bombing gear. The mission calls for light-weight, compact systems, probably patterned after APN-66 or MX-1688B, with accuracy sufficient for bombing.

A similar comment may be made regarding self-contained navigation systems for use in small low-altitude bombers. The nature of this problem restricts the choice of basic systems, and miniaturization of SPIRE seems a remote possibility for some time to come. If the use of APN-66 for low-altitude missions is proved feasible, it should be pushed in preparation for this application.

As a result of recent emphasis on tactical air operations, a need has arisen for a self-contained navigation aid for tactical and fighter craft. This could be made available in the minimum time by the use of a dead reckoning computer. The accuracy of navigation by this means will depend upon the precision and frequency of position and wind velocity data introduced to the computer by the pilot. If a more automatic system is required before introduction of AN/APN-79, MX-1688A, or FINE-type navigators, an interim doppler (e.g., APN-82 or APN-67) or inertial system may be made available for short ranges (say 200 - 300 miles between fixes). This work should not be allowed to disturb the development of the longer range fighter-navigators and might profitably be given to component and minor systems manufacturers. If this development is deemed desirable, it should be kept as a program for sound engineering application of the present state of the art.

In attempting to place the SIBS, MX-1688B, and K-1 Secure projects in proper perspective, it appears that the equipments resulting from these developments will not differ significantly in time of availability for operational use. In addition, if position and velocity fixes are made enroute when using SIBS or MX-1688B in the same manner as planned for the Secure system operation, then essentially the same accuracy can be expected from all three systems.

The two programs for the development of the Brass Ring Navigator at North American Aviation and Sperry Gyroscope Company are very similar. Closer coordination of the efforts of the contractors appears desirable to reduce duplication of effort.

If a coordinated effort were initiated with the express purpose of providing an adequate supply of quality accelerometers, gyros, star trackers and computing equipment to those involved in the production of systems, we might expect to gain a year or more in the time required to introduce automatic navigation systems into service use. At present, at least two development programs exist on each of these components, while no such production effort has been initiated. The need for guidance components of the highest quality can be established now rather than to wait for system prototype testing to be completed. The experience of Minneapolis-Honeywell in this field indicates that manufacturing of these components is a formidable problem and that considerable time is required in order to gain the experience needed to mass-produce this kind of equipment. If an adequate supply of such components were available by, say mid-1954, the final design and production engineering jobs would be reduced greatly, and the remaining development work would be simplified as a result of the availability of these components.

Some fundamental investigations would be useful to the system development groups. There exists no adequate picture of the inter-relation of parameters controlling the employment of gyros and star trackers as a means of obtaining an inertial reference. The factors of speed, range, and time of flight are seen to be important here, and no fundamental information regarding this problem is available. The use of doppler radar may be limited under some conditions of maneuver and of low-altitude flight over rough terrain. In addition doppler radar may be subject to large errors due to wave motion when flying over water. An early treatment of these problems would be most useful to the various development and planning groups.

III. Introduction

Present developments in the field of navigation and guidance for long range bombardment aircraft and missiles have produced many new systems and components which are applicable to the design of self-contained navigation aids and navigation systems. It is the intent of the present work to discuss these developments and to propose a planning program in which they may be applied to advantage. The discussion is limited to self-contained systems and does not attempt to make comparisons with ground based systems. Discussion of track monitoring by radar and visual bombing systems such as AN/APQ-24 and the newer "K" systems is not included here since the purpose of this work is to set up development objectives, and it is assumed that the potentialities of these particular systems are well known.

Estimates of time of availability and system performance are given, but since most of the systems are still in the development stage, it is to be noted that these are subject to change as a result of future testing and new developments. These estimates are valid only so long as the emphasis and priority structure remain unchanged. In many cases the results of flight tests made to date are not adequate to establish the capabilities of a navigation system. Since tactical employment of a system requires quantity production of uniform quality units the time estimates given here provide for completion of development, testing, production engineering, and finally for production to rise to a reasonable rate. It was decided at the outset that time estimates of availability beyond 1955 are extremely uncertain since these may be altered materially by a moderate change in the priority assigned to any given project. It is further true that the equipment which is not to be available until after 1955 is presently dependent upon the development of basic components; ultimate operational use thus will be delayed until completion of development, testing, engineering design, and production of both systems and components. To assign a time schedule to the completion of all of these requires, in addition to a knowledge of the expectations of success of each, a means of predicting the magnitude, and a degree of simultaneity of effort which will be applied as a result of Air Force requirements.

IV. Systems and Components

The investigation conducted for the preparation of this paper was intended to provide a "state of the art" summary rather than as an exhaustive investigation of all commercial contractors who might contribute to the guidance and navigation program. There is, therefore, no intent to exclude the mention of any single manufacturer or group of manufacturers.

In order to produce a measure of continuity while providing some background in the state of the art the following discussion of systems and components is organized here with respect to projects.

A. Dead Reckoning Computers

The Ford Instrument Company has developed, for the Air Force, a GPI (ground position indicator) computer, type A-1, which computes present position in latitude and longitude from inputs of airspeed and magnetic heading. The input from the type A-2 airspeed indicator is resolved into N-S and E-W components by use of the Sperry gyrosyn magnetic heading reference, and the components are integrated once to give distance traveled. The magnitude and direction of the wind and the magnetic compass variation (both obtained from other sources) are set into the computer by means of manual dial settings.

The type A-1 computer weighs about 44 lbs overall and consists of four units:

1. Computer proper
2. Electronic amplifier and power supply
3. Preset wind and magnetic variation unit
4. Latitude and longitude indicator.

The overall accuracy specified for the computer is 0.7 percent of the distance traveled. To this must be added the errors due to inaccurate wind and magnetic variation information. The computer is capable of handling airspeeds of 150 to 800 knots and ground speeds up to 1000 knots. Two preproduction prototype units have been completed and are ready for delivery. No commitments for production have been made but it is estimated that the computer could be in operational use by the end of 1953 if desired.

In addition to its use as a dead-reckoning GPI the type A-1 computer can be used in conjunction with the "front end" (AN/APN-81) of the AN/APN-66 doppler radar equipment. The doppler equipment would furnish true ground speed and drift angle to the computer, replacing the airspeed input and manual wind adjustment. Such a combination of equipments should be capable of an accuracy better than 2 percent of the distance traveled.

The combination of AN/APN-81 doppler radar and type A-1 computer has the designation AN/APN-82 with the title Interim Fighter Navigator. It is planned to install this in a wing tank on the F-84E and F aircraft and in the belly of the RF-84 aircraft. It is estimated that this equipment could be made available operationally in 1953.

The Hughes Aircraft Company has under development an airborne digital computer as a component of their Tactical Bomb Director Project. This is a general purpose computer which is capable of solving the bomb release problem if the altitude, airspeed and present position are fed in and if the target position and bomb ballistics are stored in the computer magnetic drum memory unit. From the computer can then be obtained steering signals and a bomb release signal. In addition to its function as a bombing computer, this computer could be used as a dead reckoning present position and course computer or could take data from a doppler radar equipment such as the AN/APN-81 (front end of the AN/APN-66).

The Hughes TED computer will weigh about 100 lbs for the first developmental model and will occupy a volume of about 4 cu.ft. It will require about 300 miniature vacuum tubes and 1000 germanium crystal diodes. At the present rate of developmental effort at least another year will be required before a preproduction prototype will be available.

B. Doppler Radar Navigation Systems

General Precision Laboratory has under development for the Communication and Navigation Laboratory, WADC, a navigation system, AN/APN-66 (Reference 2), using the transmission of radio pulses from an aircraft to the ground and reflection back to the aircraft where the doppler frequency shift is used to measure the ground speed and track the aircraft. If the measured ground speed is resolved into components by use of a heading reference and the components continuously integrated, the present position of the aircraft with respect to an initial reference point can be determined. If for any reason the doppler signal is lost, the system automatically goes on "memory" or dead reckoning operation using measured airspeed corrected by the wind vector last determined by doppler measurement.

In the AN/APN-66 equipment, one-microsecond radar pulses of X-band frequency are transmitted on four beams formed by flush-mounted linear array antennas symmetrically oriented with respect to fore-aft and right-left axes of the aircraft and directed downward at an angle of 20° with respect to the vertical. The antenna array is gyro stablilized and is oriented through its servo system so that the difference frequency between the doppler signals on the oppositely crossed pairs of antennas is zero, thus aligning the antenna system along the ground track of the aircraft. The doppler shift in frequency between the signals received on one single pair of antennas is then a measure of the ground speed of the aircraft.

