Operational Flight Control for Saturn Boost Vehicles

C. W. Steeg Jr.,* M. Pesando,† and G. Filias‡
Radio Corporation of America, Burlington, Mass.

Operational Flight Control (OFC) monitors and assesses the operating status of the Saturn launch vehicle and its systems during flight, predicts potential malfunctions which could affect achievement of mission objectives, and takes appropriate corrective actions. It is this characteristic that distinguishes the OFC from the normal operating systems of the vehicle. The status of the vehicle and of the mission are measured and evaluated in real time to determine the required commands and then to initiate these commands. Should performance degradation rule out the achievement of the primary mission, then OFC selects and initiates one of several preprogrammed alternate missions to make best use of the remaining vehicle capability in relation to the payload carried. The measurement of the vehicle systems status is available from onboard instrumentation, whereas data concerning over-all status of the vehicle and of the flight are available from both onboard and ground instrumentation. The onboard functions, by means of a closed-loop system, provide maximum rate of response. The ground functions, with access to both onboard data and ground data and without the usual onboard system restraints of weight and size, provide a more complete and accurate assessment and allow human participation to provide judgment and flexibility to cope with unforseen circumstances.

Introduction

THE basic flight-control process (Fig. 1) for Saturn launch vehicles involves the vehicle itself, a guidance system for generating instantaneous flight references, information sensors for measuring the error between the flight references and the actual vehicle flight situation, and a control system for adjusting the vehicle attitude by thrust deflection to minimize the attitude error signals. The guidance system also determines the time for engine cutoff and initiates the cutoff procedure. The first (S-I) stage is guided by preprogrammed attitude commands, which are functions only of the time from liftoff. The second (S-IV) stage uses the "adaptive guidance mode,"[1] which accepts instantaneous vehicle trajectory data and propulsion parameters as initial conditions and defines (usually on a minimum-energy basis) the future flight path to meet the mission requirements. In either stage, the vehicle trajectory is determined solely by onboard equipment, with no provisions for alternative or remedial action (except for Range Safety commands) in the event of component failure in either the guidance or control system.

Operational Flight Control (OFC) extends the mission flexibility by complementing the adaptive guidance concept and enabling the vehicle to complete the primary or an alternate mission despite serious deviations because of environmental conditions or subsystem malfunctions. For example, OFC circumvents guidance malfunction problems by using an onboard sensing and control subsystem, which can assume control and perform the guidance calculations required to keep the vehicle on course. The predictive capability of the system enables time-to-failure to be estimated; hence, action can be delayed until the last possible moment. This feature is extremely important, because even though a parameter is deteriorating, it may continue at a level sufficient to accomplish the primary mission, in which case compensating action is not required. If conditions do prevent achievement of the primary mission, alternate sets of guidance coefficients, either prestored onboard the vehicle or transferred to the vehicle from the ground OFC, are used to implement the alternate mission.

Examples of typical actions are: The shutdown of an ailing engine when vehicle integrity is in jeopardy (engine-out capability is inherent in the Saturn C-1 design), or all engines in event that the normal cutoff system malfunctions, thereby preventing an overspeed insertion into orbit; system sequence changes to compensate for a prime system malfunction or to accommodate alternate modes for achieving the prime mission or a secondary mission; and inhibition or expansion of onboard OFC control depending upon the status of the communications or specific mission demands.

System Approach

It was realized: 1) that the OFC should provide means for using both airborne and ground-derived information, 2) that its implementation should be based principally on the extension and improvement of monitoring and deviation-correction functions by the reorganization of the existing system, and 3) that these requirements would not be achieved by the addition of equipment to provide parallel systems (dead weight except in abnormal circumstances) or by fundamental redesign of the primary Saturn system. Rather, the scheme should consist of an integration of monitoring data from all sources and a correlation of these data with stored information to provide the basis for optimum control of the vehicle. In specifying the OFC, particular care was taken to avoid disrupting the functions and implementation of the basic Saturn, the system, the mission, or the over-all program, and specifying unwarranted changes in guidance, control, and propulsion subsystems. Yet the OFC had to be sufficiently flexible to take full advantage of any new developments in the Saturn operations complex or the vehicle-borne or external hardware available to implement the system at any future time.

