significantly different times, as indicated by the answer to the preceding question. (See the answer to the next question.)

J. Otterman (University of Michigan, Ann Arbor, Mich.): Has consideration been given to carrying out macro-operation No. I on a separate smaller computer?

With all Minitrack stations in operation what is the percentage of times the computer will be idle (or reserve operation time)? Can the system handle data simultaneously on two satellites?

Mr. Quarles: No serious consideration has been given to carrying out macro-operation I on a separate smaller computer.

In the present manner in which the programming system is operated, 24-hour-per-day utilization of the 704 would permit simultaneous handling of the tracking calculations for from six to ten satellites. It should be possible to increase the number of satellites which could be "simultaneously" tracked by a significant amount when further experience has been obtained and/or by reducing the volume of output information.

E. H. Weiss (Applied Physics Lab., Johns Hopkins University, Baltimore, Md.): You mentioned that "other checks" are used to ascertain the accuracy of input and output. What are some of those checks and how reliable are they?

Mr. Quarles: I was specifically referring to the data transference checks such as: check sums used in connection with transference of information between magnetic tape or magnetic drum and magnetic core storage; "echo checking" of printed output; check sums and/or double-punch-blank-column checks for certain input cards. These checks have been found to be very reliable.

However, macro-operation I, for example, also contains checks which would eliminate very unreasonable data, in addition to various other editing checks as indicated in the paper.

W. W. Youden (National Bureau of Standards, Washington, D.C.): How accurate were your predictions?

Mr. Quarles: The present accuracy of predictions obtained with this programming system varies with the satellite in question. It has been possible to obtain considerably better accuracy for predictions of Vanguard I than for any of the other satellites launched to date. In part this is felt to be due to the availability of more better-calibrated Minitrack stations for recording observational data, but probably primarily due to the greater perigee distance and consequent lower distortion of the orbit due to atmospheric drag. More specifically, predictions made for Vanguard I, and commencing shortly after its launching, have been accurate to within a small fraction of a minute of time.

Use of a Digital Computer for Airborne Guidance and Navigation

S. ZADOFF[†] AND J. RATTNER[†]

INTRODUCTION

RECENT developments in computer instrumentation have permitted a vast increase in speed and complexity with no increase in the size of the large-scale digital computers designed for scientific computation.

These developments have also made possible a new application for digital computers, namely, "real-time" computation in the field of control systems.

By way of definition, a digital computer is said to operate in "real time" when it is an integral part of a physical control system. One of the requirements for real-time operation of a digital computer is rapid computation consistent with changes in the input physical quantities and the output data rates required by the system.

Historically, the analog computer has been used in control applications. However, the analog computer is intrinsically limited in its ultimate accuracy, whereas digital-computer accuracy can be increased with little change in size or basic complexity.[1] Problem-handling capacity can also be increased for the digital machine with little or no change in its size although this may imply a change in rate. This latter is far from true for the analog computer since its complexity is in one-to-one correspondence with that of the problem it solves.

From this, it follows that there is a point of diminishing returns by way of weight and size in the use of analog computers over the digital type as problem complexity or accuracy needs increase.

The development of simple, reliable logic techniques has reduced the number of vacuum tubes in many computers. Magnetic elements and transistors are on the verge of totally replacing those vacuum tubes still required. The net decrease in size and weight produced by these components is further enhanced by their lesser power requirements. It should be noted that this progress is far from stabilized.

These component developments affect the size and weight of analog computers also, but the increases in speed and reliability in the digital field combined with demands for more complex real-time computers have made the digital machine eminently practical for this purpose.

GENERAL DISCUSSION

In real-time computation the problem to be solved is generally described by a system of nonlinear differential equations. The analog computer is a direct physical approximation of these equations. When using digital techniques, an equivalent set of difference equations is set up

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[†] Sperry Gyroscope Co., Great Neck, N.Y.

[1] J. Von Neumann, "The General and Logical Theory of Automata" in "The World of Mathematics," Simon and Schuster, New York, N.Y., vol. 4, p. 2070 ff.; 1956.

and solved by the digital computer. It is necessary that the solution of the difference equations be asymptotic to the solution of the differential system and that the same stability criteria must hold.[2]

Finally, the computation must be performed in a time commensurate with the response characteristics of the physical system.

In addition to solving systems of difference equations, the digital computer can be used as a function generator and a decision device in the control application.

Evidence of the progress of digital computation in the field of automatic control is its use in airborne systems. The Cytac system is an example of an airborne guidance and navigation system using a digital computer in a control loop.

Cytac is a long-range, all-weather, ground-controlled navigation and tactical bombing system. It was developed and tested by Sperry Gyroscope Company under a contract with Rome Air Development Center and Wright Air Development Center.