The AN/APN-66 will weigh about 580 lbs complete. It consits of two major units:

1. AN/APN-81 - antenna array, transmitter, receiver and doppler frequency tracker. Weight about 285 lbs.
2. AN/APN-95 - computer which gives present position in latitude and longitude, ground speed, drift angle and course to be followed to a set-in target position.

It is planned that the Kearfott N-1 gyrocompass will be used as the heading reference.

The desired accuracy of the AN/APN-66 equipment in measuring ground speed is 0.1 percent. The desired accuracy of drift angle measurement is 0.1 degree. The errors in position measurement are expected to be about 1 percent of the distance traveled from the last fix. The position accuracy is critically dependent on the availability of an accurate heading reference. At present the equipment is limited to altitudes below 70,000 ft and speeds below 700 knots, but studies are under way to extend the speed range to 1300 knots.

Quantity production of the AN/APN-66 equipment is planned to start late in 1952. Accordingly, one might expect that the AN/APN-66 can be in operational use by the middle of 1954.

In addition to the AN/APN-66 the C and N Laboratory has under development the following equipments that use the doppler principle:

1. AN/APN-82 - This consists of the AN/APN-81 front end in conjunction with the Ford Instrument Company Type A-1 computer. This equipment is the

Interim Fighter Navigator and will be installed in the wing tank of the F-84E and F and in the belly of the RF-84 aircraft.

2. AN/APN-78 - Doppler navigator for helicopter use being developed by the Laboratory for Electronics, Cambridge, Massachusetts.
3. AN/APN-79 - Fighter navigator. The accuracy of this equipment for ground speed measurement is expected to be 0.5 percent. The total weight is hoped to be 100 lbs of which 75 lbs will be in the front end.
4. The application of doppler to blind landing is being investigated.

The Naval Research Laboratory has under development a doppler navigation system, AN/APN-67, which uses continuous wave X-band radio transmission from fixed and unstabilized antennas with computer compensation to replace gyro stabilization. A Kearfott gyro vertical is used in the computer as a vertical reference and the General Electric G-2 compass is used as a heading reference, the latter having an accuracy of about 0.5°. The equipment is being redesigned for production by Ryan Aeronautical Company with the expectation that it will weigh about 175 lbs. The accuracy specified for this equipment is 2 percent of the distance traveled.

An important recent application of the doppler principle of ground velocity measurement is its use to provide damping of initial errors and bounding of noise errors in inertial and stellar inertial navigation systems. The Northrop guidance for the Snark missile will use the AN/APN-81 equipment for initial guidance and for damping. The North American Aviation guidance system for the Snark will use the AN/APN-81 for damping of errors. The AN/APN-81 will be used in the K-1 Secure bombing system to obtain a velocity fix just before going on Secure operation and for damping.

Investigations of the use of inertial navigation components such as accelerometers and precision gyros in conjunction with the AN/APN-66 system to improve its instantaneous accuracy and remove some limitations are being carried on by General Precision Laboratory.

The doppler navigation systems are subject to certain limitations.In flying over water, the roughness of the surface must be at least Beaufort 2 to provide an adequate signal return. Since the speed measured is relative to the water, currents may introduce small errors which probably can be compensated by a knowledge of the currents. However, a larger error arises from the fact that the doppler equipment apparently measures velocity relative to a frame of reference moving with a velocity which is a function of the water wave velocity (Reference 24). On the basis of limited experimental data General Precision Laboratory claims that velocity errors not exceeding 10 knots can result from this cause. This could result in serious errors in navigation for long periods of time over the ocean.

The allowable maneuvers of the aircraft carrying doppler equipment are limited by the stabilization employed. In addition the long smoothing time (5 to 10 sec.) required to obtain an accurate velocity measurement and the time required in the AN/APN-66 equipment to position the antenna array along the ground track may limit the rate of turn if the accuracy is not to be impaired. This may be an important consideration in the application to tactical and fighter aircraft.

Flight tests of the General Precision Laboratory system No. 5 (Reference 25) indicate that the probable error in "instantaneous" drift angle is of the order of 1°. The drift angle error averaged over a 50 mile course is claimed to be less than 0.2°. The experimental techniques employed are inadequate to determine the accuracy of drift angle measurement by the doppler equipment more precisely than this. Further flight tests over greater ranges are necessary to establish the over-all navigation accuracy of the doppler system. In view of this it is doubtful that quantity production of the AN/APN-66 as a complete navigation system should begin in 1952.

Since the doppler system requires radiation of radio waves there exists the possibility of countermeasures by the enemy, specifically jamming and passive homing. Because of the narrow beamwidths and the fixed downward looking antennas, the doppler system will present difficulties to a potential jammer. Preliminary tests at WADC have indicated that the emitted signals from the AN/APN-66 could not be picked up on a search received at moderate range. Calculations indicate that considerable difficulty would be encountered in searching for and acquiring the signal from a distance the order of 10 miles (Reference 22). Airborne Instruments Laboratory has a contract from WADC to investigate countermeasures against the AN/APN-66.

The accuracy and response time of the doppler navigation system do not appear to be adequate for blind bombing. Position fixes obtained by visual or radar means can, of course, be used to improve the accuracy of position determination and a knowledge of ground speed and drift angle obtained from the doppler system can be of material benefit in solving the bombing problem. However, the use of doppler will not eliminate the need for a radar (or visual) bombsight.

C. Radar Map Matching Navigation

Goodyear Aircraft Corporation has under development an automatic radar map matching system of navigation (ATRAN) intended primarily for missile use (Reference 11). In this system navigation is accomplished by comparing the radar image of the terrain below on the radar plan position indicator (PPI) with a radar picture on a photographic film of the course obtained by photographing the radar indicator display on an earlier reconnaissance flight over the course.

Goodyear has made numerous flight tests of ATRAN laboratory equipment over selected courses that have been previously mapped by radar with repeatability reported to be the order of one-quarter mile. An error analysis by RAND of the radar map matching system (Reference 12) showed that the errors of the system would not be less than about 3000 ft.*

It is planned that the ATRAN equipment together with the AN/APS-48 Unattended Radar under development by Consolidated Vultee Aircraft Corporation will be installed and tested in Matador missiles. The ATRAN equipment exclusive of the radar is expected ultimately to weight about 110 lbs. The ATRAN equipment is not limited to missile use but could be used equally well in manned aircraft.

Radar map matching is limited by its unfeasibility over water out of sight of land, and in polar regions over ice. In addition there may be serious problems in its use over certain types of terrain. Considerable basic research upon the characteristics of terrain radar return needs to be done and extensive flight tests of ATRAN carried out before a full evaluation can be made of the value of radar map matching for navigation. Another limitation of the system is the requirement for prior radar reconnaissance of the course at essentially the same altitude and (at least at present) with the same kind of radar equipment. The possibility of constructing usable synthetic radar pictures from terrain models and using the radar trainer technique is now under investigation.

Since the ATRAN system requires radar radiation from the aircraft there exists the possibility of countermeasures by the enemy, specifically jamming and passive homing on the radiation. Insufficient information is available as yet on the vulnerability of the ATRAN system to jamming.

It is not anticipated that an automatic radar map matching system can be made available operationally either for manned aircraft or missiles before 1955.

- - - - - - - - - -

* As a result of later refinements in ATRAN, Goodyear claims that some of the values of component errors assumed in this report may be high by a significant amount.

D. Magnetic Guidance

Consolidated Vultee Aircraft Corporation has under development a system of navigation, intended primarily for missile use, utilizing the earth's magnetic field (Reference 3). In this system the magnitude of the earth's total magnetic field is measured by a magnetometer similar to that used to detect the presence of submarines during World War II (MAD equipment). If the strength of the magnetic field at the destination is known, then the aircraft can be guided along the isodynamic line (line of constant total magnetic field) of that value and thus will pass over the destination. Since the total field strength is measured, rather than any components, an accurate reference direction (e.g., the vertical) is not required in the aircraft.

A number of successful flights using this equipment have been made by CVAC with accuracies of the order of 5 to 10 miles from the specified isodynamic line. The equipment is small and light weight (approx. 60 to 70 lbs) and could be placed in production in the near future. Several units are currently being fabricated by CVAC for installation and test in Matador missiles.

