6673
Memorandum M-2035

Air Traffic Control Project
Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

SUBJECT: VISIT TO FEDERAL TELECOMMUNICATION LABORATORIES, January 23, 1950

To: 6673 Engineers

From: C. R. Wieser

Date: February 2, 1950

Abstract: Current work on distance measuring equipment (DME) and omni-range systems was discussed. The DME accuracy specifications are ± 1/5 mile from 0-20 miles and ± 1% above 20 miles. An omni-range system under development is expected to achieve ± 1/2 degree accuracy for radial flight. The signals from both systems contain a good deal of noise, which is caused mostly by multi-path propagation, and it is the opinion at Federal that the noise prohibits differentiation to obtain dynamic rate signals.

The Federal Telecommunication Laboratories were visited January 23, 1950 to discuss air navigation and traffic control. Those present from M.I.T. were J. W. Forrester, N. H. Taylor, W. G. Welchman, and C. R. Wieser. Several members of Federal were present. The general discussion was carried on with H. Busignies, Richardson, Alexander, and R. I. Colin. More specialized discussions were held with S. H. M. Dodington on distance measuring equipment (DME), with Lundberg, Himmel, and C. Adams, on omni-directional range, and with G. Deschamps on analogue-to-binary conversion.

Unfortunately Mr. P. R. Adams, who specializes in traffic control, was absent because of illness, and Mr. Sandretto was unable to spend much time with us. As a result the discussions were confined for the most part to navigation.

The Navar system (described in M-2003) has been built, though not in the complete form proposed by Federal, and some test work has been done. The two-color superposition of displays from two PPI scopes has operated satisfactorily, although alignment is difficult. The Navar system uses air-derived and ground-derived position information. The latter is retransmitted to the aircraft to provide a display of other nearby aircraft. The retransmission system, or "three-path radar", has not yet been tested to determine its accuracy.

The Federal DME[1] consists of the usual "count-down" system in which several aircraft interrogate a single ground transponder. The system saturates at about 25 aircraft with the three-path radar and about 50 aircraft with air-derived distance only. Its maximum range is 100 miles, and its accuracy specifications are ± 1/5 mile from 0 to 20 miles and ± 1% at ranges greater than 20 miles.

The time required for automatic search and lock-in depends on range and is about 7 seconds on the average. The search time, which is determined by the number of pulses which must be received in order that an aircraft may positively identify its own reply from the transponder, is reduced by increasing the pulse-repetition rate from 30 to 150 pulses per second during search. It was stated that the search time might possibly be reduced to 1 second (with equipment modification). The search time is important in air traffic control since the aircraft receives no position information during search, which is necessary after switching from one transponder to another.

There was a discussion of the sources of error in the DME system and their importance. The errors in airborne time-measuring equipment are quite low. Time measurements are made by automatically driving a goniometer (excited at 8 kc) to a position where the phase shift produced is equivalent to the round-trip time for a DME pulse.[2] The goniometer, which is geared to the distance indicator, serves as a fine measuring system with a sensitivity of 10 miles per revolution. The errors caused by the goniometer and gearing are of the order of 1/100 mile. At present, errors caused by drift of the excitation frequency are greater, but could easily be reduced by crystal control if desired. Ambiguities caused by full revolutions of the goniometer are eliminated by a phantastron which is used as a coarse time-measuring device.

The goniometer servo drive includes a tachometer which is used to stabilize the servo and display on a meter the aircraft's rate of increase or decrease of distance from the transponder. The rate information is stated to be accurate to about 10 to 15% and is usable only when the meter is so highly damped that its time lag is about 30 seconds. A large part of the fluctuation in the rate information is caused by imperfections in the goniometer. Even though the goniometer is linear to about 1/4 degree, its errors occur as abrupt discontinuities and hence cause violent fluctuations in measured rate. The rate meter was first connected without the large time lag and oscillated violently through its ± 600 mile-per-hour limits.

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1. E. Busignies, "High-Stability Radio Distance-Measuring Equipment for Aerial Navigation", Electrical Communication, Sept. 1948.

2. Federal Telecommunication Laboratories, "Preliminary Handbook for Airborne Distance Measuring Equipment AN/APN-34(XA-4). (In Barta Library.)