The system is built around a hyperbolic radio-navigation aid which was also developed by Sperry[3] and is now known as Loran-C. Loran-C is essentially an extension of the principles of the standard Loran system which is presently in use in the Atlantic and Pacific as a long-range aid to marine navigation. Fig. 1 shows a typical configuration. A master station, S_m, transmits radio-frequency pulses at a uniform repetition rate. The two slave stations transmit similar pulses synchronized to the master. A receiver in the service area measures the time differences of arrival of the master pulses and each of the slaves to obtain a fix at the crossing of the corresponding lines of position. Measurements are made only on the groundwave portion of the received signal.

Loran-C achieves long range by using the low-frequency transmission within the internationally allocated band of 90 to 110 kc. Loran-C is a two-step system and obtains high precision by making a measurement of the phase of the radio-frequency cycles within the received pulses, achieving an instrumental accuracy of 20 to 30 mμsec. The system is fully automatic with respect to both signal acquisition and time-difference measurement and indication.

The output of the time-difference measuring receiver is continuous fix information in hyperbolic coordinates. In the Cytac system the digital computer is used to combine the inherent long-term accuracy and stability characteristics of radio-derived data with the accurate dynamic character of air-derived data in the form of airspeed, compass, and altimeter indications, to provide navigation information having the best qualities of each. This was essentially the first application in which such techniques were used in long-range navigation and guidance.

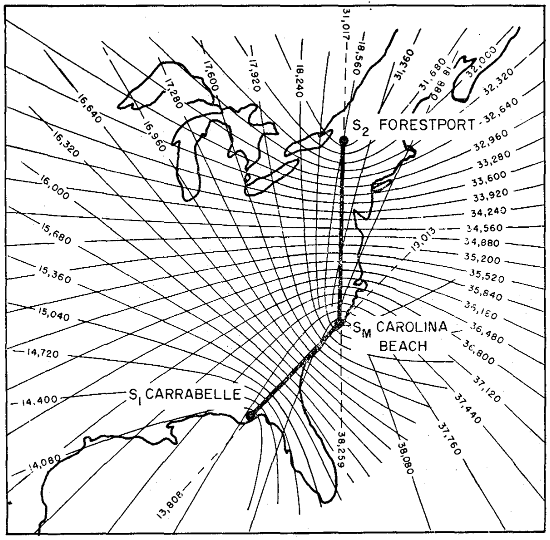

Fig. 1—Typical configuration of Loran-C stations.

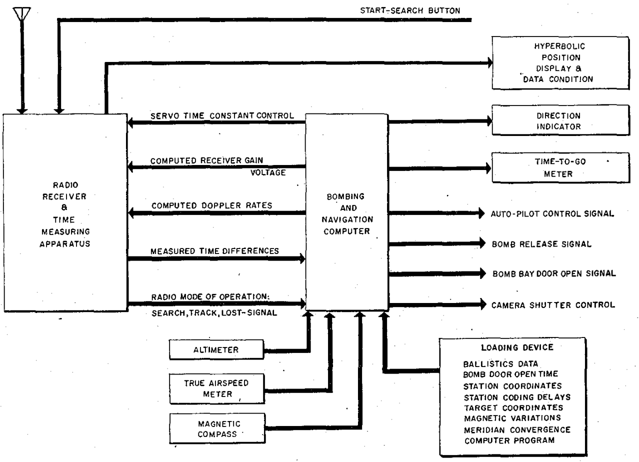

Fig. 2—Block diagram of Cytac system.

Fig. 2 is a block diagram of the Cytac system. The time differences of arrival of radio signals are measured in the radio receiver and time-measuring apparatus and are fed out in the form of shaft rotations. These are converted to digital data by the computer input equipment. The computer also accepts instrument panel information including compass heading, altitude, true airspeed readings and mode of operation of the radio system (*i.e.*, acquisition, track, or lost signal). These inputs are in the form of shaft rotations, which are also converted by analog-to-digital converters at the computer input, or are in the form of relay settings. After operating on these inputs, the computer converts the digital information back to analog or relay data to be used by the other equipment.

The computer output consists of an analog voltage to an autopilot to guide the aircraft toward a correct bomb release point and a signal to control the bomb-bay doors and the actual bomb release. Additional computer functions include:

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[2] H. J. Gray, Jr., "Numerical methods in digital real time simulation," *Quart. Appl. Math.*, vol. 12, pp. 133-140; July, 1954.

[3] W. P. Frantz, W. N. Dean, and R. L. Frank, "A precision multi-purpose radio navigation system," 1957 IRE NATIONAL CONVENTION RECORD, pt. 8, pp. 79-85.

1) Dead reckoning in the event of lost radio signals
2) Computation of time-difference rates
3) Computation of expected radio receiver gain settings
4) Control of certain servo time-constants and gains in the radio receiver during receiver switch from acquisition mode to track mode of operation
5) Generation of timing signals for control of reconnaissance-camera equipment.