Existing or planned facilities and equipment were examined to assess their suitability and adequacy for OFC purposes, because system performance depends on the inherent reliability and accuracy of individual components, as well as the redundancy and flexibility incorporated in the system design.

Presented as Preprint 63-42 at the IAS 31st Annual Meeting, New York, N. Y., January 21–23, 1963; revision received January 13, 1963. The study program from which this paper is taken was conducted by the Radio Corporation of America under joint sponsorship of NASA and the U. S. Air Force.

* Presently Director of Operations, International Telephone and Telegraph, Industrial Laboratories, Fort Wayne, Ind.

† Presently Senior Consulting Engineer, Avco Research and Advanced Development, Wilmington, Mass. Member AIAA.

‡ Presently Senior Engineer, Head of Development Engineering Services, Philip Morris Research Laboratory, Richmond, Va.

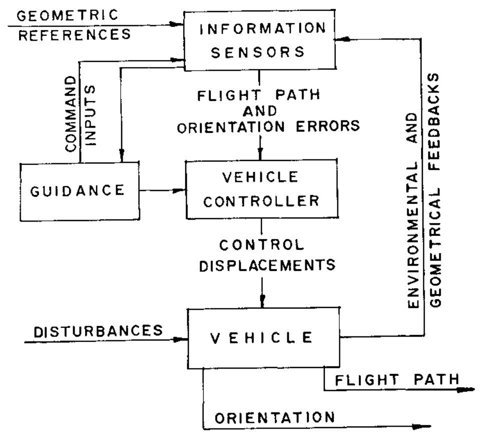

Fig. 1 Conventional flight-control process.

Minimizing the over-all system cost, as well as maintaining a realistic time schedule, required the optimum use of installed equipment, the best choice of sites among those available, and a gradual buildup of system capability consistent with the increased system performance requirements of the Saturn program.

The preliminary study also included consideration of two other primary approaches: 1) an inflight maintenance and repair system, discarded because the majority of boost-vehicle equipments are neither modular nor centrally located, and 2) an intensified reliability program, discarded because of cost, time, and effort required, and because hardware selected for implementation would not reflect state-of-the-art advancements. Newly developed self-adaptive control schemes and modified versions of the path-adaptive guidance mode were also examined in sufficient detail to verify that the methods developed previously for Saturn did satisfy optimally the usual requirements of the flight-control process. From these studies, the approach that appeared best to meet the specified requirements was real-time mission control, that is, an OFC which would 1) continuously measure pertinent vehicle and subsystem performance values during all phases of powered flight; 2) compare measured performance values with those required for mission success as a function of elapsed flight time; 3) analyze deviations to determine hazard to primary mission; and, if appropriate, 4) select one of a number of predetermined alternate courses of action or flight plan to minimize the effect of malfunction.

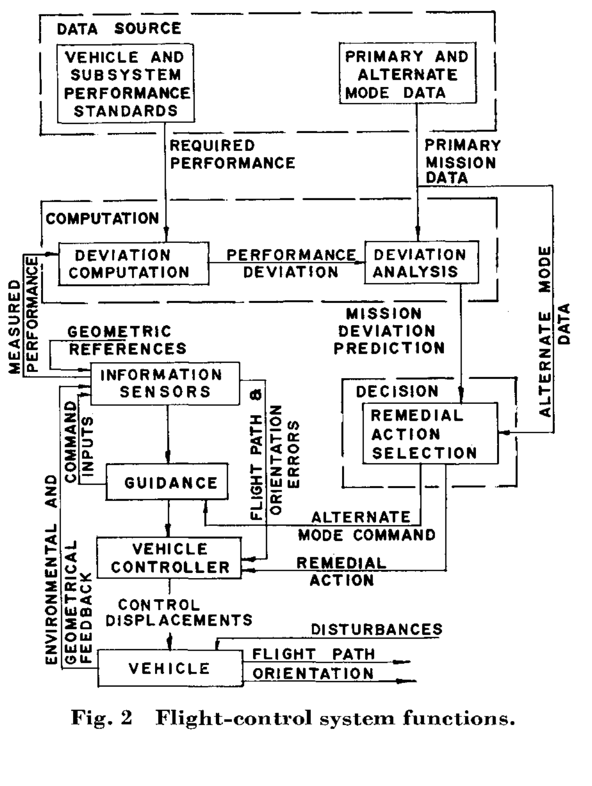

Fig. 2 Flight-control system functions.

