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MERCURY FLIGHT CONTROL FACILITIES AND OPERATION

INTRODUCTION

This paper presents some of the concepts used in the design of the Mercury network and, in particular, the Mercury Control Center. In contrast to many data gathering and communications systems suitable primarily for postflight analysis, the Project Mercury facilities were designed to provide monitoring and flight control of the space vehicle in real-time during each phase of the mission. In addition to describing facilities, the methods of performing flight control throughout the various phases of the flight are also presented. Finally, some remarks on training and simulation aids are included.

It is not implicit that the Mercury flight control plan should be considered as a blueprint for Apollo; however, it is hoped that this presentation will foster appreciation of the need for a sound operational approach. It will be evident that the facilities required for the relatively simple earth orbital mission are complex and that to minimize complexity and insure operational adequacy, the ground monitoring and control concepts and facilities required for Apollo will require sound and intensive planning fully integrated with the space vehicle concepts and design.

MERCURY NETWORK

When the design of the network was begun several years ago, determination of the orbital elements of an earth satellite was an extremely difficult task and very often took many days to accomplish.

Such long delays were unacceptable to Project Mercury because of the requirement to know, in real-time, the present position of the Mercury vehicle and the impact point if reentry were initiated at any point should it become necessary. Therefore, the following basic requirements were formulated for the Mercury network design and these are presented in figure 1.

First, it was desirable to maintain continuous real-time contact throughout the powered phase of the flight and the initial period following orbital insertion by means of radar tracking, voice contact with the astronaut, and surveillance of the vehicle systems and astronaut by telemetry; second, to obtain similar contact periodically during each orbit; third, to provide continuous real-time tracking during the normal reentry phase; and, finally, to maintain continuous real-time Impact Point prediction.

On the basis of these fundamental requirements and many other criteria, such as the desire to use equipment already available and, of course, limitations as a result of economic considerations, the various tracking sites were chosen.

MERCURY CONTROL CENTER

Let us now turn to the basis for design of the Mercury Control Center (fig. 3) which is considered the focal point for the entire operation, particularly once the vehicle has left the ground. Prior to lift-off, the check-outs of the launch vehicle and space vehicle are conducted by separate crews. The assimilation of information on all other phases of

the operation is carried out in the Control Center as shown in figure 2. This includes the readiness of the launch vehicle, the preparations and check-out of the astronaut and space vehicle, the countdown preparations and readiness of the network, the preparedness of the recovery forces, the weather conditions in the launch and primary recovery areas and along the entire ground track, and, finally, the readiness of the flight control teams in the Cape Canaveral and Bermuda Control Centers and the remote sites around the world.

After lift-off, in order that proper flight control decisions can be made, certain data must be available and presented in the proper form to those performing control of the flight. These data include telemetered information regarding the launch vehicle, the space vehicle, and the astronaut, and voice communication with the astronaut, trajectory information on the performance of the launch vehicle, and the final conditions at power cutoff with regard to orbital insertion, or the actions to be taken should early cutoff or an abort occur. In addition, provision for initiation of certain commands to the vehicle were required. Initial plans called for event commands to back up all automatic launch and reentry events. However, the astronaut was already provided with manual overrides to these programmed events, and in the interests of simplicity for better reliability, this dual backup provision was deleted except for command of abort, changing the timer initiating retrofire, and direct command of reentry.

Idealistically, it would be desirable to have all of this information presented to one individual or even to some automatic decision-making

machine. However, because of the many different analyses that must be made in the relatively short time of powered flight, the responsibilities were divided as follows: In the rear of the room there are three desks occupied by the directors of the various command functions of the operation. The NASA Operations Director sits in the middle and is responsible for directing all operational aspects of the project and makes the over-all decisions leading up to the launch of the vehicle. The commander for recovery operations sits at his left and the commander responsible for network support sits at his right.

