NEW LABORATORY FOR
THREE-DIMENSIONAL GUIDED MISSILE
SIMULATION

Louis Bauer
Project Director
Project Cyclone
Reeves Instrument Corporation
New York, New York

Introduction

Project Cyclone at the Reeves Instrument Corporation is under the cognizance of the Bureau of Aeronautics of the Navy. The function of Project Cyclone is primarily the development and operation of a Guided Missile Simulator, and the establishment and operation of a Simulation Laboratory. Problems in other fields are also studied and analyzed using the computing machinery of the Simulation Laboratory.

The original Guided Missile Simulator consisted of two types of flexible computers, and one large computer with DC and AC components which were permanently connected to handle those equations which were common to all Guided Missile problems. This large computer was known as the Ballistic Computer. The flexible computers were a DC analog computer with servomechanisms units (now known as the Reeves Electronic Analog Computer, or REAC®) and an AC analyzer. The flexible units were intended for simulation of those aspects of Guided Missile problems which could be expected to vary widely from one problem to the next.

Because of the immediate success of the flexible DC analyzer and because of the pressure of problems awaiting solution on it, the AC analyzer was somewhat neglected; it never performed as well as the REAC and was later abandoned. Work on the Ballistic Computer was continued until a satisfactory solution to a three-dimensional check problem was obtained. However, by that time REAC techniques had advanced sufficiently so that it was possible to obtain the solution to this check problem on REACs. After careful consideration of the relative difficulties of setting up such problems on the Ballistic Computer, and of making the problem work (i.e. making the machine perform), it was decided to replace the Ballistic Computer by a large installation of REACs and servo units. Other considerations in this decision were the greater flexibility of the REAC equipment which would make it unnecessary to express all Guided Missile problems in the coordinate systems used in the Ballistic Computer, and the fact that a much greater variety of navigational systems was encountered than had been envisaged in the design of the Ballistic Computer.
The result of this decision is the new laboratory for three-dimensional Guided Missile simulation at Project Cyclone.

Basic Block Diagram of Guided Missile Problems and Coordinate Systems

The equipment in the new laboratory was planned to be more than sufficient to handle anything that could be handled on the old Ballistic Computer. The basic elements of all GM simulation problems can be represented in the block diagram shown in Figure 1.

Starting, say, from the aerodynamics computer, we see that the angles of attack and the control surface deflections are accepted as inputs and the forces and moments are produced as outputs. In the force unit the equations of motion (translation) are integrated once, yielding a complete description of the velocity vector. The velocity vector may be given in terms of magnitude and flight path angles, or in terms of its components. In the moment unit the first integral of the equations of motion in rotation is obtained, yielding the angular velocity vector in terms of its components. In the angle of attack computer the kinematic equations of rotation are integrated, yielding the attitude angles; knowing the velocity vector and the attitude, the angles of attack are computed. From a knowledge of the velocity vector the missile coordinates are obtained by the integration of the kinematic equations of translation. Error distances or angles are determined from the missile position and target position. Those in turn form the inputs to the control system which produces the control surface deflections.

The following coordinate systems have been used in the solution of GM problems. (All are righthanded systems; thus the third axis is always completely defined after two axes have been fixed.) (See Figure 2.)

1. Earth Coordinate Systems (ECS): 1E direction is north, 2E east, 3E down. The missile motion is usually determined in this system; sometimes the force equations are solved in this system.

2. Missile Coordinate System (MCS): 1M along missile axis, 2M along right wing, 3M down, as determined by 1M and 2M. The moment equations are most easily solved in this system (Euler equations). The MCS is also used in homing problems when the relative motion of target and missile is computed.

3. Velocity-Earth Coordinate System (VECS): 1VE along the velocity vector, 2VE perpendicular to 1VE
and in a horizontal plane, $3\text{VE}$ determined by $1\text{VE}$ and $2\text{VE}$. The force equations are frequently solved in this coordinate system.

4. Velocity-Missile Coordinate System (VMCS): $1\text{VM}$ along the velocity vector, $3\text{VM}$ perpendicular to $1\text{VM}$ and contained in the missile symmetry plane (down); $2\text{VM}$ determined by $1\text{VM}$ and $3\text{VM}$. The VMCS differs from the VECS by a roll angle, and differs from the MCS by the angles of attack. This coordinate system was believed to be essential for a realistic handling of aerodynamic data obtained from wind tunnels. We have found, however, that many times the aerodynamic data are given to us in the missile coordinate system. In such cases it frequently turns out to be more convenient to disregard the VE and VM systems entirely, solve the force equations in the MCS and resolve the motion directly into the ECS.

Additional coordinate systems are encountered in many problems, e.g. Radar CS, Gyro CS, and in the case of wind, a Relative Wind CS.

### Computing Equipment

Because of the necessity of converting from one coordinate system to another a number of resolvers are provided in the new simulation laboratory. The availability of DC resolvers was a strong factor in favor of an all DC computing system, as opposed to the hybrid DC and AC system in the old Ballistic Computer.