To perform these functions in real time, the OFC requires four classes of activity, which must answer the questions indicated.

1) Measurement: onboard sensors and transducers to determine current subsystem parameters and ground instrumentation for added trajectory data; how can one distinguish when a measurement is indicative of an impending failure?

2) Data storage: nondestructive digital memory to allow comparison of current parameters with expected values; how is the pattern or group of patterns characteristic of subsystem malfunction determined?

3) Computation (analysis): processing to localize faults; how can the future performance of the subsystem be extrapolated from current measurement?

4) Decision and command: use of stored analysis of potential situations as well as human assessment of unforeseen circumstances; how is a timely and pertinent decision reached?

These activities are shown in Fig. 2, superimposed on the original flight-control process of Fig. 1. The measured performance quantities go to a computation group, where deviations are computed by comparison with vehicle and subsystem performance standards. These standards, together with primary and alternate mode data, are stored in the data source blocks. Performance deviations and predictions of expected mission deviations go to the decision operation where remedial action is selected. Commands either to change mission or to initiate actions for minimizing failure effects are then inserted into the existing control system. Figure 3 shows three loops capable of taking corrective action. The inner loop, which consists of onboard control only, has the highest real-time reliability (fastest response), but greater accuracy would result by use of the automatic ground control loop, to which are available both the onboard sensor information and inputs from ground-based sensors. The outer loop brings in the added factor of human supervision (semiautomatic), which incurs a penalty in response time, but many malfunction conditions allow sufficient time for human decision.

No automatic system can take effective action in a situation not included in its programming, and no human operator can exercise reliable judgment in situations completely foreign to his experience. The essence of the OFC concept is the ability to exercise efficient real-time control of the vehicle and the mission through effective evaluation techniques coupled to comprehensive preprogramming of actions to compensate for recognized deviations from acceptable conditions. Extensive preflight system functional analysis, statistical malfunction analysis, and mission simulation are condensed into a limited number of operational programs, which account for a multitude of inflight circumstances, and which determine the corre-

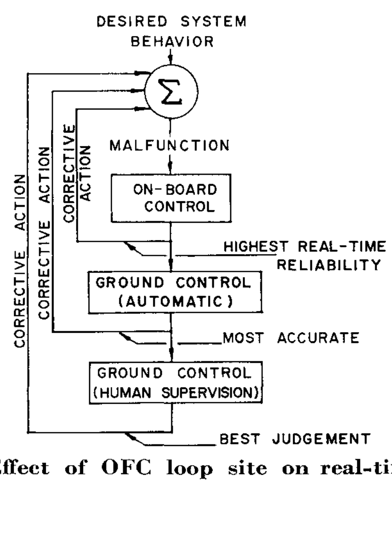

Fig. 3 Effect of OFC loop site on real-time criteria.

sponding OFC action to minimize the adverse effects of abnormalities.

Concept Feasibility

When the four classes of activity had been defined, the next step was to establish the technical feasibility of the concept through two separate analyses. A techniques analysis was concerned with specific technical and/or analytical problems in each of the four activity classes that threatened to bar implementation of the system. A malfunction analysis was made on all C-1 subsystem failures to detail their causes and symptoms, and thereby define instrumentation for sensing abnormal deviations. This information was then screened in terms of remedial actions to establish the proper degree of flexibility and completeness.

The techniques analysis solves the four major technical problems as follows.

1) Measurement: A statistical regression analysis technique is based on previous flight experience or simulations to define both static and dynamic limits, as required, on sensor outputs.

2) Data storage: Two techniques, variations of parameters and correlation analyses, provide solutions to this problem area.

3) Computation: Here again, two techniques are applicable: a statistical prediction, which involves the assumption that the basic phenomenon of performance depends upon a Markov process and can be treated in terms of the probability of transition between consecutive related states of the system, and a deterministic prediction, which is applied to trajectory characteristics which result from well-defined equations of motion.

4) Decision and command: The Hamiltonian function, which is a direct measure of energy (and has been used by NASA)[2] is combined to determine the appropriate alternate mission. Specific actions for subsystem malfunctions are derived by a malfunction analysis technique.