The use of this system for navigation suffers from several serious limitations:

1. There does not appear to be any feasible magnetic method of determining range along an isodynamic line. Thus the system cannot give a complete position fix, but only one coordinate, i.e., lateral deviation from an isodynamic line. Position along the line would have to be determined by other means.
2. The earth's magnetic field is subject to unpredictable variations (magnetic storms) which might introduce large errors. However, it is estimated that the system is usable up to 95 percent of the time.

3. Advance magnetic reconnaissance at least in the vicinity of the target is required. In addition, knowledge of the location of the appropriate isodynamic line is required and the mapping of local magnetic anomalies along the course may be necessary.

Because of the above limitations, this system does not appear feasible for use as a general navigation system. It may have application in certain specialized cases such as photo-reconnaissance.

E. Automatic Celonavigator

Kollsman Instrument Company has under development for the Navy Bureau of Aeronautics an automatic celestial navigation system for manned aircraft. This system operates on principles very similar to those of conventional astro-navigation used in aircraft, that is, two star fixes measured relative to a bubble level reference are used to obtain a position fix. A turret sextant containing four star trackers with rigid relative orientation is used for tracking the four stars, Polaris, Deneb, Arcturus and Capella. Since Polaris must always be tracked, the equipment is limited to use in the Northern hemisphere, preferably above 20°N. latitude. In addition to Polaris any one or two of the other three stars, whichever happen to be visible at the time, are tracked. The turret requires an astro-dome 5 inches high and about 10 inches in diameter mounted on top of the aircraft. A two-degree-of-freedom pendulous accelerometer consisting of a liquid in a container with an optical pick-off to detect the orientation of the free surface is used to determine the vertical. Rough stabilization of the turret is accomplished by the use of a Kearfott gyro vertical. The equipment includes a so-called "course monitor" which establishes the great circle course between present position and a desired target point whose coordinates are set into the equipment. It is necessary for proper operation of the equipment that the aircraft be flown by autopilot.

The sequence of operations for initially acquiring the stars is as follows: The sextant turret is leveled by means of the vertical gyro and the accelerometer. The azimuthal orientation is determined roughly by means of a gyrosyn compass. The altitude of Polaris (the latitude of present position) is fed to the Polaris telescope and Polaris is acquired by a search phase if necessary. Then the sextant is rotated about the polar axis until the other star (or stars) is acquired. The star trackers utilize blue sensitive photomultiplier tubes and the system is limited to nighttime operation.

Recent flight tests of the Kollsman Model 1 equipment (Reference 1) indicated that 90 percent of the fixes were within 7 miles of the true position (CEP = 4 mi. assuming a gaussian distribution). It is hoped that the accuracy of fix eventually will be 90 percent within 3 miles.

Kollsman hopes to deliver two prototypes of the Model 2 equipment to the Navy by February 1952. This equipment will be flight tested initially in a 300 knot aircraft and later in a 600 knot craft. The total weight of an installation of this equipment in an aircraft will be about 400 lbs. including cables, but not primary power supply.

It is estimated that the Kollsman Celonavigator could be placed in operation by the end of 1953 with an accuracy about the same as that obtained by use of a manual aircraft sextant under good conditions (References 16 and 17). Additional tests appear to be necessary to determine the limitations and the capabilities of the equipment, such as, for example, its use in daytime at high altitudes and the effect of turbulent air on the accuracy.

F. <u>Mass. Inst. of Tech., Instrumentation Lab., Project SPIRE</u>

The navigation work at MIT, Instrumentation Laboratory is experimental in nature; two major projects exist, one, Project SPIRE, to develop a long-range fully automatic bombing system, the other, Project FINE, to develop an inertial navigation equipment for use in fighter aircraft. Project FINE will be discussed in detail elsewhere in comparison with similar work. Both projects exclude any radiation reference to the earth or to the fixed stars; thus, this work excludes radio, radar, infrared and optical aids to navigation. It is considered desirable to be able to navigate between two distant points, the base and target, and to complete the bombing mission independent of any outside measurements or sources of information. This has been referred to as the "blind navigation problem," the theory of which is discussed in detail in two RAND reports (Reference 19).

The Instrumentation Laboratory is developing a set of very high quality system components. The primary components deserving to be mentioned are the gyros, accelerometers, and signal and angle generators. The MIT gyros, for example, show a random drift rate after compensation of about $.015^{\circ}$ per hour, with some units showing better performance under strict laboratory conditions. However, a rather comprehensive procedure of compensation, consuming more than 24 hours must be completed every time the gyro unit is shut down and recycled. So far, none of these units has been fabricated under production conditions.

The long range navigation systems work at MIT Instrumentation Laboratory is directed toward the development of the SPIRE system and has been well documented in Instrumentation Laboratory reports, (Reference 18). In principle the SPIRE system consists of an inertial reference frame which is maintained by gyroscopes and a local heading and vertical reference which is maintained by accelerometers employed in an air mass stabilized feed back network to compensate for interaction of accelerations due to gravity and those of the aircraft. Positions are determined, and navigation signals are generated, by measuring the orientation of the local vertical reference frame relative to the inertial frame.

The intent of the SPIRE system is to provide a means of long range great circle navigation with sufficient accuracy to complete the bombing problem. Obviously, since the accuracy to be realized by this system is directly dependent upon the residual errors of gyros, servos, and angle generators, high component performance is required. Although the Instrumentation Laboratory is working on these, it is not likely that the completed SPIRE system could be available for operational use until well beyond 1955. Even then, it would be subject to severe tactical limitations since no provision is made to change great circle course in flight and the system requires an excessive warm-up time prior to flight in order to stabilize and compensate the component instruments. Any operational employment of the developments made in the SPIRE project will probably arise through the work of AC Spark Plug on SIBS or the work of a similar group. Although the completed SPIRE system may not be available for operational use for some time to come, it is quite possible, in the mean time, to make use of some of the component developments and system concepts in navigation equipments having less exacting requirements.

G. Stellar Inertial Navigation for Manned Bomber

The AC Spark Plug Division of General Motors Corporation has under development a Stellar Inertial Bombing System, Project SIBS, (Reference 7). It is recognized that, by using optical reference to the stars in addition to the gyro reference, the drift of an inertial reference frame, arising from random gyroscope wander, may be held within bounds which are set by the star tracker noise level. In general, the pattern of SIBS will follow quite closely the developments at MIT Instrumentation Laboratory using air mass damping. SIBS will incorporate an additional feature providing for alteration of great circle course during flight. The goal of SIBS is to supply a system capable of 1 mile probable error in establishing position in space for bomb release and by incorporation of a conventional bomb sight to bring this probable error to 0.1 of a mile. The latter figure appears to be exceedingly optimistic in view of other estimates of bombing accuracy (Reference 15).

The operational employment of SIBS is dependent upon the completion of development and production of components, the most critical of which are the gyros and star trackers. At present the plan is to purchase the star trackers and angle generators; AC feels that they must attempt to manufacture their own gyros and accelerometers in a program of self-education before this work can be sent out to a component manufacturer. The tactical limitation of gyroscope compensation and warm-up period which is characteristic of SPIRE would also be applied to SIBS.

The program for SIBS development is presently set up in three stages:

1. A design study,
2. To provide a flying breadboard model, and
3. To provide a pre-production model.

The basic philosophy through the entire program is to bridge the gap between laboratory and production. This may be called "product development". If the present program is maintained and goals are met in time, operational use of SIBS is not to be seen prior to 1955. At the present, the SIBS program has completed the design study and is entering the second phase of the program mentioned above. A pre-production model might be expected in about two years followed by flight-testing, design for production, and final production work. This would consume at least 4 years for the entire operation.

North American Aviation Inc. has under development a latitude-longitude star-supervised inertial autonavigator, Project MX-1688B (Reference 9). The principles of operation of this equipment are the same as those of other stellar-inertial navigation equipments being developed by NAA (Brass Ring, Snark guidance, Navaho guidance), except that complete freedom of course to follow is allowed. The system will continuously indicate the following information:

1. Present position in latitude and longitude coordinates.
2. Destination coordinates (changeable in flight) set in manually.
3. PDI (Pilot's Direction Indicator) showing course to destination.
4. Range to destination.

Information on ground speed and direction and drift angle can be made available as input to a bombing computer.