Before take off, the program is stored on the magnetic drum memory of the computer, together with the constants required in the equations and the target coordinates.

System operation is initiated by pressing a "start" button on the pilot's control panel. This puts the radio equipment into its acquisition mode of operation in which it proceeds to locate the radio pulses in time and lock on to the received pulses. The computer notes that signals have been acquired, and normal operation begins.

In the event of lost signals the radio system gives the computer an indication of this condition. The computer then ignores further radio time-difference data and dead reckons on the basis of the last reliable radio information. It continues to feed computed Doppler rates to the radio system so that, if the lost signal is due to a temporary interruption of signal transmission or reception, the radio equipment will be in position to track the pulses as they are received again. This eliminates the need for the receiver reverting to the acquisition mode under these conditions. On the other hand, if the radio-data indication does not show good signals within a reasonable time, the computer directs the radio equipment back to its full acquisition mode.

Fig. 3 is a functional block diagram of the computer operation. The two-step measurements of time difference obtained from radio pulse-envelope measurement and radio-frequency phase measurement within the pulses are converted from shaft rotations to binary form and introduced at block 1. The coarse pulse-envelope time differences and fine radio-frequency phase differences are compared and a pair of consolidated time-difference numbers are obtained. The time-difference numbers corresponding to the center lines between the master and slave stations are subtracted from these numbers to provide a set of numbers suitable to geometric computation.

A conversion from hyperbolic to rectangular coordinates is performed in block 2.

A dead-reckoning computation of the aircraft position in rectangular coordinates is made in block 3, based on air-speed, altitude, and heading. Heading is derived from a Sperry J-2 Gyrosyn® gyromagnetic compass, and suitable corrections for magnetic variations and meridian convergence are provided in block 6. Magnetic heading is then converted to rectangular coordinates and the dead-reckoned rectangular coordinates are compared with the radio-derived data in the same coordinates in block 4. A portion of the difference is fed back through smoothing block 5 to correct the dead-reckoning computation of block 3.

By feeding back only a portion of the difference, the equivalent of an exponential smoothing factor[4] is obtained which reduces the effects of random variations. The correction is applied to the dead-reckoned, apparent wind vector which is substantially invariant for short periods of time. Aircraft steering control is derived from the dead-reckoned solution. Since the long time-constant smoothing is applied to a quantity substantially independent of aircraft heading, it does not materially affect aircraft stability.

On the basis of the corrected, smoothed position and velocity, further computation of the steering from present position to target is done in block 8. The time-to-go and the bomb-release point are computed in block 9. The distance to the stations and the velocity relative to the stations (or the Doppler rates) are computed in block 10. Bomb-ballistics data for a range of airspeeds and altitudes appropriate for each mission are stored in the computer, and exact ballistics for actual airspeed and altitude are derived from the stored data in block 7 for use in the steering and bomb-release computation.

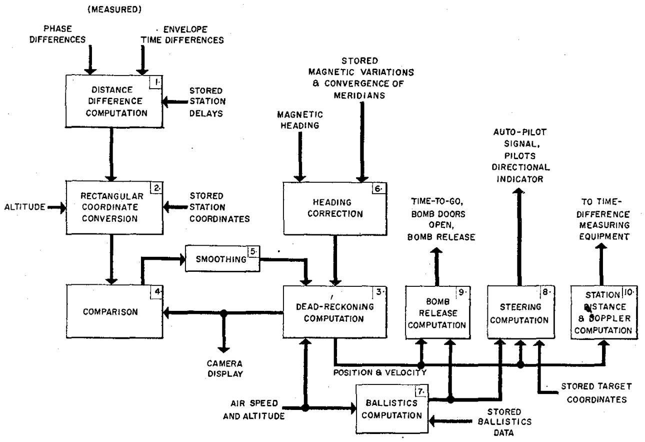

Fig. 3—Block diagram of computer operation.

The next diagram, Fig. 4, shows the two major control loops of the system and their interaction. One of these is a fast control loop comprised of an autopilot, airframe controls and surfaces, heading, airspeed and altitude measurements, and dead-reckoning computation. This control loop is a conventional autopilot arrangement except for the fixed delay introduced by the dead-reckoning computer. It will be noted that this control loop does not contain any long time-constant or narrow-band circuits.