The malfunction analysis was used (primarily) to determine the expected effectiveness of the OFC system by means of a computer program involving the following: 1) complete listing of malfunctions at all levels, 2) probability of occurrence of each malfunction, 3) probability of catastrophic effect on the vehicle, and 4) the estimated capability of the OFC to minimize the malfunction effect.

Failure data from Ref. 3 were used and were supplemented by others discussed with cognizant NASA and Air Force personnel for subsystems that had not previously been thoroughly documented. The 819 malfunctions listed in Ref. 3 resulted from more than 1024 at the component level, but 316 of those were eliminated because they occurred prior to liftoff (i.e., within the cognizance of automatic launch and checkout equipment). It became apparent from the analysis of these data that malfunction relationships could be specified more precisely on the systems and/or subsystems level than on the component level. When the component malfunctions were appropriately grouped (Fig. 4), 417 of those which produced only slightly reduced total system performance were segregated into only 12 subsystem malfunctions. By a functional analysis of the guidance and control, this number was mapped into 50 equivalent system malfunctions, each of which required a different remedial action. The total of 708 component malfunctions were reduced to 303 systems malfunctions. Actions were determined to minimize the effects of 198 of these, leaving 105 for which no actions corresponded. Of the latter, 31 occurred in less than 50 msec with no sensible warning and were of such violence as to preclude remedial action, and the other 74 either had a probability $<10^{-6}$ or did not warrant the expense and complication required to isolate them (e.g., some were sensed by chamber pressure but were not isolated as particular faults).

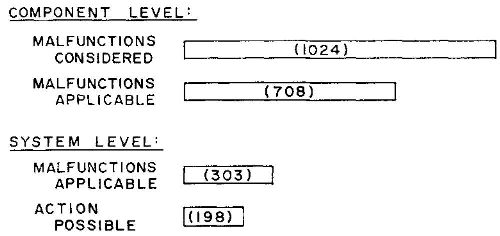

Fig. 4 Malfunction analysis results.

Approach to Malfunction Analysis

As previously noted, lists were made of component failures and their levels of hazard to the mission. Then, from a Saturn reliability study prepared by ARINC[4] for NASA, only those components whose unreliability was above a specified level were retained. The next step was to develop a method whereby the selected components could be monitored and component malfunctions detected and identified. A malfunction would exhibit certain symptoms, such as low pressure or high temperature. A symptom, by itself, might not identify the malfunctioning component, because similar malfunctions could have near-identical symptoms. A scheme was therefore developed to relate the malfunction first to the symptom and then to the sensor, in order to relate the sensor and the malfunction to the possible corrective action.

The matrix structure for this analysis is shown in Fig. 5. The initial matrix relates the malfunctions M_i to the symptoms E_i by the shaded areas. The next matrix matches the applicable sensor indications with the appropriate symptoms. The sensors and their locations on the SA-5 vehicle were used directly, except where engineering judgment arranged additional or new sensors and corresponding locations. The first two matrices lead to the final matrix, which indicates the combinations of sensor indications associated with each malfunction. The ultimate results of this scheme relate the sensors and corresponding malfunctions to appropriate OFC actions in accordance with the vehicle flight segment in progress.