The greater part of the inaccuracy of the DME system is the uncertainty in the time at which the transponder is triggered. A large part of this error is caused by the rise-time of the pulse received from the aircraft. The present specification of the uncertainty of the transponder delay is ± 0.8 µsec. The pulse rise-time is restricted by the available bandwidth.

When an aircraft is flying at an altitude which is low compared with the line-of-sight zone of the transponder, the triggering uncertainty is greatly aggravated by the presence of earth reflections caused by grazing incidence of the air-to-ground transmission. The small difference in the length of the direct-pulse and reflected-pulse paths causes the reflection to arrive very soon after the direct pulse. It may cause appreciable interference before the direct pulse has risen to an amplitude large enough to trigger the transponder. The varying phase relation between the direct-pulse carrier and the reflected-pulse carrier causes the measured distance to jitter by 0.1 to 0.2 mile. This effect is worst at long ranges and is serious at altitudes below 10,000 feet at 100 miles.

The uncertainty caused by the rise-time of the pulses received by the transponder cannot be reduced by using automatic gain control, because the transponder is shared by many aircraft flying at various distances.

The DME systems now being built use paired pulses with separations up to 77 µsec for channel identification. The interval is controlled by a mangetostriction delay line which introduces further errors because of temperature drift. Temperature compensation will probably be provided in the future. Ten pulse separations are provided to give ten channels air-to-ground and ten channels ground-to-air. These may be combined to furnish 100 channels.

There was some discussion of analogue-to-binary conversion. Apparently the people at Federal have been principally concerned with the conversion of shaft position to a binary number.

The time measuring goniometer mentioned above can readily be used as a conversion device if the time interval generated by phase shift in the goniometer is used to gate a fixed-frequency counter. (This is the same system that Roger Sisson has used in his thesis work here.) The goniometer used by Federal is a standard Bendix Autosyn resolver designed to operate with 400 cycle-per-second excitation. They have used 8-kc excitation successfully and have heard that RCA has done similar work using 15-kc excitation. The size of the goniometer unit in the DME equipment is 7 1/2 x 5 x 10 inches, exclusive of power supply.

We inquired about the use of capacitance goniometers for conversion of shaft position to a proportional time interval. Mr. Richardson stated that Federal prefers the inductive goniometer because the capacitance device (1) has too high an impedance and (2) is adversely affected by parasitic capacitance in the associated circuits.

The DME equipment referred to above was made by Federal on a contract with Watson Laboratories. They have also built a VHF omni-range facility (VOR), described below, for Watson Labs.

The VOR built by Federal operates in the 112-118 mc band, which is the band now used by the CAA installations. The Federal equipment seems quite similar to the CAA equipment except that Federal has improved its characteristics, principally by better antenna design. The Federal people quoted ± 1 degree average error at a good site (versus about ± 1.8 degree for the CAA equipment) and an overhead cone of confusion of about 10° included angle (versus 90 degrees for the CAA equipment).

There was a discussion of the various errors in omni-range systems. The errors, which were classified as (1) goniometer, (2) octantal, (3) polarization, and (4) multipath, are discussed below.

Goniometer errors arise from imperfections in the construction of the goniometer, which controls the excitation of the various elements in the antenna array. These errors produce a non-ideal radiation pattern.

Octantal errors are caused by antenna imperfections which result in a non-ideal radiation pattern even though the excitation of the antenna elements is perfect. These errors are fixed, and are a function of the aircraft's bearing.

Errors are introduced by a small component of vertically polarized radiation which cannot be wholly eliminated. The vertical component causes the signal received by the aircraft to shift slightly with changes in its attitude. This behavior is detrimental to precise control, and will sometimes cause instability in automatically controlled flight. If the aircraft is, for example, flying radially with a small error it must bank to correct the error. The effect of banking may shift the apparent radial course enough to reverse the error. This results in wobbling flight, even though the average path may be unaffected.

