Air Traffic Control Project
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SUBJECT: VISIT TO SPERRY GYROSCOPE CO. (C. R. Wieser, W. K. Linvill)

To: 6673 Group

From: W. K. Linvill

Date: February 2, 1950

Abstract: Sperry has built a 5000-megacycle, continuous-wave combined omni-range and distance measuring facility. Tests at Sperrry indicate a range of 30 miles, azimuth accuracy ± 0.5 degree, distance accuracy ± 0.1 mile. Multipath propagation has been minimized by selection of carrier frequency and careful antenna design. Bandwidth requirements have been held to a minimum. This equipment has been designed to be incorporated in an aircraft automatic guidance system. Studies of the guidance system which have been made with attention to the dynamic behavior of the aircraft, indicate that the most serious limitations are imposed by imperfections in the navigation equipment. The guidance system includes an airborne automatic path follower, which is now being developed.

1.0 Introduction

The purpose of the trip to Sperry was to get more information on the work done there which would be broadly usable in air traffic control. The people consulted were Joseph Lyman and George Litchford who gave us details on the navigation system Sperry is building, P. Halpert and G. F. Jude who discussed aircraft automatic control. The discussion of our findings will be divided into three parts. First the navigation system will be discussed, second the control problem will be described, and finally the automatic path follower will be described briefly.

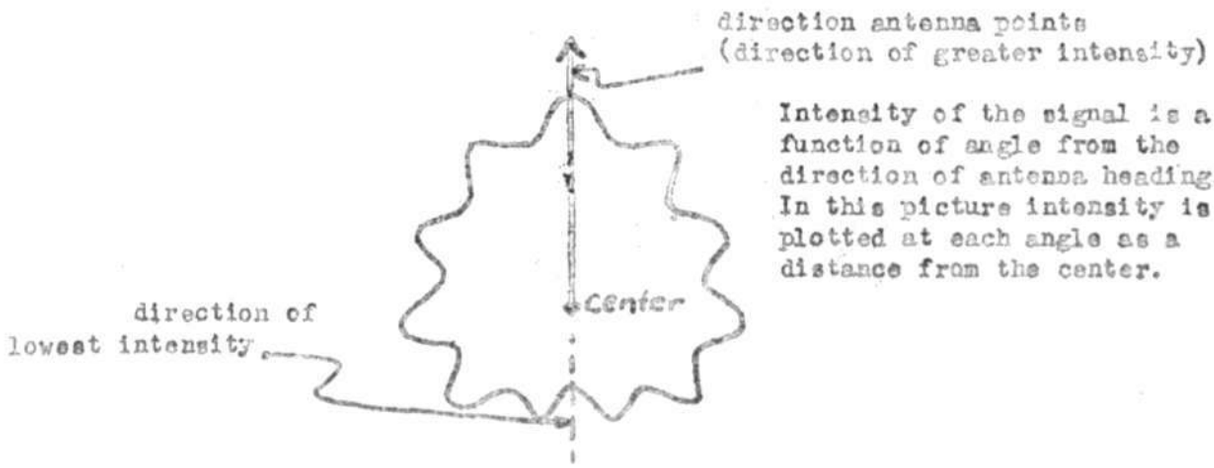
2.0 The Navigation System Being Developed by Sperry

The control of an aircraft on a prescribed flight path according to a given schedule requires at the outset an accurate measure of the aircraft's position. In aircraft control as in any form of control, one can't control a variable more accurately than he can measure it.