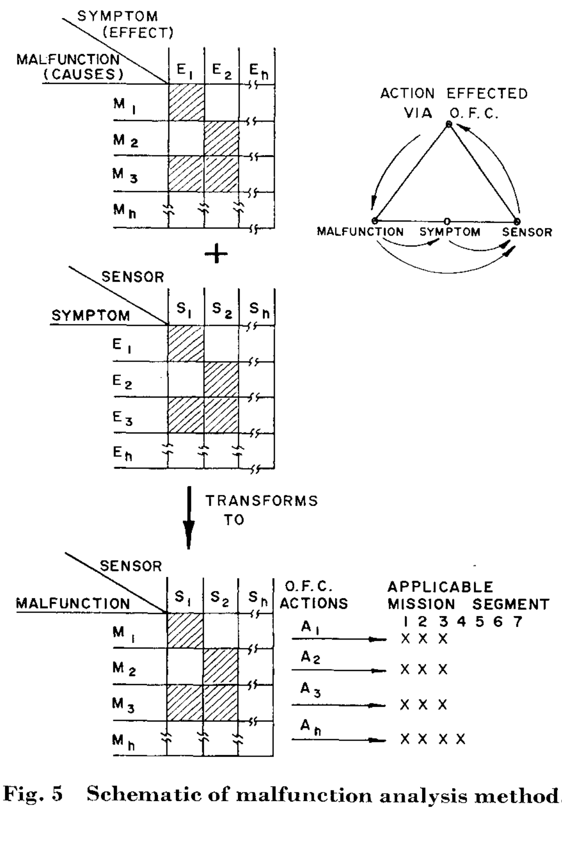

Fig. 5 Schematic of malfunction analysis method.

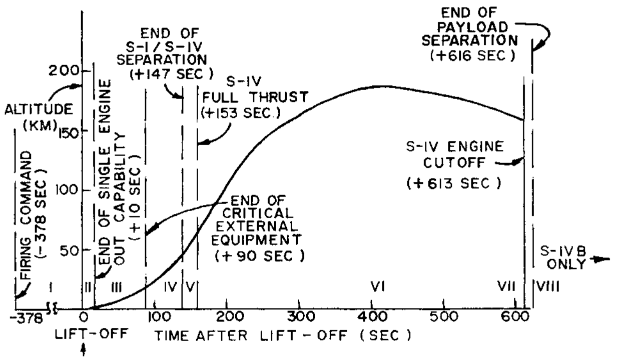

Fig. 6 Typical Saturn Block II vehicle flight segment breakdown.

Malfunction Analysis Procedure

Subsystem flow diagrams, which include the primary sensors, were developed first. A working chart for each subsystem documented it in terms of its components, the types of malfunctions, the associated sensors and symptoms, the time from malfunction occurrence to its effect on vehicle performance, the component time operative (duty cycle), and the types of possible actions. Another requirement was to relate OFC actions to appropriate flight segments: in certain segments, conditions external to the vehicle, such as atmospheric winds, were critical factors in vehicle operation as a function of flight time; in other segments, conditions internal to the vehicle, such as duty cycles of specific subsystems (for example, S-IV staging sequences), were just as important. Table 1 and Fig. 6 show these relationships.

During the beginning of the study, the emphasis had been on malfunctions, but it was soon evident that the types of OFC action required had to be determined. One action was almost self-evident—engine cutoff. Another possible action of the many considered was a means of locking the engine hydraulic actuator in the event of a hydraulic malfunction. The first stage (S-1) has eight H-1 engines, of which the outer four are hydraulically actuated for booster attitude control.

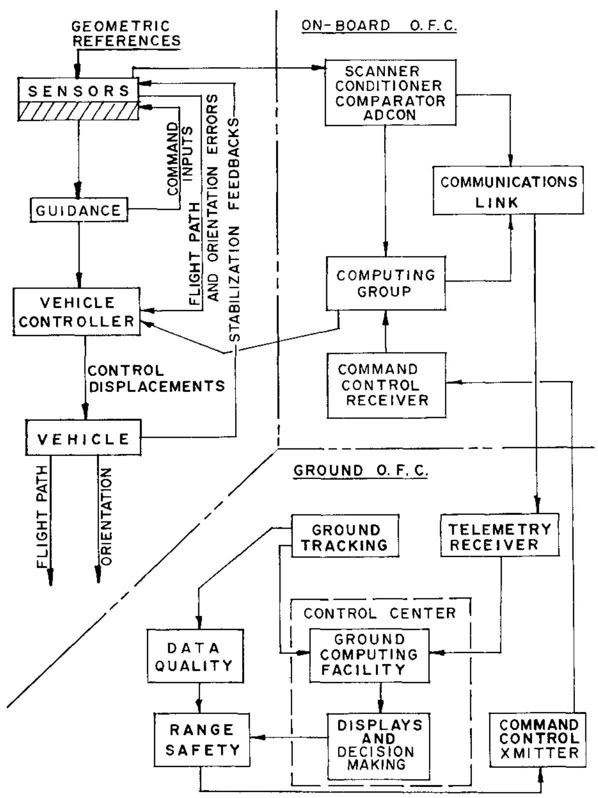

Fig. 7 Equipment complement.