The second loop is a slow control loop which includes the autopilot, airframe controls and surfaces, radio time-difference field, time-measuring apparatus and transfer or smoothing function, computer coordinate transformation, and dead-reckoning computation and computer smoothing. This secondary slow control loop has a narrow-band circuit in the time-measurement smoothing and a very-

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[4] R. E. Spero, "Effectiveness of two-step smoothing in digital control computers," PROC. IRE, vol. 41, pp. 1465-1469; October, 1953.

narrow-band circuit in the computer smoothing. Were it not for the fast control loop, severe stability problems would be encountered. Because of the action of the fast loop, however, only noise and signals due to errors in the dead-reckoning computation pass through the narrow-band circuits. Errors in the dead reckoning may be caused by wind changes and also by errors in heading, airspeed, and altitude measurements. Insofar as the problem of stability is concerned, only heading, airspeed and altitude-measurement errors, and wind changes are of importance. Since these errors are small, the secondary slow control loop will remove any cumulative effect of such errors, but will have a minor effect on the airframe stability.

A tertiary control loop is provided by the computed Doppler rates which are generated by the dead-reckoning computation and fed back to the time-measuring apparatus. This is provided primarily for the purpose of providing a memory function in the time-measuring apparatus during a lost-signal condition, and does not affect the basic stability or smoothing considerations.

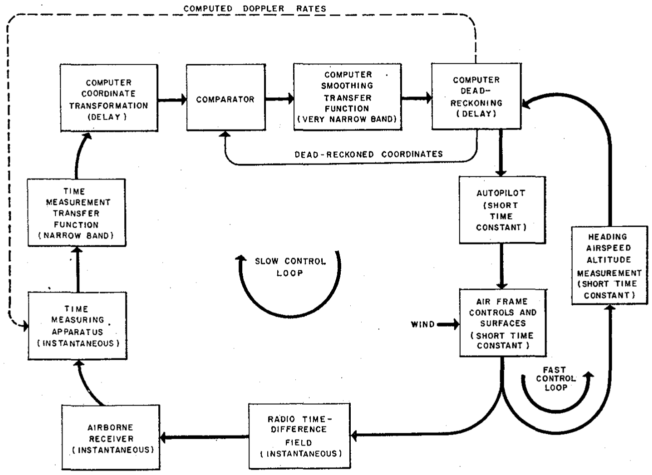

Fig. 4—Control loops of system.

Analysis performed at the beginning of the Cytac development program indicated the need for a computer to perform certain calculations with stipulated accuracy and speed. In order to meet the time schedule for the experimental instrument, an airborne digital computer was procured from a contractor.

This computer is capable of performing all required functions. The computer was programmed for a bombing mission and the pilot could select any of three preset targets. The operating range, distance from all transmitters, and speed and altitude of the aircraft were satisfactorily executed by the computer. In addition, other auxiliary functions for control of radio-system components were programmed for simultaneous solution. However, doubts were raised as to whether this computer was the best possible for the Cytac system. It seemed likely that a digital computer developed specifically for this system and utilizing the latest techniques and components would prove more satisfactory.

The digital computer used in the Cytac system is an optimum-programmed, serial, magnetic drum-storage computer. The drum storage contains 31 order channels, 7 number channels, and one channel for modifiable orders. Read and write are performed by separate heads, the write head being disconnected from the write amplifier for those channels which contain nonerasable program and problem constants. The drum also has one channel for high-speed access.

A novel feature of the drum is the varying of the spacing between the read and write heads of the numerical storage channels. This is advantageous in reducing access time.

The wordlength is 16 binary bits plus sign. There are 64 words per channel providing a total memory capacity of 2496 words. The arithmetic unit consists of an accumulating register, a shift register, an operand register, and the add-subtract matrix. The three registers are dynamic circulating registers.

The arithmetic orders include addition, subtraction, multiplication, division, and square root.

The input-output equipments operate through the input-output unit which automatically writes onto and reads from the drum, utilizing a separate set of heads on those numerical storage channels selected for input and output. A manual control console which is necessary for test procedures and for loading the drum contains the usual display lights and required switches. There is also an array of auxiliary equipment for testing, monitoring, display, problem preparation, and output recording which are not part of the control system.

The computer was designed with the goal of a fast, small volume, low-weight computer which would be just adequate to perform the required functions in about one second. In consequence, the computer was difficult to program and code. This was justifiable only because the code would remain unchanged and be retained on the drum once it was debugged. For those unfamiliar with the problems of an optimum-programmed computer, it may be said that optimum programming requires extensive juggling of orders and intermediate storage positions to achieve adequate results.

Those parts of the computer actually part of the airborne-control loop weigh about 300 pounds and occupy about 6 cubic feet. It is estimated that this computer could easily be reduced to less than 150 pounds and 3 cubic feet by using more modern instrumentation.

While the computer was being utilized, a study was made to find a more suitable computer. This study concluded that a machine using magnetic-decision elements as a basic unit and a magnetic drum as a storage device would be better for the Cytac system.

The set of equations for the Cytac system was selected as that best suited to the characteristics of the digital computer. These equations and their programming were de-