If one is to bring airplanes to an airport runway accurately enough to permit two landings per minute, he must control the flight to close tolerances for several miles before the airport is reached. This is true because the speed and direction of an airplane flight can't be changed quickly. An airplane is about as maneuverable as an automobile on icy streets. It simply is not possible to exert forces on the airframe which are great enough so that its speed or flight direction can be changed rapidly. After considerable thought, Sperry engineers have agreed among themselves that close control should be exercised on the plane within a circle of 30 miles radius about the airport to insure 1/2 minute scheduling at the runway. Using the (r,e) system of navigation, they have developed equipment which can be made to have sufficient accuracy. This system operates at 5,000 megacycles. Many aspects of its operation are described in the Interim Report on the Further Development of a System for Airport Traffic Guidance and Control published by Sperry. Important characteristics of the navigation system are the use of continuous wave rather than pulses in order to cut down band width of the transmitted signals, and the use of an antenna with radar lens to keep the radiation off the ground. This procedure cuts down the multipath transmission problem and makes navigation measurements much more precise than was possible on previous schemes. There are two measurements involved in the determination of position, azimuth and radius. These measurements are made in the aircraft and are presented on a map in the plane by a simple servo. The various steps in the measurement and presentation are discussed in considerable detail in the report cited above. Their operation will be summarized here merely from the point of view of one who wishes to use them as tools in air traffic control.

2.1 Azimuth Measurement

Azimuth measurement is made by comparison of the phase of the amplitude modulation envelopes of two signals. A continuous-wave, constant-amplitude signal is sent out on a rotating directional antenna with an intensity pattern which is a limacon having eleven fingers. Fig. 1. The antenna rotates at 27.5 cycles per second.



Because of the shape of this intensity pattern and the antenna rotation, an observer at a fixed point receives an amplitude-modulated wave with a modulation frequency of 27.5 x 11 = 302.5 cps. The phase of this modulation envelope would depend upon the azimuth of the observer. A second wave, a frequency-modulated wave, is sent out on the same antenna with its frequency modulation synchornized with the rotating antenna position. By comparing the envelope phase of the rotation-modulated signal from the rotating antenna and the phase of the modulation of the frequency modulated wave, an observer determines his azimuth. There are 11 azimuth locations where the observer could measure a phase of any given value. Note also that the intensity pattern has a shape which gives a 27.5 cps modulation in addition to that at 302.5 cps. This modulation allows one to pick which of the 11 azimuth angles is the proper one.

2.2 Distance Measurement

The distance measurement is accomplished by measuring the time delay required for signal transmission from the aircraft to the ground station and back to the aircraft. This delay appears as a phase shift between the modulation envelopes of the transmitted and received signals at the aircraft. The signal used is an amplitude-modulated 5000-megacycle wave. Since this system requires all aircraft to use the same ground equipment and since only one aircraft can use it at one time, a time-sharing system is worked out. The ground station interrogates each aircraft on the basis of its azimuth. Upon reception of an interrogation signal, a given aircraft sends out its signal and receives a re-transmitted signal back from the ground. The ground receiver has a directional receiving antenna which reduces multipath troubles. The direction of the receiving antenna at the ground is synchronized with interrogation signal sent from the ground station. At present each aircraft makes a distance measurement each 6 seconds. This rate can be increased enormously by a new system Sperry has under development.

2.3 Presentation of Plane's Position On Its Own Map

Both azimuth and distance are observed in the aircraft in terms of phase shifts between two modulation envelopes. These phase shifts are converted to mechanical angle by use of electromagnetic phase shifters which produce an envelope phase shift of the same size as that observed between the two signals. The angular position of the rotor of the phase shifter is the mechanical angle. The position of the aircraft is presented on an airborne map where the center represents the ground station. The plane is represented by a moving point whose radius and angle with respect to the center of the map are made to correspond to the distance

and azimuth measurements. The fine control of the azimuth indicator is represented schematically in Fig. 2