The infrared star tracker developed by Hughes Aircraft Company will be used in this equipment. Because of the highly accurate gyros employed, the system is capable of operation under cloud cover for periods of time up to one to one and half hours duration.

The equipment is expected to weigh about 800 to 1000 lbs. Contractual accuracy is specified as 5 miles probable error after 12 hours time of flight, and the design objective is 1 mile probable error. The equipment will accommodate speeds up to 600 knots. The equipment will be designed to operate only at latitudes below 80°. Prototype models are supposed to be delivered to the Air Force in mid-1953. Operational use of this system cannot be expected prior to 1955.

H. Brass Ring Navigator Project MX-1457

The Brass Ring Project will involve the guidance of a B-47 bomber as a pilotless aircraft for a distance of 5000 miles with a duration of 12 hours. Two contractors, North American Aviation Inc. and Sperry Gyroscope Co., are developing stellar inertial guidance equipment for this project (References 5 and 6). Although the configuration of some of the components used in the two equipments will differ, the method of operation of the equipment and function of the components are essentially the same and the description of the system operation contained in the next paragraph will be common to both equipments.

A gyro stabilized platform is used upon which are mounted two accelerometers with their senitive axes orthogonally oriented, one in the range direction along the great circle course which the aircraft is constrained to fly and the other in the direction perpendicular to the plane containing the great circle course. The accelerometer outputs are fed into a computer whose output is present position which is used to control the aircraft to fly the predetermined great circle course from takeoff to target. In addition, the position information is fed back to torque the stabilization gyros so that the platform is always oriented perpendicular to the local vertical. A star tracker mounted on the stable platform is used to detect and correct the gyro drift. At the target a bombing computer will be used to determine the release point since it is planned to drop the bomb and not dive the aircraft into the target.

The North American equipment (Mark 2a autonavigator) will use the Hughes star tracker, NAA developed gyros and inertial distance meters (kinetic double integrating accelerometers) both with air bearings. The Sperry equipment will probably employ the Pacific Mercury star tracker, MIT gyros (3×10^6 cgs units of momentum) and the Sperry single integrating accelerometers (identical with those used for the Secure system). Both equipments will weigh approximately 1000 lbs. The accuracy desired for both equipments is one nautical mile at the end of 5000 miles range. NAA is scheduled to deliver two prototype models by June 15, 1952. Sperry expects to fly a system in a B-50 aircraft by February 1953.

The indicated time schedule and accuracy for these equipments appears to be somewhat optimistic. The availability of these equipments operationally before 1955 as reliable navigation equipments with the accuracy specified appears doubtful.

I. K-1 Secure Navigation and Bombing System

Sperry Gyroscope Company has under development for the Armament Laboratory, WADC, a modification to the K-1 navigation and bombing equipment (Reference 4) that will permit inertial navigation (without the necessity for radar operation) for a period of up to one hour duration and will, if necessary, permit completion of the bomb run without the use of visual or radar sighting of the target.

The K-1 Secure modification consists of the replacement of the stabilization element of the K-1 system by a gyro-stabilized, star-tracker-monitored, stable platform upon which are mounted two orthogonally oriented accelerometers, and the addition of a computer and possibly radar doppler equipment (the AN/APN-81 "front end" of the AN/APN-66). The outputs of the accelerometers are fed into the computer whose output (the present position in latitude and longitude) is fed back to maintain the stable platform horizontal. The doppler equipment is used to provide an accurate ground velocity fix and to permit damping of initial errors in the platform orientation with respect to the vertical. The Kollsman periscopic sextant is used to provide an accurate heading reference for platform azimuthal orientation. The Secure equipment is operated from takeoff and the optical and radar functions of the K-1 system are used to obtain position fixes on check points during flight to correct errors in the indicated position output of the Secure computer. Just prior to the final hour's inertial operation, accurate position, velocity and heading fixes must be made and fed into the computer. At the time of bomb release every effort will be made to obtain a visual or radar fix on the target to correct the errors that have accumulated during Secure operation even though the bombing can be completed using Secure operation only.

Some of the components that are planned to be used in the Secure equipment are as follows:

1. MIT type flotation gyros (3×10^6 cgs units of angular momentum).
2. Pacific Mercury star tracker.
3. Kollsman periscopic sextant - a heading reference of 1 to 2 min. of arc is required.
4. Accelerometers - these are under development at Sperry and consist of a hollow metal float immersed in a cyclinder containing a silicone fluid. The cylinder is rotated about its axis thus positioning the float on the axis of rotation. Due to the viscosity of the liquid, a constant force (e.g., caused by a constant acceleration) applied to the float along the axis of rotation will cause the float to move with constant velocity. Hence, if the velocity of the float is proportional to the acceleration, then the position of the float along the axis of rotation will be proportional to the velocity of the accelerometer case. The position of the float is detected by an electrostatic pickoff and this output is proportional to the first integral of acceleration.

The Secure equipment is expected to weigh about 800 lbs. exclusive of the rest of the K-1 equipment. The total installation will weigh about 400 lbs. more than the unmodified K-1 installation or about 1800 lbs. overall. The accuracy of bombing with the Secure system is hoped to be one-half mile probable error. The time schedule calls for flight tests in a B-50 by February 1953.

The advantage of the Secure system is that it will permit the final hour of navigation prior to reaching the target and the bombing run to be made without use of radar emission. This might result in a reduced probability of detection by the enemy, prevent the homing of enemy fighters on the radar by passive detection techniques, and allow bombing in the presence of jamming that might render the use of the radar ineffective. Except perhaps in the presence of radar jamming, it is not believed that the Secure operation will result in more accurate bombing than that obtainable at present by visual or radar means (Reference 15). Hence the accuracy goal of one-half mile probable error quoted above appears to be somewhat optimistic as an operational estimate.

The Sperry accelerometer described above appears to be subject to a fundamental accuracy limitation in the assumption made concerning the nature of the fluid flow. In addition the temperature of the accelerometer must be maintained very uniform since temperature gradients cause convection currents in the fluid which give rise to serious errors.

Because of the complexity of the system and the present state of development at Sperry it is not believed that the Secure system could be in production and operation before 1955.

J. Inertial Navigation for Fighter Aircraft

North American Aviation Inc. has under development an inertial autonavigator for fighter type aircraft Project MX-1688A (Reference 10). This equipment is similar to other NAA guidance and navigation equipments in that it consists of a precision gyro-stabilized platform upon which are mounted two orthogonally oriented accelerometers (distance meters). However, since the range of operation of the fighter aircraft is limited, the platform is maintained normal to the local vertical existing at the take off point (for longer range - up to 1500 miles - the platform can be oriented with respect to the vertical at some intermediate point along the expected course to be followed). Correction torques for the components of the gravity reaction forces thereby introduced into the distance meters are computed and applied to the distance meters. The output of the equipment will be position coordinates - miles North-South and East-West with respect to an initial reference point. The choice of two ranges will be available to the pilot, one, 500 nautical miles range from the initial point and the other, 1500 miles range from the initial point. Five indications are available from the computer:

1. Present position indicator.
2. Destination indicator - position set in manually.
3. Pilot's Direction Indicator (PDI) showing course to destination.
4. Miles to go to destination.
5. Time to go to destination.

The equipment is expected to weigh about 300 lbs. and occupy 10 cu.ft. of volume. The desired probable error of the equipment for the 500 mile range is 2 miles per hour of flight. For the 1500 mi. range an error of 2.5 miles for the first hour of flight is specified and the error is not to exceed 5 miles for 3 hours of flight and 7 miles for 5 hours of flight. It is expected that two flight tested developmental units will be delivered to the Air Force by the end of 1953.

Since the MX-1688A equipment employs no star tracker for correction of gyro drift, highly accurate gyros having low drift are required. North American Aviation expects to use their Navan scheme of limiting gyro drift in this equipment. This is accomplished by reversing the direction of rotation of the gyro rotor. Tests at North American Aviation have shown that this tends to reverse the direction of gyro drift, and hence the performance of the gyro can be improved by periodic reversal of the direction of rotation of the rotor. While this effect shows promise, it requires further investigation to establish its value in the case of gyros with initially high performance.

The Instrumentation Laboratory, MIT, is working on Project FINE to develop an inertial navigation equipment for a fighter aircraft with no radiation reference to the earth or celestial bodies. The desired accuracy is 5 miles at the end of a two hour flight. This project is in a very early stage of development and the configuration and mode of operation of the equipment have not been decided upon, nor have the required components been determined. However, they expect to fly a breadboard unit by the first of 1953 using components available from Project FEBE.