The earth and man-made obstacles reflect radiation and cause multipath errors, since the aircraft receives, in addition to line-of-sight radiation, reflected components. The resultant radiation pattern then has errors which depend on the relative bearing of the reflecting surfaces and their efficiency as reflectors. The reflected wave behaves in a manner similar to a reflected light wave, and the resultant radiation received by the aircraft may be considered as the sum of the direct radiation and radiation from an equivalent source in line with the reflecting object. The aircraft sees a pattern equivalent to the resultant of two separated omni-range stations having different signal strengths. The reflected wave (or equivalent second source) produces a component of radiation whose carrier and modulation envelope both differ in phase from the direct wave. Since the phase of the modulation envelope is the means by which bearing is measured, the shift due to reflections causes an error which depends on the reflector's location and efficiency. This error is serious, particularly at an unfavorable site. Phase shift of the carrier produces similar errors, except that the carrier shift due to reflection varies rapidly with change in the aircraft's position, because the wave length of the carrier is quite short (about 3 meters). The resultant radiation pattern contains standing waves about 3 meters apart. If the aircraft is flying at right angles to the standing waves, it passes through them very rapdily, and the resulting bearing measurement contains a high-frequency oscillatory error component which is easily filtered out. If, however, the aircraft is flying almost parallel to the standing waves, it crosses them slowly and produces a low-frequency oscillatory error in measured bearing. The latter condition would lead to wobbling flight if the VOR signals were used for automatic control.

It is apparent from the discussion of the various errors in omni-range that the most critical problem is control of the radiated pattern. A technique of easing this problem is the use of a multi-lobe rotating radiation pattern rather than the single limacon alone. A system of this type (also used by Sperry, M-2034) is under development at Federal.

The multi-lobe system uses a 9-lobe radiation pattern. Hence the change in phase shift, $\Delta\phi$, measured for a change in bearing $\Delta\theta$, is given by $\Delta\phi = 9\Delta\theta$. After the phase shift is measured in the aircraft, it is translated into indicated bearing by choosing a scale such that $\theta = \frac{\phi}{9}$. Since errors caused by imperfections such as vertical polarization and multipath affect the phase, ϕ, the maximum value of bearing errors is reduced by a factor of 9.

The nine-lobe system alone will permit 8 ambiguous bearings in addition to the correct one, and a single-lobe system must be used in addition as a coarse system to resolve the ambiguity. In the Federal system the single-lobe and nine-lobe patterns are transmitted one-at-a-time on a time sharing basis. The single-lobe pattern is rotated at 1800 rpm and the nine-lobe pattern at 200 rpm so that both are received as a 30 cycle-per-second modulation. The carrier is also frequency modulated by pulses to distinguish between the two patterns in the aircraft. The time sharing cycle has not yet been finally chosen, but successive intervals of 0.5 second for each pattern are probable. From the point of view of control, this may be bad since it imposes a sampling system with a one-second sampling period.

The accuracy specifications for the multi-lobe system, which is being built for the Air Force, are $\pm$ 0.5 degree for radial flight and ± 1 degree for orbiting at one mile. The additional lag during orbiting is caused by a velocity error of about 1/5 degree per degree per second in the indicator. During orbiting at constant angular velocity the error caused by switching off the nine-lobe pattern is negligible, because the indicator drive has a "memory" capacitor which holds nearly constant rate of change of indication during the switching period.

Federal is also developing an omni-range for the Navy. Since we were not cleared for this project, it was not discussed in any detail.

The Federal people, Busignies in particular, seem to consider the accuracy of a rotating-beam type of azimuth measurement system (similar to Navar) superior to the omni-range. In the beam-type system a narrow beam is rotated and a pulsed timing signal is sent out at the instant the beam is pointed North. When the beam sweeps across the aircraft, it triggers the receiver, and the elapsed time from reception of the North signal to the reception of the beam is proportional to the aircraft's bearing. This system was tried by Federal, and its accuracy was found to be limited by variations in antenna speed caused by wind loading. Apparently no work is being done on this system at present. From the control standpoint, this is a sampling system with a period approximately equal to the time required to rotate the antenna through one revolution.

It may be stated in conclusion that the most serious drawbacks of the DME and VOR systems are (1) lags caused by sampling and (2) errors caused by reflection of the transmitted signal. Both of these imperfections not only reduce the accuracy of measurement, but introduce noise of either a cyclic or random nature. The noise level is so great that the men at Federal do not see any possibility of differentiating the position signals to obtain usable dynamic rate signals, which would be very desirable for precision guidance of aircraft. Mr. Alexander suggested that rate signals might be obtained by using a separate Doppler rate measuring system. This scheme evidently has not been studied at Federal since there is, at present, no demand for dynamic rate measurement.

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