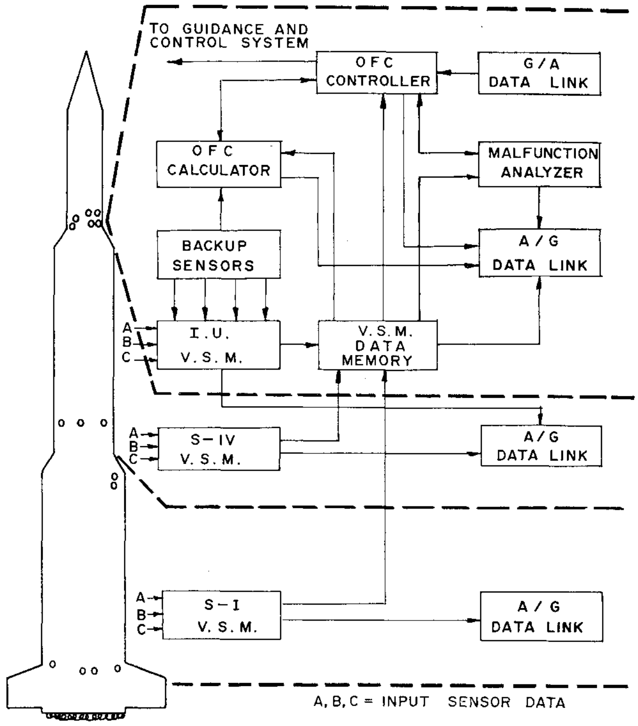

Fig. 8 Onboard OFC configuration.

Each of the four engines also has an independent electromechanical system; hence, if its hydraulic system malfunctioned, it could be driven to a neutral position and locked there. The remaining three control engines would still provide adequate control for most flight situations. Such an action would not necessitate the shutdown of the locked engine.

At this point, the forementioned malfunction-sensor matrices were developed, and the possible corrective actions were indicated for each subsystem in the vehicle. As the analysis was developed further, additional information pertinent to the OFC conceptual design was determined. This information included estimates of sensor limits, rates-of-change of the measurements, the minimum sampling rates required for each measurement, the designation of existing and new sensors, and finally, an indication of the applicable cross-correlation of sensor data between subsystems. The final determining factor in the selection of malfunctions (and their corresponding sensors) was specifically dependent upon the actions that the OFC could initiate as required by measured performance deviations.

Table 1 Definition of OFC flight segments for typical C-1 Block II vehicle mission

Flight segment no.	Time range, sec (T = 0 = liftoff)	Region(s) covered
I	−378 → 0	Automatic countdown sequence
II	0 → +10	Critical thrust level
III	+10 → +90	Critical external environment
IV	+90 → +147	S-1 normal operation through S-1/S-IV separation
V	+147 → +153	S-1/S-IV separation through S-IV engine ignition to S-IV full-thrust indication
VI	+153 → +613	S-IV normal operation through S-IV engine cutoff
VII	+613 → +616	Payload separation sequence
VIII	+616 → indefinite	Orbital operation (S-IVB only)