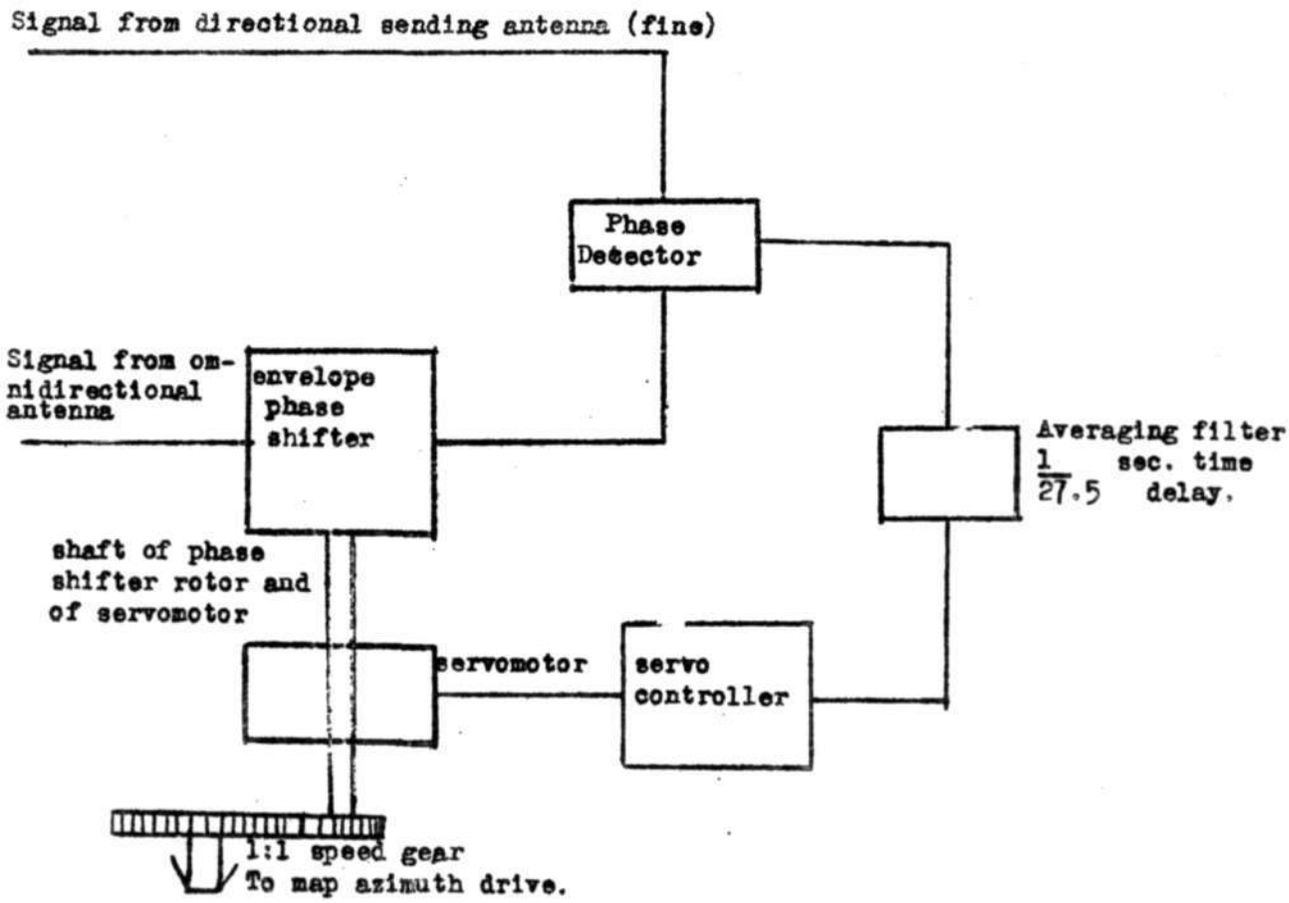


Fig. 2 Equipment to Indicate Azimuth

The envelope of the reference signals is shifted by rotating the rotor of the phase shifter. This rotation is done by the servomotor whose signal comes from a [illegible] deviation between the signal from the sending antenna and the phase-shifted reference. The rotor of the phase shifter and the azimuth indicator on the map are coupled to the same shaft by 1:11 speed gearing. A coarse system identical to the fine but with 27.5 cps. modulation instead of 302.5 and no averaging filter is coupled directly to the azimuth indicator. The operation of this coarse-and fine system is entirely conventional. The function of the averaging filter after the phase detector in the diagram of Fig. 2 is to average the fine

azimuth data obtained from a reading on each of the eleven intensity lobes of the directional antenna. Figure 3 shows the mechanical arrangement which presents the plane's position on the map.