It is anticipated that an inertial navigation device of either the above types might be in operational use in 1955, but not before that time.

K. Guidance for the Snark Missile - Project MP-131

Stellar inertial guidance equipment for the long range (5000 mi) surface-to-surface Snark missile is under development by both Northrop Aircraft Company and North American Aviation (Reference 8). The Northrop system requires the missile to fly a specified trajectory with a predetermined time program. Star trackers are employed to establish an inertial frame of reference, and accelerometers are used to determine the local vertical. The angular relationship between the inertial reference and the vertical is precomputed as a function of time in advance of launching and stored in the missile on magnetic tapes. The missile is then controlled through the aerodynamic control surfaces and the thrust of the propulsion system to maintain the predetermined relationship. Initial guidance is required from the time of launching to the time when the automatic celestial navigation takes over at altitude.

Current plans at Northrop call for the development to proceed in two successive stages - the resulting equipments being designated Mark 0 and Mark 1. The Mark 0 now being assembled is intended for the first missile tests with guidance scheduled to take place in the Fall of 1952. This system will be limited to nighttime operation only and will use a ground-based radar for initial guidance. The expected accuracy of the Mark 0 system is stated to be 2 mi. for a range of 1500 miles. The Mark I equipment is intended for the first operational missiles. It will be capable of daytime operation (Northrop has underway a program for the development of daylight star trackers) and will use the AN/APN-81 equipment for initial guidance and for damping of initial position and velocity errors during the midcourse phase. The total weight of the Mark I system including the doppler equipment and autopilot will be about 1800 lbs. with a size of about 85 cu. ft.

The North American guidance equipment for the Snark (NAA Mark 2C equipment) will employ the same principles and essentially the same components as are planned for the Navaho missile and the Brass Ring project. In addition the AN/APN-81 doppler equipment for damping and the star tracker developed by North American Aviation will be used. A circular probable error of 1500 ft. is hoped for. The delivery of five experimental units in September 1952 is called for in the contract.

The operational use of Snark missiles in quantity during 1955 does not appear at all likely. Although Northrop is in the process at present of flying a nighttime celestial system (not the Mark 0) in a B-29 aircraft, it is understood that this system is not completely automatic and requires human monitoring of the star tracker outputs. Both Northrop and North American have a considerable amount of development work yet to be done on the integration of the doppler equipment with the guidance system. In addition, North American has a rather formidable computer problem. At present NAA is assembling their Mark X-2 developmental precursor of the Mark 2 systems for tests in a motor van and later in a C-97 aircraft. In view of this, the delivery date of September 1952 for five units of NAA Snark guidance appears very optimistic as does the accuracy figure of 1500 ft. CEP.

L. Guidance for the Navaho Missile

North American Aviation is developing a stellar inertial guidance equipment (NAA Mark 2B) for their Navaho missile (Reference 13). This equipment will employ the same principles and essentially the same components as are planned for the NAA Snark guidance and the Brass Ring Navigator. A daylight star tracker for use in this and other navigation projects at North American is under development. The first missile test of the Mark 2B equipment will be in a 400 mile range test vehicle. Two experimental models are expected to be available for this purpose sometime in 1953. The first operational use will be in the Navaho II missile having a range of 3600 miles. Ultimately the goal is the Navaho III having a 5000 mile range. The accuracy quoted in each case is 1500 ft. circular probable error.

The operational use of the Navaho II missile cannot be expected before 1958. The accuracy figure of 1500 ft. given above appears to be quite optimistic. Calculations made at RAND (Reference 20) on the accuracy of a ram-jet vehicle somewhat faster than the Navaho indicate an accuracy of about 8000 ft. may be obtained with an undamped accelerometer system for a range of 5000 mi. and with components that might be available in production by 1960.

Although considerable progress has been made in the development of star tracking devices (References 13 and 26), the problems of using a star tracker in a supersonic missile appear formidable, and satisfactory solutions to the problems of errors caused by looking through the shockwave and turbulence and by the effect of unequal heating of the window have not yet been found.

M. Automatic Astrocompass

The Kollsman automatic astrocompass, under development for the Air Force, is a device for providing a heading reference more accurately than that given by a magnetic compass. The instrument incorporates a star tracker that tracks a predetermined star, planet, or the sun; it will work down to third magnitude stars at night. The same type of star tracker and scanning mechanism are used in the astrocompass as in the celonavigator. The astrocompass requires as input for its computer the latitude and longitude of the position of the aircraft and the magnetic compass heading reference. The computer aligns the tracker to a predetermined star; provision is made for a 5 degree search cone for the acquisition of the star. After the tracker acquires the star, the magnetic compass reading is corrected to provide an accurate heading reference. A Kearfott gyro vertical slaved to a pendulum is used to provide a stable horizontal reference. The astrocompass consists of three units: the star tracker and gyro stabilization weighing 30 lbs, the computer weighing 40 lbs, and the electronic amplifier weighing 20 to 30 lbs. Thus the complete equipment weighs 90 to 100 lbs. An astrodome 2 1/2 inches high and 4 7/8 inches in diameter is required on the top of the aircraft.

The accuracy of the astrocompass at present is claimed to be better than 1/4 degree and the accuracy is expected to be ultimately about 5 minutes of arc. The sources of error in decreasing order of importance are as follows:

1. Gyro vertical - 10 min. of arc.
2. Mechanical errors - 6 min.
3. Error due to uncertainty of position.
4. Star tracker error - 1 min.

Kollsman expects to deliver the first model of the astrocompass to the Air Force in the Spring of 1952. This is a prototype model which would require some engineering for production. Kollsman estimates that the equipment could be in production within a year afterward thus allowing operational use to begin by the end of 1953.

The automatic astrocompass does not, of course, constitute a complete navigation system. Its primary purpose is to provide a more accurate heading reference for dead reckoning navigation and for use with the AN/APN-66 doppler navigation system. However, it has been pointed out by Kollsman that the use of two astrocompasses provides the essential elements of a celestial navigation system similar to the Kollsman Celonavigator. It is believed that this application of the astrocompass should be investigated and possibly exploited. However, it is not believed that this could result in a navigation system for manned aircraft in operation before the Kollsman Celonavigator, and it would be subject to the same limitations as the Celonavigator.

N. <u>The Kearfott Company</u>

The Kearfott Company is presently engaged in manufacture of the N-1 gyrocompass on a production basis (Reference 23). The N-1, a gyro-slave compass, is being used as a heading reference for the B-36, B-47, and B-52 airplanes. It is claimed that the N-1 compass is capable of providing a heading which is accurate to 0.2°. The gyro itself when used as a free unit appears to be good to about 1 degree per hour drift rate. It is quite conventional in design using ball bearings throughout and is not a floated unit. The engineers working with this gyro feel that, with development, it might ultimately provide 0.10° per hour, but that no more precision could be expected without introducing flotation and abandoning the use of ball bearings. Some enchancement in performance of this gyro and the N-1 compass might be expected by mounting it on a stable platform.

The Kearfott people are beginning work on an inertial guidance or navigation system under a new contract with the Bureau of Ordnance. This work is intended to provide production of a heading reference and airborne stable vertical with sufficient accuracy to make it useable for 20 minutes to one hour of flight. At this time the project has not advanced much beyond the original proposal, hence no estimates can be made regarding the system and it is mentioned here primarily as a development to be watched with interest.

The Kearfott Company is a manufacturer of components for systems which are used in aircraft and missiles. These include servos, indicators, synchros, resolvers, and a gyro vertical. Some stable platform and accelerometer work is being done much of which is applicable to airborne fire control rather than to navigation.

Although, the facilities of Kearfott do not appear to be appropriate for development of large scale, long range systems, it seems that this organization is one of many precision manufacturers who might relieve the large system development laboratories of some of the load of component development, while producing units which are usable in interim quality navigation aids.

O. Arma Corporation

It has become apparent that if long range self-contained navigation systems are to assume operational significance, our industry must become proficient in the production of highly precise gyroscopic elements. Although laboratory units at North American Aviation and MIT, Instrumentation Laboratory have exhibited excellent performance we must consider the mass production potentiality of these units. Arma Corporation has completed work on a prototype precision gyro and is now prepared to produce these units in quantity as a part of their Mark 24 gyro compass.