The new laboratory contains 13 REACs, 14 servo units and 3 special cabinets with additional amplifiers, limiters, relays, etc.

A REAC contains seven integrating amplifiers, seven summing amplifiers, six inverting amplifiers and 23 scale-factor potentiometers. (Figure 3.) The computing amplifiers are identical in basic design and differ only in their feedback and input networks.

Ordinary linear differential equations with constant coefficients, up to the seventh order can be solved on one REAC. Diode limiters are provided, and permit the handling of some non-linear effects. Variable coefficients and non-linearities other than limiting effects can be handled by using a servo unit.

Seven of the servo units are of standard Reeves design, and seven units have special design to handle any additional resolutions that may be necessary in our problems.
A standard servo unit has four separate servos; two of those have four linear multiplying potentiometers and two functional potentiometers each; the other two servos have three linear multiplying potentiometers and one DC resolver each. (These figures do not include the follow-up potentiometers.)

Six of the seven special servo units have two servo motors, each of which drives two DC resolvers and seven linear multiplying potentiometers. The special servos have to be more powerful than the others, because they are driving a heavier load.

Finally there is one special servo cabinet with only one servo which is driving four DC resolvers and seven linear potentiometers. This servo has continuous rotation. In planning the layout for the computer it was expected that provision for resolution about an unlimited rotation would have to be made. In some three-dimensional GM problems the missile may roll over many times. Resolutions of error angles, of aerodynamic forces, etc. about the roll angle can be accomplished by means of this special servo unit. Since the angle in the case of continuous rotation cannot be conveniently represented by a DC voltage, but its derivative can, this servo has also been designed to accept a rate input, i.e. the servo acts as an integrator. The follow-up in this case is a DC tachometer generator. The servo can be reset by switching the follow-up to a potentiometer. Continuous rotation may also arise when the servo is used in "polar", i.e. when the servo rotation is the arc-tangent of the ratio of two voltages. If the two voltages vary in a certain way continuous rotation of the servo will result. This special servo can also be used in this form. Finally provision has been made for adding a synchro if it should ever become desirable to repeat the position of this servo with some other specially constructed servo. We, at Project Cyclone, have not yet had an opportunity to use this servo unit. It was given on loan to Project Typhoon, and has not yet been returned.

The DC resolvers are accurately wound sine and cosine potentiometers (made by Electronic Associates), accepting as inputs DC voltages $A$, $-A$, $B$, $-B$, and a rotation $\theta$, and putting out voltages $-A \sin \theta$, $A \cos \theta$, $B \sin \theta$, and $B \cos \theta$. In order to make the operations more convenient, inverting amplifiers are provided with the servos, so that only $+A$, $+B$, and $\theta$ are required as input voltages. The sine and cosine cards are approximately 50K per quadrant and are intended to work into a 1 megohm load; they are wound to compensate for the loading due to such a load, and are accurate to .15 volts (100 volt peak) under these conditions. The quantities $(A \cos \theta + B \sin \theta)$ and $(-A \sin \theta + B \cos \theta)$ which are used in resolutions have to be formed in the REAC summing amplifiers.

190
A recapitulation of available servos and resolvers follows:

7 "A" type servo units (standard):
   2 servos with multipliers and functional pots.,
   2 servos with multipliers and resolvers.

6 "D" type servo units:
   2 servos with multipliers and
   2 resolvers each.

1 "C" type servo unit:
   1 servo with multipliers and 4 resolvers (C.R.).

In total, there are 42 resolvers on 27 different shaft rotations. There are 41 different shaft rotations altogether.

The laboratory also contains input and output equipment in the form of 6 recorders, 2 plotting boards and 4 input-output tables.

Figure 4 shows how the new laboratory is laid out. Basically it has been divided up into seven units (minus one REAC), each unit consisting of two REACs and two servos. One such unit is shown in Figure 5. Since the new type of servo does not permit enough room for a patch bay, extra cabinets with patch bays were provided between servo units. These cabinets also proved to be necessary for extra amplifiers used in connection with the resolvers. The three special cabinets (A105) were inserted in various locations, shown in Figure 4. Interconnections between cabinets are made by using 1) long patch cords, 2) interconnections provided between the four cabinets comprising any one unit, and 3) interconnections provided between every cabinet and one master interconsole patch bay.

The power supplies are located in a room behind the computer room; power is provided for two halves of the room separately.

Some of the regulators are in the power supply room; two of them are in the computer room. All cabling involving power leads and grounds is kept separate from the computing leads and ground. This is especially important for the relay power supply because of the relatively heavy current drawn by the relays. The relays are used to control the operation of all amplifiers, and as many REACs as desired may be used simultaneously by paralleling their relay connections and operating from one REAC.

Figure 4 also shows the layout of the other computing labs; lab 3 consisting of older computing equipment (4 REACs, 4 servos and 2 special cabinets) and lab 2, the lab for test simulation which contains one REAC, 1 auxiliary unit, some servos and several one axis roll tables which may be necessary in connection with the tester work. A system of interlab wiring has been
installed so that computing connections can be made between labs; this makes additional equipment available in any of the labs.