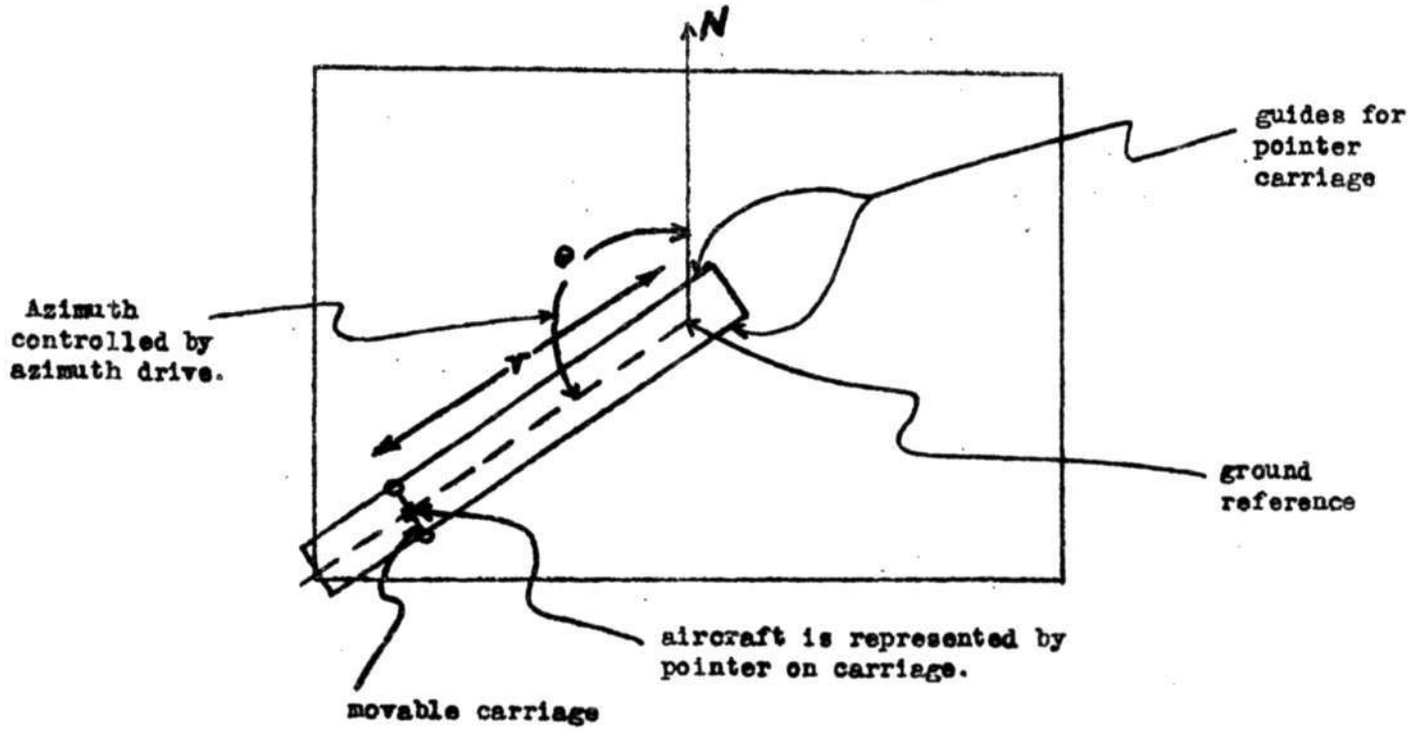


Fig. 3 The Map and the Moving Point Which Follows the Position of the Aircraft.