In brief, the Arma gyro unit is a high speed, high density, rotor enclosed in an evacuated case which is then mounted in gimbal rings and floated in a high density fluid. Small torsion wires are used in place of gimbal bearings and the displacements of the rotor case about these elements are maintained at null by the use of electro-magnetic pick-offs to servos acting on an additional set of gimbals external to the case. By this means friction and random torques may be reduced to the limit of servo design. Any further increase of rotor angular momentum which becomes possible as a result of development may be expected to reduce the detrimental effect of residual servo errors resulting from hunting and servo dead space. This gyro unit when used as a gyroscope alone will have dimensions of about 11 inches in diameter by 13 inches long and the gyro itself weighs approximately 20 lbs while the associated electronics and servo equipment would increase the weight to about 75 lbs. The flotation fluid, Hooker Chemical Company Flurolube, must be maintained at a controlled temperature plus or minus 0.1°C. Approximately 1 hour preparation would be required in order to align the gyro and accomplish thermal warm-up.

While the Mark 24 gyrocompass is not suitable for aircraft use, the gyro unit itself might be used as a component in some airborne systems. Since the unit is designed for 10,000 hour service life in a combat tank, it is considered rugged enough for aircraft service. Tests on the Mark 24 gyroscope indicate that the present unit is capable of providing an inertial reference within a drift rate of about 0.1 degrees per hour. While this falls short of the requirement for systems such as SIBS, MX-1688B, or any of the other long range bombing systems, it is a degree of accuracy which might be employed in a system having short time of flight or relaxed requirements on accuracy. These units, which will undergo tests at Wright Field, might be expected to be available in production quantities in mid-1953, if a requirement for them were to be established soon. The Arma engineers have a development program in mind which appears, conservatively, to be capable of providing an increase in angular momentum, and hence an improvement in drift rate, of this gyro by a factor of about 10. This improved unit could probably be made ready as a production item before 1955, but again subject to early establishment of Air Force requirements.

Other component work in Arma Corporation includes the manufacture of synchros, servos, and computers. The Arma computers have inter-changeable sub-assemblies and overall accuracy is claimed to be about 0.1 percent.

Some navigation system study has been conducted at Arma, but there is no progress and no hardware being made at present. In conception, they propose a system using two two-degree-of-freedom gyro units and a vertical maintained by accelerometers in an 84 minute feedback loop. At present this is only a drawing board study; hence no real estimate of its quality can be made. The Arma people feel that they are capable of developing and producing a system of this type which could provde a present position indicator for small aircraft within an accuracy making it usable for periods as long as 5 hours. It seems doubtful however that this unit could advance to the prototype stage before the completion of project FINE or MX-1688A unless by the result of some sort of cooperative effort.

P. Pacific Mercury Research Center

Development work on daylight star sensing devices is being conducted at Pacific Mercury Research Center, (Ref. 26). Theirs is a continuation of the work which was initiated at Hughes Aircraft Company. This work has produced an infrared sensitive star tracker which is capable of maintaining the line-of-sight to a star within about ten to twenty seconds of arc under favorable day or night conditions.

The stellar inertial work at AC Spark Plug Division anticipates the use of Pacific Mercury star trackers which will be fabricated under experimental conditions not as production units. Other stellar inertial navigation projects seem to be planning to use this star tracker, and yet no program exists to execute a production phase of this work. If Air Force requirements in 1954 will include a quantity of these or similar units, it seems imperative that production engineering and the search for manufacturing facilities be initiated in order that this unit will be available as a production item, with completed flight tests, when required by other developments.

The Pacific Mercury Research Center has a number of other projects involving the use and employment of infrared devices. This includes work in the field of seekers and detectors. Some fundamental work in the field of infrared is being conducted at Pacific Mercury. No production or manufacturing facilities are planned by Pacific Mercury at the present.

V. A Critique of the Development Program

Development plans must be formulated with a clear understanding of the problems to be solved and the native limitations that are placed on the equipment by expected operational conditions. In the navigation of military aircraft, three logical sub-groupings immediately present themselves, they are:

1. Navigation of tactical or fighter craft,
2. Long range automatic navigation and bombing equipment,
3. Missiles.

The very nature of each of these fields of military operation requires each one to be treated separately since equipment serving each function must meet different requirements.

A. Navigation of Tactical and Fighter Aircraft

The difficulties of automatic navigation are reduced for aircraft of this class because of the characteristic short time of flight resulting from their high speed and the nature of their mission with subsequent reduction in those errors which increase with time. We have chosen the range for these craft to be about 1000 miles, round trip, and time of flight of 3 to 5 hours for purposes of estimating performance.

The tactical and intercept missions will normally include low altitude and high maneuverability requirements placing certain restrictions on a satisfactory navigation system. One such restriction is that any automatic reference to the celestial sphere, (i.e., star trackers) cannot be considered. Further, unless a system is to depend upon a series of position fixes some form of good stable vertical must be included. In the case of interdiction and intercept missions, navigation may be required simply as an aid to finding the target or target area in a cruise or homing phase. Under these conditions of flight the problems involved in obtaining an acceptable stable vertical are reduced since a stable platform on a craft of restricted maneuver need not incorporate provisions for large changes in the orientation of the craft relative to the local vertical.

If a navigation system is to be used in addition to bomb direction or sighting equipment the accuracy required of the navigator is relaxed somewhat. Certainly this relaxation must ultimately be limited by target visibility under the tactical conditions concerned. Within the limitations of the state of the art as outlined above we are able to suggest a number of solutions to the navigation problems for these craft which are presently under development, or might profitably be placed under development in the near future should such a requirement be seen to exist.

The dead reckoning computer is one of the simplest forms of self-contained navigation aid which, when coupled with a satisfactory heading reference, will relieve the pilot of the need to compute his "course to go". Extended navigation may be accomplished by repeated ground position fixes. From these fixes and a pre-designated, but alterable, destination the computer should be capable of accomplishing the arithmetic required to indicate the desired course. Repeated fixes and position comparisons will provide a reasonable estimate of wind conditions. If airspeed and heading are also introduced to the computer in some way, a fair measure of present ground position would be available as output.

Computers of this type are now under development and could probably become available in 1953 if requirements exist. They are, for example, the Ford Al Dead Reckoning Computer, and the airborne computer being prepared for the Hughes Tactical Bomb Director. The first mentioned computer does not presently include course computation, but simply a means of computing present position by dead reckoning. If course computation is not required, the Ford A-1 computer is now ready for production. If, on the other hand, computation is considered as a necessary element it could be added to the Ford instrument or it might be available from another source, say the Tactical Bomb Director Computer. There should be no difficulty in providing a sufficiently precise heading reference for this device, either an N-1, or a gyrosyn compass should be sufficient, and the accuracy of the entire system is directly dependent on the frequency and correctness of the pilot's position fixes. Some simple sighting gear, possibly mounted on a stable platform, could be used to improve the quality of position fix data if such aids are not now available.

Navigation by dead reckoning computer has limited precision if its input is of the nature mentioned above. That is to say, airspeed indication is insufficient for precise navigation and correction by frequent position checks is required. The navigation of tactical craft may be somewhat improved by using velocity data from a more precise source, such as doppler radar. Such a system, the Interim Fighter Navigator, AN/APN-82, will use the "front end" of the AN/APN-66 bomber navigator to provide ground speed and drift angle data to the Ford Instrument Company computer Type A-1, and will use the gyrosyn compass for a heading reference. Since it is planned to have the AN/APN-66 in production by the end of 1952 and since the Ford A-1 computer can be in production within a year, the Interim Fighter Navigator could be in operational use by 1953.

The use of doppler radar systems in tactical and fighter type aircraft may impose limitations on allowable maneuvers. Further investigations are necessary to determine the effects of such limitations on the accuracy and feasibility of the systems using doppler.

Accelerometer, or inertial, navigation systems are under development for use in aircraft having short-range missions. These systems (Projects FINE and MX-1688A) will be capable of providing a complete source of navigation data, but they are in the early development stage. Hence, completed systems of this type cannot be expected as soon as one might wish to employ self-contained automatic aids to navigation. A moderately simple system having tolerable precision might be developed along the lines of the inertial navigation project at Kearfott Company where an accelerometer system capable of 20 minutes to one hour stable performance is being developed under a contract with Bureau of Ordnance. The attainable accuracy of such a system should be in the neighborhood of 10 miles in each 1,000 miles of flight with reduction in errors arising from the use of more frequent position fix data.