The Flight Director sits in the center of the next row and has over-all responsibility for control of the flight from lift-off to landing. His duties are to coordinate the efforts of the flight control personnel within the Control Center and throughout the network. In addition, it is through his decision that the mission would be aborted or terminated during this period.

To the Flight Director's right is the Network Status Monitor, who acts as the test conductor for the Mercury network facilities.

Seated next to the Network Status Monitor is the Launch Vehicle Monitor. Certain telemetered parameters regarding the performance of the launch vehicle are presented to him on a continuous track recorder. These data deal with the quantities measured by an automatic abort sensing system within the launch vehicle.

The two consoles to the left of the Flight Director were originally to be used by a Range Safety Officer and a Recovery Status Monitor.

However, experience has shown that both of these functions were not required as a part of the flight control function. These consoles, however, have been profitably used by personnel furnishing assistance to the Flight Director and the Operations Director.

The position on the far left is occupied by the Support Control Coordinator, who coordinates the efforts of all of the technical support required for the operations room including all forms of communications and data transmission equipment.

To the right of the Support Control Coordinator is the Flight Surgeon who has over-all responsibility for all of the aeromedical aspects of the flight during both the prelaunch countdown as well as the actual flight. In addition to the basic aeromedical data displays, he has certain environmental system displays for correlation of the astronaut's condition with his environment.

The Environmental Systems Monitor, next to the Flight Surgeon, is responsible for observing all data associated with the space vehicle environmental system.

The Capsule Communicator, whose position is filled by one of the astronauts, is seated at the next console (fig. 3I). He is responsible for all communications to and from the astronaut and for keeping both the astronaut and the Control Center informed of the progress of the flight. In addition to conducting communications, the Capsule Communicator has event indication light displays for both normal and aborted missions. These include built-in timers to warn of early or late events.

In addition, a multichannel television display is provided for over-all reference of launch area activity, lift-off and initial powered flight. Similar event and television displays are provided to the Flight Director who has, in addition, abort command capability.

The Systems Monitor observes the performance of the other major space vehicle systems, including the control systems and the electrical power systems.

Two consoles to the right of the room support the Flight Dynamics Officer and the Retrofire Controller, who monitor the various trajectory displays during all phases of the flight. Originally, it was thought that these two functions could be performed by one individual, but detailed analysis has indicated that the volume and complexity of the data made this impractical, therefore the responsibilities were divided as follows: The Flight Dynamics Officer is concerned with the launch vehicle performance and the important orbital insertion parameters. The Retrofire Controller's duties are to monitor the impact predictions made by the computer and to determine the required time of retrofire. Details of the displays presented at these two consoles will be discussed later.

In addition to meter displays at the various consoles, continuous track recorders are provided for time histories of certain of the measured quantities.

The wall map at the front of the room presents the ground track of the flight on which the real-time position of the space vehicle is plotted. Also, the position of the various remote sites is given with the

over-all status of each site and its equipment presented in the form of color circles and symbols on this map. The map furnishes quick over-all status of the network and the flight to the controllers and the Operations Director. Subsequent to monitoring the launch in real-time by means of telemetry and voice reports, each Flight Controller continuously monitors information obtained from the remote sites and makes recommendations to the Flight Director on the basis of these data. To aid in this assessment, the areas adjacent to each side of the map are used to plot this data so that trends can be determined.

Bermuda

The site at Bermuda was designed and is operated with the same concepts as those used at Cape Canaveral in that it was considered to be a backup to the Mercury Control Center in certain instances such as command control following an abort decision. Figure 4 shows an over-all view of the Operations Room at Bermuda. It can be seen that the layout and the consoles are similar to those at the Control Center. No further details will be presented here except to note that certain additional computing facilities are provided at Bermuda to perform the backup function of determining the conditions of the orbit or times of retrofire associated with aborts.