The aircraft is represented by a pointer on a movable carriage. The carriage rides on two tracks or guides which are rotated relative to the map by the azimuth drive. The center of rotation for these guides corresponds to the point on the map which is the ground reference for the (r, θ) system. The distance from the pointer representing the plane to the ground reference point on the map is controlled by the distance measured by the distance measuring equipment. As was pointed out in section 1.2, the distance is measured by the difference in phase between the envelopes of a transmitted and a received signal. This phase difference is converted into a shaft rotation in the same way it is done in the azimuth indication equipment shown in Fig. 2. The angular position of the envelope phase shifter in the distance-measurement equipment is transmitted to the map by a repeater servo which moves the pointer carriage to the proper radius from the map center.

The main time delay in representation of the plane's distance results from the 6-second interval between samplings. The delay in the distance presentation is about 20 seconds. This delay can be decreased by increasing the sampling rate. The azimuth presentation has a time lag of roughly 1/30 second from the averaging filter and another one of roughly the same size associated with the servo which controls the phase shifter. This whole azimuth presentation servo is mounted on the map and the same servo which rotates the phase shifter also rotates the carriage guides relative to the map. The azimuth presentation never lags more than 100 milliseconds behind actual azimuth of the plane. At present the accuracy of measuring and presenting azimuth is $\pm$ 1/2 degree. The accuracy of measuring and presenting distance is $\pm$ 1/10 mile. It is believed that azimuth accuracy can be increased by a factor of 5 by increasing the number of lobes on the limacon to 55. At 30 miles the distance measurement is much more accurate than equivalent lineal accuracy of the azimuth. Assuming 60 degrees equal 1 radian, at 30 miles 1/2 degree corresponds to $1/2 \times 1/60 \times 30 = 1/4$ mile.

3.0 Aircraft Control

Given a navigation scheme to measure the position of an aircraft, one next considers the means which can be employed in controlling that position. A very good short summary of the problem of aircraft control is contained in a paper by P. Halpert of Sperry entitled The A-12 Gyropilot (in Barta Building Library). It was presented to the Society of Automotive Engineers at their National Aeronautic and Air Transport Meeting in New York on April 13-15, 1948. There are two steps in aircraft control, attitude control and path control. In attitude control, the attitude of the aircraft is so modified that the major forces acting on the crafts, the lift and the thrust, are directed to cause desired direction of motion of the plane. Hence, the control of the path must necessarily be exercised indirectly through attitude control. Two main path controls, altitude and lateral path control, have intermediate attitude control. Altitude control is obtained by controlling the pitch of the aircraft. Pitch control is attitude control. Lateral path control is obtained through bank control. Bank control is the second attitude control. Speed control has no intermediate attitude control associated with it.

Summarizing, there are two path controls, altitude and lateral path control. The two have an intermediate attitude control. Pitch controls the rate of climb, bank controls the rate of turn, or the second derivative of lateral position. A plane's flight is controlled through climb or dive (pitch control), bank right or left, and speed-up or slow-down commands. To a first approximation one can assume negligible time lags in attitude control responses. The correlation between error in altidue and the resulting pitch command and between lateral position error and the resulting bank command is made in such a way that a control system results which is stable and as free as possible from

extraneous disturbances. At present the greatest deterrant to good path control is noise in the navigation data which is used in obtaining error in path position. If navigation data were improved so that attitude responses could be made the limiting factor, then the usual time constants associated with attitude controls would be important. These time constants are about 3 seconds in present-day aircraft. The path control time constants in today's equipment with limited navigational data range from 15 to 20 seconds for altitude and lateral path control. In speed control the time constants average from 20 seconds in reciprocating-engine planes to a minute or so in jet planes. For reciprocating engine planes, these time constants can be shortened provided that the range of speeds over which the control system operates is reduced to prevent saturation effects. Since the lag in engine response is fundemental to jets, the time constants of jet plane speed control can't be decreased until jet-engine time constants are decreased.