Figure 6 shows an overall picture of the equipment. Some problems were patched in at the time this picture was taken.

At the present time a number of improvements and additions to the laboratory are being planned and carried out. The most important item which still remains to be done is the installation of some form of flexible prepitch system with one or two master control consoles. Other items are more routine improvements which will tend to make the operation of the computers easier.

**Operation**

The new laboratory has been in operation since early October, 1952. As has happened before, equipment was used on problems just as fast as it became available. This has led to some difficulties when equipment had not been given a final "computer check".

Checking procedure which is considered appropriate for the equipment consists of two phases:

1. So-called Equipment Checks: routine checks of all amplifiers, servos, and potentiometers for accuracy and performance; e.g. the input resistors of amplifiers are checked for accuracy, all servos are checked for accuracy and freedom from noise, etc.

2. So-called Computing Checks: problems to which the answer is known are set up on the machine and run. In the course of these checks most troubles that escape detection in the equipment check are discovered. Due to the pressure of problems waiting to be solved this phase is frequently neglected; this means that the first problem is then solved more slowly, and with more frequent break-downs than would otherwise be expected. The acceptance check for this installation consists of a three-dimensional problem for which a numerical solution has been obtained.

Some complicated two-dimensional problems have been handled in the new laboratory. One three-dimensional problem is now being worked on, and another one or two are in preparation. One observation that has been made was that the more complex problems frequently call for the construction of special equipment which are no longer minor items when it comes to preparation
and scheduling of work. (Example: in our current flutter problem a pot panel of 196 pots is being constructed to handle a matrix of $14 \times 14$ coefficients.)

The project has at present a staff of 32 mathematicians, physicists and engineers at various levels. The engineering section has recently been enlarged because of the increase in engineering problems arising from more complicated problems.

The maintenance of the equipment including all three labs, and accessory equipment has required the full time service of at least two technicians. Between problems the machines are subjected to a thorough equipment check, and repairs and replacements are made, if necessary.

The problem of determining whether and when a computer solution is correct is sometimes very difficult. In making such a decision one has to know that the problem has been set up correctly and with the best scale factors possible, and whether the machine is performing properly. In the cases of problems involving many computing cabinets the difficulty involved is obvious. Two approaches are being used to get an answer to the problem of checks. One is the acquisition of a small scale general purpose digital computer for the purpose of obtaining numerical solutions for all problems for which the contractor is unable to furnish one. The other is embodied in some work now being done on error analyses for analog computers such as the REAC. At present we rely on some check solutions obtained numerically, and depend on the assumption that the solutions are continuous functions of the parameters of the equations.

Fig. 1
Block diagram of typical guided missile problem.

Fig. 2
Spherical Diagram showing Coordinate Systems.

Fig. 3-REAC Computer Cabinet.
Figure 4. Layout of Laboratory.
Figure 5. Computer Unit consisting of two REACs, two servo units and one servo patch bay cabinet.

Figure 6. Photograph showing Laboratory.
A NEW CONCEPT IN ANALOG COMPUTERS

Lee Cahn
Beckman Instruments, Inc.
South Pasadena, California

1. The Pattern of Use

Analog computers can solve a wide variety of engineering problems. Why, then, doesn't every engineer use one? This paper will discuss the pattern of use of analog computers in the recent past and as the author thinks it will be in the future.

Technically, the field of application of analog computers is extensive. They may be used in studies of automatic control systems, of aircraft and missiles in flight, of electrical circuits, dynamic instruments such as accelerometers and pen recorders, of certain economic and biological systems, and of many other phenomena. They may be used in purely analytical studies, or they may be used with part of a complex physical system to simulate the rest of it. If analog computers are not widely used, lack of technical applicability is not a reason.

The big reason is cost. In the last few years a single computer installation commonly cost upwards of $100,000, and the whole cost had to be taken from capital or facilities funds, where it hurt more than operating expense money. Only the largest engineering organizations could afford a computer, and then probably only one.

A second limiting factor has been the technical difficulty of operating a computer installation. This may be divided into two parts. First there is the computer itself. It may require special accessories, such as function generators, which have not been adequately provided by the original manufacturer. Or some of the users may be able to get better performance from the basic components than the original manufacturer did, much as hot-rod enthusiasts can do with automobiles, after half a century of development in that field. Thus many installations have found it desirable to keep computer development engineers working full time.

Second, even if the computer itself is working satisfactorily, skill is required to ascertain that it is working and to lay out and connect problems. This latter skill is like languages; anyone can learn broken English in a short time, but years are required to speak it faultlessly. An expensive installation needs a professional to make best use of its limited time.

A single computer can only handle one problem at a time. By going to multishift operations and other artifices the number may be raised to two or three. An engineering organization large enough to afford a computer may have dozens of problems which the computer can solve, at one time. Priority is then given to the most crucial problems, and those where the computer is most effective in saving manpower.

Indeed, if the computer takes six men to keep it running, and the wages of six more to amortize it, a problem that only one man is working on may not be economically justified. The computer would have to save twelve times the time it required, to break even, in this example.