Remote Sites

The remote sites were primarily designed to provide information to the Control Center on the status of the astronaut and the space vehicle,

to keep the astronaut updated on mission progress, and to provide tracking information to the computer. A picture of a remote-site Operations Room is shown in figure 5. Each site has a Capsule Communicator, Aeromedical Monitor, and a Systems Monitor. The duties and displays of these monitors are essentially equivalent to their counterparts in the Control Center.

Computing and Data Flow

Now let us consider in some detail the facilities and data required to perform the flight control function. Perhaps the most important and by far the most complex system is the computing and associated data flow facilities required.

Figure 6 presents the various sources of tracking data and computing systems which are required to provide the necessary information on trajectory, times of retrofire, and impact prediction. All of the computations necessary for the flight are performed at Goddard using two IBM 7090 computers for redundancy. Because of the critical nature of the launch and orbital insertion period, multiple sources of data are provided to insure decision and action capability should a data failure or aborted flight occur. The Atlas launch vehicle is tracked and controlled by the G.E.-Burroughs guidance system. This system is the most accurate source of data available and therefore is considered primary for position and velocity data which are transmitted by means of high-speed data lines to the Goddard computers. In addition, other data are supplied directly to the Control Center.

Once the launch vehicle cuts off, it is desired to track the space vehicle rather than the launch vehicle; therefore, the source is switched to FPS-16 data either through the 7090 Impact Predictor, or direct. The AZUSA system also tracks the launch vehicle, and is used as backup to G.E.-Burroughs data. G.E. data can also be supplied directly to the plotboards but retrofire time would be lost as this is only computed by the Goddard computers. In addition to the tracking data, event information occurring during the launch is provided to the Goddard computers from the Control Center.

The Bermuda radars provide similar trajectory information to Bermuda Flight Controllers through an IBM 709 computer. In addition, the data from this computer, or directly from the radars, are supplied through an automatic teletype transmission system to the Goddard Center.

Once the capsule is in orbit, data from the remote-site radar systems are transmitted by teletype to Goddard and automatically processed in the computer to update the various displays at the Control Center. Also, once the reentry maneuver has taken place, this data system provides for accurate impact prediction.

Plotboard Displays

The data obtained from these facilities are presented in the Control Center to the Flight Dynamics Officer and Retrofire Controller in both plotboard and digital display form. Figure 7 is a photograph of their consoles and four plotboards used to display trajectory and impact

prediction information. As shown in figure 8, plotboard no. 4 on the far left is used to present impact prediction. Plot No. 2 presents altitude and cross-range deviation as a function of down-range distance.

Plotted on Board No. 3 (fig. 9) are velocity and acceleration as a function of elapsed time. The most important chart is chart no. 1 which plots flight-path angle versus velocity ratio, that is, the ratio of the present velocity to the velocity required for orbit at the desired altitude. This plot is presented in three different scales such that when the velocity ratio reaches 0.9, the greatly magnified third scale allows the important GO - NO-GO decision to be made at the time of launch vehicle power cutoff.

During powered flight, the Flight Dynamics Officer uses these charts to determine that the launch vehicle is performing satisfactorily, and to determine the time for abort should this become necessary. During the last 15 seconds of powered flight, he concentrates on the magnified plot of flight-path angle. From this plot he can determine that the proper orbital parameters have been achieved and at the same time the computer presents its GO - NO-GO recommendation by means of lights on this same plotboard. Also, at the same time, the computer presents to the Retrofire Controller the times of retrofire associated with the cutoff conditions achieved. For an abort, or NO-GO decision, the time of retrofire required to land in a particular recovery area will be displayed. If a GO condition is reached, the time of retrofire at the end of a normal three-orbit mission and the time at the end of each intermediate orbit will be displayed.

The plotboards present other data at various times during the mission; however, all of these cannot be included in this paper. As data are received from the remote sites, the times for retrofire and the other trajectory information are continually updated. In addition, the computer supplies to each site, by means of teletype, acquisition information, and updated retrofire times for normal and contingency recovery areas.