There are two types of aircraft flight control problems which arise in special situations. One is glide-path control and the other is in-flight control. Glide-path control which is used in landings is difficult because sensitivities in the control system change with the great speed changes involved and because the use of azimuth measurement to get distance becomes difficult when the radius changes radically. At 30 miles, 1 degree in azimuth corresponds to 1/2 mile lineal distance whereas at 0.3 mile 1 degree corresponds to 1/200 mile. Glide-path control must be attacked as a special problem apart from in-flight control. We learned little more than that Sperry is working on it. In working on the general problem of air traffic control, one needs to know little more about glide-path control than what contraints it applies to the flight control paths and schedules near the airport. In-flight control can be exercised by use of the Sperry Automatic Path Follower.

4.0 The Sperry Path Follower

The navigation scheme described in section 1 and the usual automatic flight controls can be combined to give an automatic lateral flight-path follower for in-flight control. The navigation system locates the aircraft on a map on which the desired flight paths is traced. The instantaneous bank angle commands for the controlled plane are determined by the instantaneous lateral deviation of the plane's position from the desired position. This deviation is indicated continuously on the map. The details of the system operation are sketched in what follows.

A heavy line (about 1/4 inch wide) is traced on the map to represent the desired flight path. A photocell scanner which represents the aircraft position is placed on the movable carriage instead of the

pointer (Fig. 3). The photocell scanner has an opening like that shown in Fig. 4 below. The scanner is so oriented on the map that its approximate heading corresponds to the airplane heading as read on the gyro-compass.

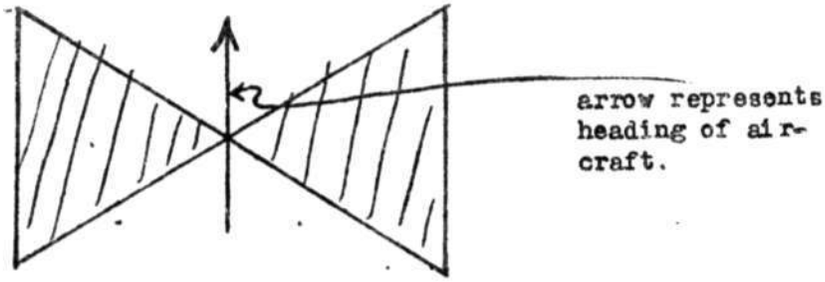


Fig. 4 Light Opening Used in Photocell Scanner for Automatic Curve Follower.

Each half of the light opening has a photocell associated with it. The control system so operates that the plane's position is modified in order that the scanner shall straddle the path. This control serves merely as lateral path control and not as altitude or schedule control. By putting time markers on the path, one could include schedule control. The photocell scanner is a balancing device wherein the light entering one half of the scanner just equals that on the other side. This implies that accuracy of following is not limited by the width of the line tracing the course on the map. One distinct characteristic of this curve following scheme is that the map must be laid out ahead of time. This device has been built to test feasibility of automatic flight-path control, but it might be used as one type of intermediate link in an air traffic control scheme.

If the path needed to be changed during flight (as surely will be essential) one might have a number of path maps available in the aircraft and use the one prescribed by the ground computer. Another scheme is to fit the map together from standard pieces much as a plumbing system is laid out. One could have standard turns, standard straight-line flights and so on. These could be pieced together to give finally a path which could appear on the map. Regardless of what final system is used the Sperry automatic path follower is a very good intermediate tool for testing the accuracy of automatic flight control.

5.0 General Remarks

We were very much pleased by the cooperative attitude of all of the engineers whom we consulted at Sperry. In addition to Lyman, Litchford, Halpert, and Jude we met Mr. Heins and Jay Browder who are associated with Lyman and Litchford in developing the 5000-megacycle navigation system. Marvin Klayton, who is the engineer from Watson Labs associated with this project visited Sperry the same time we did and joined our conference the first day.

Signed: William K. Linvill
W. K. Linvill

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