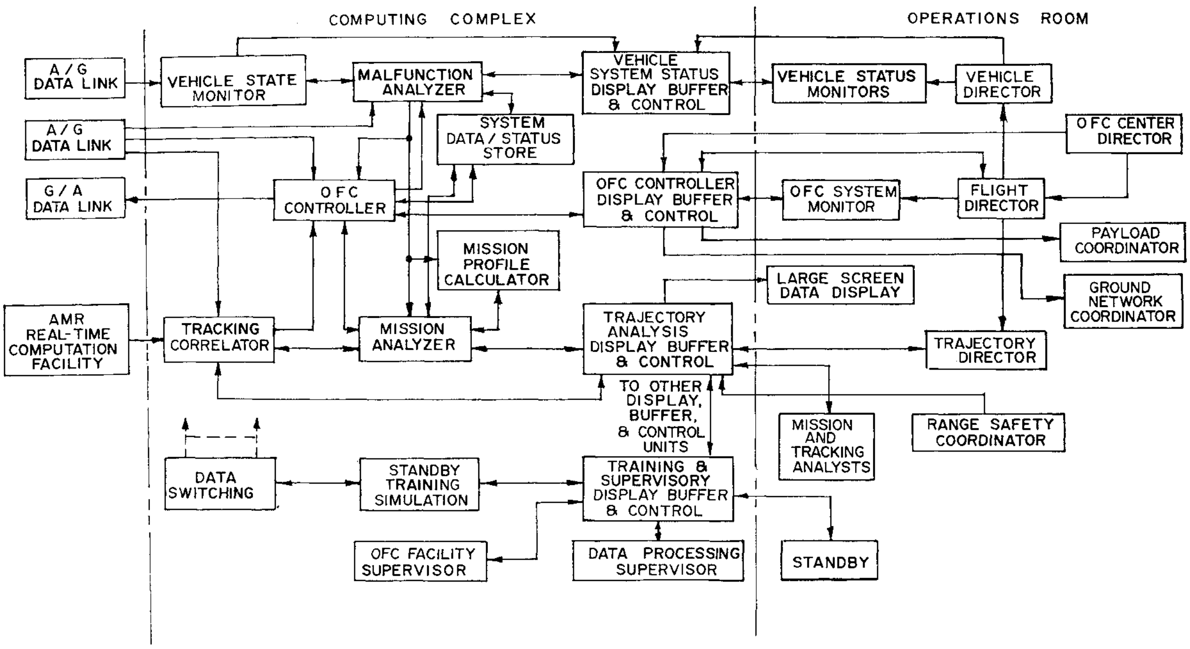

Fig. 9 Ground OFC configuration.

Primary and Alternate Missions

If a malfunction is detected which will affect the primary mission, appropriate action is instituted to compensate for the malfunction. Should performance degradation be so serious as to prevent achievement of the primary mission, then one of a number of preprogrammed alternate missions, representing optimum utilization of the remaining vehicle capability in relation to payload requirements, is selected and initiated. A graded list of primary and alternate missions that were considered is shown in Table 2.

System Design Configuration

As soon as solutions in each of the four major technical areas mentioned were found, it became evident that Operational Flight Control could be provided with the current state-of-the-art, and that its volume, weight, power, and cost would not exceed acceptable budgetary limits.

The OFC concept that evolved comprises both onboard and groundbased functions of measurement, assessment, and command, as shown in Fig. 7. The onboard functions, by means of a closed-loop system, provide maximum rate of response. The ground functions, which have access to both the onboard data and ground data but are not restrained by weight and size, provide a more complete and accurate assessment, and allow human participation, which provides judgment and flexibility. Such a system, in addition to its prime function of providing maximum utilization of vehicle capability after a malfunction occurs, has the basic elements required for 1) monitoring systems and initiating action to prevent malfunctions from becoming catastrophic, and 2) the real-time operational mission control activities, which will be required by certain sophisticated missions of the future as the basic means of achieving prime objectives.

Onboard System

It is convenient to regard OFC as an inflight management system, with the onboard OFC acting as a supervisor under the direction of the executive ground system (Fig. 8). The onboard system samples sensor data at appropriate rates for onboard use and for transmission to the ground OFC, evaluates the data by limit comparisons and logical analysis to determine abnormal situations, performs backup guidance calculations so that it can assume control of the primary or alternate missions in the event of a guidance system malfunction, and initiates commands for corrective action in those cases where there is insufficient time for ground decision.

In most cases, the onboard system uses sensors already used or planned for Saturn. The measurements are conditioned

Table 2 Primary and alternate missions

	Alternate missions								
Primary mission	Ocean recovery	Ballistic test S-1	Ballistic test S-IV	Eccentric orbit	Low life	Low altitude	Development test for future missions	Midcourse corrections	Launch alternate (rendezvous)
100-naut-mile circular orbit	√	√	√	√	√	NA	√	NA	√
300-naut-mile circular orbit	√	√	√	√	√	√	√	NA	√
High altitude and stationary orbit	√	√	√	√	√	√	√	NA	NA
Earth escape trajectory									
Direct	√	√	√	(or circular)	NA	NA	√	√	NA
After parking	√	√	√	√	√	√	√	√	NA
Rendezvous with tanker or space station									
With significant plane changes	√	√	√	√	√	√	√	NA	√
Without significant plane changes	√	√	√	√	√	√	√	NA	√

and then limit-compared in a Vehicle State Monitor (VSM) in each stage to identify (flag) those measurements outside acceptable tolerance. Simultaneously, the measurements are sent through telementry to the ground OFC complex. On the basis of the VSM monitoring, flagged items and selected data are directed to a Malfunction Analyzer in the Instrument Unit which identifies the malfunction and the appropriate action. Outputs are to the OFC controller for command action. In addition, by means of the OFC Calculator, guidance data required by the OFC and not readily available out of the basic guidance system are provided. By this means, additional inertial and guidance data are available for transmission to the ground and for backup to the basic guidance system in case of its malfunction.