A higher degree of precision in the accelerometer type of system may be expected to become available in 1954 or 1955 with the completion of MX-1688A at North American Aviation, or with the completion of Project FINE at MIT. The objective of both of these projects is to provide a means of navigation by inertial measurements with a probable error of 2 to 3 nautical miles for each hour of operation. One can see that for slow speed aircraft an occasional position and velocity check might be desirable; however, for high speed craft these may be eliminated. The time for development of these two systems will depend upon the progress to be made in the next year in the field of system components both at MIT and North American Aviation since the underlying principle used in both systems is quite similar and the flight schedule for both projects calls for flight testing to be in progress during 1953.

Any navigation system requires an acceptable heading reference and the inertial systems are no exceptions. The best available heading information, for short times of flight, with inertial gear is to be obtained from the gyro reference. Unlike the vertical reference, no means has been devised to damp an inertial heading. In the absence of some such means of damping the heading will depend on the use of high quality gyroscopes. While gyros of .01 degree per hour quality may be obtained in the laboratory, no quantity production of these units is presently available.

In the event that the low altitude and high maneuverability requirements for smaller aircraft may be removed, the star sensing devices, the astrocompass, and Celonavigator may be used. These will be available as a result of present work at Kollsman, or they might be developed separately with the employment of a daylight star tracker as a component. Development of daylight star sensing devices at Pacific Mercury Research Center indicates that these star trackers might be put on a production basis soon. In either event, that is, employment of Pacific Mercury or Kollsman star sensing gear, delivery of this kind of equipment might be expected some time during 1954.

B. SAC Navigation and Bombing Equipment

The navigation problem for long range craft, whether for bomber or transport is characterized by the size and the maneuver limitations on such craft. A discussion of the accuracy and limitations of standard navigation techniques for these craft is contained in Reference 17. This reference treats dead reckoning by the APQ-24 systems and estimates an overall error of about 3 percent of the range. The same paper estimates errors in position fixing by celestial means to be 6 to 10 miles.

There are at present a number of systems under development that could provide navigation and bombing equipment for SAC. These are:

1. Dead reckoning devices,
2. Doppler ground position indicators,
3. Stellar-inertial bombing systems,
4. Automatic map-matching, and
5. Inertial systems.

We shall discuss these individually.

Present standard bombing equipment includes provisions for dead reckoning; the major limitations on the accuracy of these arises in the determination of drift rate data and the accuracy of position information supplied to the computer. Optical position fix data could be improved by the use of an automatic or semi-automatic sighting device mounted on a stabilized platform. To obtain this would require a new development program using components and concepts which are available now.

In the event that the size and weight of navigation and bombing gear of the APQ-24 and K-1 class are considered critically high, lighter computers could be available soon as a result of development of the Ford A-1 Dead Reckoning Computer, the Eclipse Pioneer AN/APA-58, and the digital computer which is under development for the Hughes Tactical Bomb Director. Use of these light weight computers would not, however, improve the accuracy of the system which is a direct function of the quality of the input data.

Some sort of check point calibration near the end of a long bombing mission may be used to eliminate accumulated errors. After such a check point, navigation for say 1 hour may be obtained by resumption of the radar monitored dead reckoning, or by employment of an inertial extrapolator such as the K-1 Secure system.

The doppler radar navigation equipment, AN/APN-66, is intended for use in long range bombers. Its accuracy and maneuver limitations appear to make it inadequate to solve the blind bombing problem for long range missions. In flying over water it can accumulate serious errors due to the effect of wave motion on the velocity measurements (Reference 24). Over land it appears to be adequate to solve the general navigation problem: that is, to determine present position to an accuracy of the order of 1 percent of the range since the last fix, to determine average drift angle and wind speed, and to provide the course to follow to a predetermined target position. In view of its weight (about 400 lbs. including a heading reference), size and complexity, the increase in accuracy over a dead reckoning system appears marginal.

The ATRAN automatic radar map matching system offers the possibility of solving the complete navigation and bombing problem subject to the limitations described previously. The accuracy of position determination appears to be sufficiently high to permit bombing accuracies comparable with present radar bombsights. However, the system is still in the research stage and considerable development remains to be done.

The K-1 Secure Project is intended to develop a special purpose gear which, although probably less expensive, may not be capable of any better accuracy than the complete stellar inertial systems. K-1 Secure will be limited in accuracy by the quality of the position and velocity data introduced at the time of initiation of secure operation. If the same quality of correction data were introduced to an aircraft being navigated by SIBS or MX-1688B, for example, one would expect performance comparable to K-1 Secure. Considering the present time schedules and relative state of system and component developments, it is doubtful that the K-1 Secure program will be completed appreciably before these other units.

Laboratory and industrial development contractors are placing high priority on the development of a class of bombing systems which operates on the Stellar Inertial principle. The present development program covers a variety of these systems and the introduction of new concepts would be likely to serve to lengthen the development time for those systems now in progress. Some changes in emphasis might be useful in shortening this time.

The Celonavigator now under development at Kollsman would probably be the first such system to see operational use. This system, while not accurate enough to perform the complete bombing operation, will probably be capable of placing the aircraft within range to use its bomb sighting equipment. If given adequate priority this program could possibly produce acceptable navigation gear during 1953.

The BRASS RING project has the ambitious objective of providing a bombing CEP of one nautical mile in five thousand. Although this development is for a pilotless aircraft, there appears nothing to prevent the use of this equipment in a manned craft. Some flexibility has been sacrified for simplicity; for example, no provision is made for tactical changes in course or feinting. If such tactical restrictions are not considered acceptable, the techniques for eliminating them are available from system developments made for MX-1688B and SIBS.

Two contracts are currently active for the development of the Brass Ring equipment. Unless special considerations apply to this project, it is believed that closer coordination of the efforts of the contractors would reduce the duplication of effort that exists. Even with improved coordination, the state of component development does not appear to be sufficiently advanced to permit an unmanned craft to fly reliably for five thousand miles with such precision as to provide one mile probable bombing error at any time before the development of SIBS or MX-1688B, both of which are intended to provide a one mile probable navigation error in the presence of human monitors.

Both MX-1688B and SIBS are intended to provide a means of navigation to within one mile while permitting tactical alterations of the great circle course. The SIBS equipment includes a bombing computer while MX-1688B does not specifically include provisions for bombing. The employment of a bomb sight with SIBS, when tactically feasible, is expected to decrease the error at bomb release by an order of magnitude. The addition of a bombing computer, and perhaps a bomb sight, to the MX-1688B equipment will be required in order to make it a complete bombing system.

The SIBS equipment is estimated to have a total weight of two thousand pounds, compared with a figure of the order one thousand pounds for MX-1688B. This discrepancy for two such similar equipments is accounted for by the fundamental design and the absence of a bombing computer and sight in the MX-1688B. SIBS is based on an analogue principle where gimbal rings are oriented about selected axes, and these orientations are measured while MX-1688B will rely on computation of the equivalent orientations relative to local vertical.

Only if sufficient emphasis is placed on development and engineering of systems and components for these two projects, does it seem realistic to expect them to be introduced as operationally satisfactory systems in the neighborhood of 1955.

The SPIRE Project is intended to provide a complete system with precision adequate for bombing. This system, under development at MIT Instrumentation Laboratory, is wholly inertial and relies entirely on dynamical measurements, with no reference to the earth and stars except for the entry of initial position and velocity. The keystone in this project, as in all inertial system developments, is the high performance components required. The production of high performance units which will be required for SIBS and MX-1688B will probably provide a basis for production of the corresponding units as the completion of SPIRE draws near.

The SPIRE program represents the ultimate system for which a requirement can be established at present. Its use, however, does not seem probable until some time after 1955; consequently, no further comment is made here.

Navigation systems for low-altitude bombing missions are limited by the short time that the target is visible from low altitude. The climate restrictions placed on star-sensing devices, when used at two thousand feet or below, may be expected to permit the use of star trackers less than fifty percent of the time. (Reference 17).

Low altitude operation is not likely to reduce the efficiency of a system such as SPIRE. The SPIRE equipment will not be available, however, until so late that an interim navigator is desirable. The APN-66 Doppler Ground Position Indicator might prove to be useful in the employment of low altitude tactics. Its performance at these altitudes over a variety of terrain conditions should be investigated.