After retrofire, details of the event are transmitted from the remote sites by teletype and manually inserted into the computer to provide more accurate Impact Point prediction.

Communications

As can be seen from this discussion of information and data flow, a highly complex communications system is required to transmit radar data and information messages to and from sites around the world. The communications network to accomplish this is a subject of its own and cannot be discussed here in detail; however, certain aspects of the system are necessary to the understanding of flight control. Teletype is provided to all sites using redundant paths for high reliability and multiple paths for high density traffic during certain phases. Teletype has an inherent lag, however, and requires an average of 6 to 10 minutes to transmit a message to any given site and receive a reply. Voice communications are provided to all command sites, Woomera, Australia, and all sites in the Continental United States. Experience to date has shown that fairly reliable communications can be maintained although at certain times there are serious propagation problems. Voice communication

with all sites would be very helpful and would provide for much simpler operational procedures but is not considered a necessity.

Planning of Spacecraft-Network Operations

There are many aspects of the network which should be discussed but, because of the limited time, cannot be included. However, it is emphasized that network and operational planning should be considered in the design of any space vehicle. If this is not done, the ground support necessary to the mission will be less than desired and its completion will lag the space vehicle and, therefore, pace the program.

In order to adequately specify operational support required, a clear definition of the respective and interrelated roles of the network and the space vehicle and its occupants must be provided to support all development and operational missions and test objectives.

Once these are clearly established, the instrumentation required to support the role of the ground-flight control can be defined simultaneously with the space-vehicle crew displays and controls. In accomplishing this, the operational flight control instrumentation should be distinctly delineated from the often varying and sometimes ad hoc instrumentation used solely for postflight analysis. Since operational instrumentation is used in real-time, it must be compatible with real-time ground displays at various sites. This demands a rigid control of vehicle instrumentation in terms of replacement interchangeability and calibration.

Flight Control

In an attempt to give a better understanding of how control of the flight is achieved the rest of the paper will deal with the details of flight control during each phase of the flight. It must be recognized that an orbital flight has not been accomplished as yet and the information to be presented is the result of a number of simulated flight tests in which the astronauts and the Flight Controllers have participated. However, the Redstone launches and the Atlas suborbital flights have been used to demonstrate these techniques and, with minor changes, appear to be adequate. In fact, the Redstone flights were planned on the basis of an orbital launch in order to exercise these techniques.

Figure 10 is a presentation of launch and orbital insertion. Just prior to lift-off, final confidence checks are made with the astronaut to confirm communications and proper systems functioning. The final phases of the countdown and the lift-off are transmitted to the astronaut by the Capsule Communicator in the Mercury Control Center. At lift-off, the astronaut confirms that the onboard clock and timing devices have started and that communications are still satisfactory. Trajectory information from range safety plotboards is transmitted by voice to the Control Center to assure that the proper trajectory is being followed. The astronaut makes a communications report every 30 seconds indicating such quantities as acceleration, oxygen, and cabin pressure while the ground Flight Controllers continuously monitor various displayed data.

One of the most critical points in the launch occurs at about 30,000 feet at which time the cabin pressure seals and is maintained

at approximately 5 psi. If the cabin pressure and suit pressure were to fail, abort action by the astronaut or the Flight Director would be taken to prevent an excessive altitude being reached by the spacecraft. Continued surveillance is made by the monitors, and the astronaut is kept informed of the trajectory and the status of the flight from both a launch vehicle and spacecraft point of view. Staging of the Atlas is confirmed by both the astronaut and the Ground Controllers and 20 seconds later confirmation is given by the astronaut that the escape tower has jettisoned. In all cases of programmed spacecraft events, the astronaut is prepared to perform manual backup should it be required. After this period while the launch vehicle is being propelled by the sustainer engine, all of the Flight Controllers are making a close analysis of space vehicle systems performance and astronaut conditions such that at about 4 minutes and 30 seconds a GO - NO-GO decision can be made in conjunction with the astronaut. This is a commitment to orbit of the astronaut and spacecraft systems. Certain ground rules are formulated and agreed upon many weeks in advance of the flight upon which this GO - NO-GO decision is made.