Ground System

The ground OFC (Fig. 9) duplicates and evaluates onboard OFC operations and performs a variety of other operations more predictive and statistical in nature. The major ground-based element is an OFC Center, which houses a Computing Complex and an Operations Room and contains equipment for simulation, display, and communication purposes. Network support to the Center provides tracking, telemetry, and command-link coverage. The ground OFC coordinates activity with launch crews, the Range Safety Officer, network support facilities, and the payload mission control center. In this latter capacity, OFC can assume either a primary or auxiliary role, depending on mission requirements.

Computing complex

To minimize the weight of onboard equipment and provide greater control flexibility and system response, lengthy computations and data processing are performed by the ground OFC. Rather than duplexing the ground equipment, parallel multiple data processing techniques are used because of their reduced costs and simplified programming, checkout, timing, and operating procedures. Failure in any single element of the ground system may cause only a temporary loss of partial system functions. Buffers and other OFC peripheral equipment facilitate compatibility with existing computer or data processing systems.

Operations room

In the operations room, vehicle systems and the trajectory are monitored. It includes those real-time monitoring and control activities (if any) required by the payload during powered flight and provides for liaison required with the RSO, range support, and the launch complex. Analyses and computations are done with a group of small- and medium-sized computers as follows: 1) the Vehicle State Monitor, which flags data for 2) the Malfunction Analyzer, which identifies the malfunction and the appropriate action, 3) the Tracking Correlator, which correlates ground tracking and airborne inertial data, 4) the Mission Profile Calculator, which predicts end conditions of the basic mission, 5) the Mission Analyzer, which predicts end conditions of alternate missions, 6) the Controller, which selects and initiates commands, and 7) a Standby Computer for backup and training. Decisions and commands eminating from the ground complex are sent to the vehicle OFC Controller for onboard action initiation.

Summary and Conclusions

The OFC concept combines onboard and ground systems for maximum over-all effectiveness. The onboard system provides maximum reliability and the shortest response time for well-defined functions affecting the vehicle subsystems (propulsion, tankage, hydraulics, pneumatics, etc.). It makes the vehicle independent of ground assistance in the event of communication inadequacies or impending catastrophic situations where an immediate reaction is required. The ground-based system has the advantage of more extensive computation facilities and multisource data to provide the maximum level of confidence in the evaluations and decisions of the OFC system. In addition, human participation provides the important features of judgment and flexibility.

No action is initiated by the OFC as long as the vehicle retains the capability of achieving primary mission objectives. However, if a malfunction is detected which will affect the primary mission, then appropriate action is taken to compensate for the malfunction. Should performance degradation rule out the achievement of the primary mission, then OFC selects and initiates one of several preprogrammed alternate missions to make best use of the remaining vehicle capability in relation to the payload carried.

The over-all system design allows for the judicious assignment of functions to the onboard and ground equipment on the basis of mission requirements, with sufficient redundancy for system checkout, to preserve essential OFC capabilities under abnormal circumstances.

References

[1] Schmeider, D. H. and Braud, N. J., "Implementation of the path-adaptive guidance mode in the steering techniques for Saturn-multistage vehicles," ARS preprint 1945–61 (August 1961).

[2] "Status report #1 on theory of space flight and adaptive guidance," Aeroballistics Division, NASA Marshall Space Flight Center, MTP-AERO-62-21 (March 1, 1962).

[3] "Saturn C-1 failure effect analysis, SA-5 and complex 37-B," Propulsion and Eng. Div., NASA Marshall Space Flight Center Drawing 10M030061 (February 1962).

[4] "Saturn launch vehicle reliability study," ARINC Research Corp., Publication 141-2-199, Contract NASw-160 (December 23, 1960).