Low-altitude attacks which employ RED CHEEKS as a weapon will require a means of fixing aircraft position relative to the target with more accuracy than that required for bomb impacts. A project to develop a self-contained system for this purpose has been initiated and calls for the development of a manual radar map-matching device coupled with a doppler velocity indicator. This program might be expanded to provide a low-altitude navigation system with more general applications should the requirement exist.

If low-altitude bombing tactics are to require small aircraft it may be necessary to initiate miniaturization studies for APN-66 and SPIRE. Successful minaturization of APN-66 will be easier than for the SPIRE system and this work should be coordinated with aircraft design in order that small craft of the 1955 to 1960 era will be able to use this gear without major difficulties associated with installation.

The SAC bomber of the post 1955 era may be a relatively small, high speed craft operating at high altitude. If tactical planning does not call for the use of bombing radar some work must be initiated to design a compact system, probably patterned after MX-1688B, which will give a CEP of 1 mile or less. The present development programs are not oriented towards providing systems capable of fitting into a small bomber, and none will be available for early use in this time era which will be wholly independent of a terminal bomb sight.

The execution of some strategic bombing missions may call for the aircraft to rendezvous at some place which is remote from both the target and the base. This is a function which should be within the capabilities of any navigation gear which performs the large function of navigation from base to target.

Once the aircraft are within, say, 2 to 5 miles of each other a radiation link might serve to aid the consummation of the rendezvous. If visual means are considered inadequate, and security dictates radio and radar silence, a satisfactory aid to rendezvous might be developed employing passive infrared techniques. It seems that the use of this type of technique will inevitably call for a coordinated procedure to ensure the convergence of all craft involved.

Upon completion of a rendezvous the aircraft are frequently required to move out in a somewhat rigid formation and to maintain relative position according to some predetermined program. Since the tolerances permitted in a station keeping program are normally somewhat smaller than 1 mile it does not appear that any navigation and bombing system now in development will be capable of performing this function exclusive of a radiation link.

If escort fighter tactics are included in SAC missions it seems imperative that they obtain long range navigation by extension of the systems mentioned in the section on tactical aircraft or by use of doppler APN-79 equipment. Completion of rendezvous, and subsequent station keeping functions, would best be served by some type of radar or infrared gear similar to that required for bombers and tankers.

C. Guidance of Bombardment Missiles

Development of self-contained navigation techniques is necessary if we are to employ surface-to-surface and air-to-surface missiles. Although we may be using these navigation systems in quantity for aircraft in the latter half of the present decade, the employment of these systems in operational quantities in missiles will not come until some time later. The missiles systems must be capable of accuracy at least as good as aircraft bombing systems while meeting more stringent requirements on reliability, since no human monitoring is possible. Guidance systems for missiles are usually lighter and more compact than systems for use in manned craft, and hence will introduce new problems in design and production. These guidance systems are still under development and none have flown under simulated tactical conditions. The same components as those used for manned craft may be applied to the missiles systems. Production of adequate components for SIBS or MX-1688B would provide an adequate source of precision gyros, accelerometers and star trackers for use in missile development programs while providing a background for eventual use in missile production.

The tactical pay-off which might be gained by employment of air-to-surface missiles encourages interest in their development. While air-to-surface guidance by means of a radar television link may eventually be successful, guidance by dynamical measurements should be exploited for this purpose. Guidance may be accomplished by an autopilot and dead reckoning computer for short ranges. If longer ranges are desired a more complex system must be developed to obtain the required accuracy. In any event, precision navigation of the launching craft will be required since terminal accuracy of the missile will reflect the launching accuracy.

There appears to be no fundamental investigation of the factors affecting the optimum means of maintaining an inertial reference in missiles. At present we know that the low speed vehicle should employ a star tracker reference, since gyro drifts will cause excessive errors. The very high speed craft, on the other hand, will profit by the use of gyros alone since boundary layer and Mach cone effects will cause excessive degradations in the performance of a star tracker, while the resultant short time of flight gives rise to a lessening of errors arising from gyro drift. While this problem has been treated in the analytical design studies of various missile contractors, no basic study of the parameters affecting system performance has been conducted. The initiation of this study could be profitable in expediting the development of long-range supersonic missile guidance.

REFERENCES

1. Kollsman Instrument Co., "Progress Report No. 46 on Automatic Celonavigator," December, 1950; Ibid. Progress Report No. 48, June, 1951.

2. General Precision Laboratory Report No. A11-32, "Interim Engineering Report on an Automatic Ground Position Indicator," May 20, 1949.

3. Consolidated Vultee Aircraft Corp., "Magnetic Guidance Survey," Report No. CM-527, January 3, 1949.

4. Sperry Gyroscope Co. Interim Report No. 3, "Development Program for Passive Navigation Equipment, K-1 Bombing System Secure," June, 1951.

5. Sperry Gyroscope Co. Interim Engineering Report No. 1, "Development Program for Stellar Inertial Bombing System," December, 1950; Ibid. Interim Report No. 2, April, 1951.

6. North American Aviation Inc. Report No. EM-148, "Technical Description of Proposed System for Increased Autonavigator Accuracy for Project Brass Ring," July 27, 1951.

7. A C Spark Plug Division, General Motors Corp., "Design Study Summary, Stellar Inertial Bombing System," September, 1951.

8. Northrop Aircraft Co. Report GM-932, Vol. II, "Project Snark Quarterly Progress Report, Automatic Celestial Navigation," June, 1951.

9. North American Aviation Inc. Reports Nos. EM-115-1 through 6, "Latitude-Longitude Star-Supervised Inertial Autonavigator, Project MX-1688-B."

10. North American Aviation Inc. Reports Nos. EM-145-1 through 4, "Autonavigator for Fighter Type Aircraft Project MX-1688-A."

11. Goodyear Aircraft Corp. Report No. GER-2788, "Quarterly Progress Report No. 27, MX-778," August 1, 1951.

12. RAND Corporation Report RM-475, "Radar Map Matching Accuracy Analysis," F. P. Forbath, June 1, 1950.

13. North American Aviation Inc. Report No. EM-137, "Preliminary Model Specification for a Stellar Supervised Inertial Automatic Navigation System," June 30, 1951.

14. Consolidated Vultee Aircraft Corp. Report No. ZM-7-001, Vol. V, "MX-1593 Surface-to-Surface Rocket Missile."

15. RAND Report RM-682, "Estimation of Bombing Accuracy," J. I. Marcum, September 6, 1951.

REFERENCES (Cont.)

16. Shields, B. A., "Meteorology and Air Navigation," McGraw-Hill Book Co., 1942, p. 251.

17. RAND Report RM-723, "Resume of Aerial Navigation for Long Range Bombers," P. M. Dadant, November 12, 1951.

18. Mass. Inst. of Technology, Instrumentation Lab., "Fundamental Possibilities and Limitations of Navigation by Means of Inertial Space References," Report 6398-S-2, February, 1947; Scientific Advisory Board, USAF "Seminar on Automatic Celestial and Inertial Long Range Guidance Systems," February, 1949, Vols. II and III; MIT Instrumentation Lab. "Optimum Parameters for Automatic Airborne Navigation," B. P. Blasingame, 1950.

19. RAND Report R-144, "Blind Navigation by Dynamical Measurements," J. J. Gilvarry and S. H. Browne, July 14, 1949: RAND Report R-154, "Theory of Errors in Automatic Navigation with Accelerometer Systems," S. H. Browne and J. J. Gilvarry, to be published.

20. RAND Report R-178, "Long Range Surface-to-Surface Rocket and Ramjet Missiles - Guidance and Control," R. P. Frick, W. E. Frye, F. P. Forbath, et al. May 1, 1950.

21. RAND Report, RM-666, "Errors in Typical Long Range Surface-to-Surface Undamped Inertial Guidance Systems," E. V. Stearns, August 7, 1951.

22. RAND Report RM-751, "Passive Detection of the AN/APN-66", J. L. Hult, December 19, 1951.

23. Air Proving Ground Report No. APG/SAB/11-AC, "Operational Suitability Test of the Type N-1 High Latitude Directional Gyro Compass," October 5, 1951.

24. General Precision Laboratory Progress Report No. A11-48, August 4, 1950, p. 3-64.

25. General Precision Laboratory, Progress Report No. A11-57, March 23, 1951, p. 3-38.

26. Pacific Mercury Research Center, Report No. 73-3 "Airborne Star Tracker MX-744", October 31, 1951.