From this point on, almost complete attention is given to trajectory displays to ascertain that the proper values of orbital parameters are achieved. At insertion into orbit, the conditions achieved are immediately transmitted to the astronaut who confirms proper separation and turnaround of the spacecraft. If a GO decision is achieved, the astronaut would be informed either by the Mercury Control Center or the Bermuda site of the time of retrofire for a normal reentry at the end of the design mission. If it is a NO-GO condition, the astronaut would be so informed and the

times of retrofire necessary for landing in a preferred recovery area would be indicated to him and to the Bermuda Flight Controllers. The actions to be taken by ground control and the astronaut are, of course, dependent upon the final cutoff conditions. These actions can be extremely time-critical and the communications procedures to be followed have been worked out by intensive review and training in this particular area.

The insertion takes place about midway between Cape Canaveral and Bermuda and, approximately 1 minute after this time, control of the voice link and command to the spacecraft is transferred to Bermuda, although Bermuda actually acquires the spacecraft RF links at about 1 minute and 30 seconds before cutoff. Summarized pertinent data regarding the launch phase are immediately transmitted by voice and teletype to all remote sites.

Let us now consider that orbit has been achieved and examine the activities at a typical remote site. Figure 11 outlines the procedures followed during a normal orbital pass which, if passing directly overhead, will last up to approximately 6 minutes. Prior to contact, the station receives messages on astronaut and systems performance from the Control Center and other sites and acquisition messages and certain times for retrofire from the computer. Upon initial voice contact, the astronaut reports the over-all status of himself and the spacecraft. If all is well, he is then given the updated times for retrofire for the end of the present orbit and intermediate contingency recovery area in order that he may have the most up-to-date information should an emergency develop at any time.

Because of the importance of the accuracy of the spacecraft clock, the astronaut indicates his elapsed time since lift-off and the time of retrofire set in the clock. These are compared with the telemetered values and transmitted back to the Goddard computer and used in future calculation of times for retrofire. During this time, radar data from the site is transmitted to the computers for updating the orbit characteristics. The astronaut is informed of the progress of the mission and is kept updated on certain matters concerning recovery and worldwide weather. Then, if necessary, the astronaut makes a detailed report regarding any changes he may have made in mode of operation, his physical condition, any communications phenomena or problems, and any other thing concerning mission control. Also, over some sites certain tests will be made to further evaluate the astronaut's ability to perform in a space environment. Following loss of contact with the spacecraft, the site transmits a message to all sites regarding the status of the astronaut and spacecraft systems.

This process is followed from station to station until time of retrofire. The normal retrofire maneuver is performed by a countdown from the ground to the astronaut with retrofire initiated simultaneously by the astronaut and the Capsule Communicator. The onboard retrofire timer will be used primarily as a backup to these commands.

Training and Simulation

In order to train both the astronaut and the ground crews in flight control problems, and to develop the procedures necessary for flight

control, facilities were constructed both at the Control Center and at Langley Field which allow complete flight simulation. At both of these facilities, a procedures trainer is provided with outputs provided to flight control consoles. Complete realism can be obtained by introducing such problems as space vehicle and astronaut malfunctions, telemetry and radio noise and dropouts, etc. In addition, at the Control Center, complete trajectory simulation is provided. These facilities have proven to be extremely useful and are considered one of the most important training devices to be developed for Project Mercury. Such facilities will be a mandatory requirement for the Apollo program. These facilities should be considered during the design phase of the vehicle so that ground crew and astronaut training can begin as soon as possible.

It is realized that only a cursory look has been given to the Mercury network and the flight control aspects of the project. Engineers from the divisions responsible for these aspects of the project are devoting time to Apollo and the contractor is urged to take advantage of Mercury experience through these people.