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APOLLO EXPERIENCE REPORT - FLIGHT-CONTROL DATA NEEDS, TERMINAL DISPLAY DEVICES, AND GROUND SYSTEM CONFIGURATION REQUIREMENTS

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16. Abstract

The development of flight-control facilities for the Apollo Program is reviewed from the viewpoint of the user organization. These facilities are treated in three categories: data systems, ground-based display and control systems, and configuration management. The effects of certain Apollo Program factors on the selection, sizing, and configuration management of these systems are discussed. Recommendations are made regarding improvement of the systems and the reduction of system sensitivity to the program factors.

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FLIGHT-CONTROL DATA NEEDS, TERMINAL DISPLAY DEVICES, AND GROUND SYSTEM CONFIGURATION REQUIREMENTS

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SUMMARY

The successful accomplishment of the Apollo Program objectives depended to a large extent on the mission control and monitoring provided by the flight-control team located in the mission control center at the NASA Lyndon B. Johnson Space Center (formerly the Manned Spacecraft Center). Therefore, a major flight-operations activity has been the development of flight-control facilities. These facilities are viewed by the user organization in terms of data needs, the selection of ground-based display and control systems, and the management of the configuration of these systems to meet the data needs. The relationships between certain program factors and this development, selection, and management process are reviewed in this report.

The most significant Apollo Program factors are the developmental nature of the flight program, the number of mission phases, the level of activity in each mission phase, the number of vehicles, and the launch intervals. The sizing and loading of the ground-based systems were affected by all these factors. However, the two concepts significant in reducing the sensitivity of the ground-based systems to these factors were based on establishing a balance between general-purpose and special-purpose display and control systems and displaying a small amount of data with rapid access to all other data. The configuration-requirement leadtimes were also dependent on all the factors, especially the launch interval. Long leadtimes for configuration requirements combined with short launch intervals represented a major problem in configuration-requirement management. Two methods are recommended for leadtime reduction without compromising flight-control effectiveness.

INTRODUCTION

This report covers experience gained during the Apollo Program with the ground system used to support the flight-control function. The concept of centralized control has been applied to every manned space flight program since Project Mercury, but the ability to achieve centralized control from a facility standpoint has been limited by the worldwide communications bandwidth and reliability constraints. Because of these constraints, manned sites equipped with voice and teletype communications to the mission control center (MCC) were used extensively during Project Mercury and the Gemini Program. If time permitted, all decisions and actions were approved by a centralized mission-control team located in the MCC; the remote-site team relayed decisions and implemented approved actions. However, if time did not permit, the remote-site team could take action and make decisions based on mission rules that were established premission. Early in the Apollo Program, the approach of centralized control included both manned and unmanned remote sites. This dual approach necessitated two unique sets of remote-site computer programs. The programs for the unmanned sites provided high-speed telemetry and tracking data to the MCC and command control of the spacecraft from the MCC, where reliable communications could be provided. The programs for the manned sites provided displays of telemetry and tracking data and local command control to flight-control personnel located at the site. This approach imposed a heavy program-development, checkout, and maintenance workload. The results were elimination of many desirable requirements, late delivery of the programs to the sites, and degraded reliability. When communication satellites became operational before the Apollo 5 mission, reliable worldwide communications were available; therefore, manned remote sites were eliminated for the remainder of the Apollo Program.

FLIGHT-CONTROL DATA NEEDS

The instantaneous bandwidth of the combined vehicle telemetry downlinks (i.e., 100 to 200 kbps) greatly exceeded the flight-control data needs; therefore, the concept of "display a few parameters at a time with rapid access to all others" was adopted and applied to the data flow from the remote sites to the MCC and to the data display in the MCC. The data-flow system provided a library of data-flow formats (each format containing a maximum of 2.24 kilobits of vehicle telemetry data) from the remote sites to the MCC (table I). The formatting technique used was a combination of vehicle selection, parameter selection, and sample-rate reduction techniques.

During the first few Earth-orbital missions, involving only a booster and either the command and service module (CSM) or the lunar module (LM), only one high-speed data format at a time was required from each remote site. During the lunar missions, the need was increased to two simultaneous high-speed data formats from each remote site. This change was a result of the two new high-activity phases: the lunar-landing and the lunar-launch phases, in which both the CSM and LM were active. High-speed data-format-selection control was exercised from the MCC.

The concept of "display a few parameters at a time with rapid access to all others" was also applied to the computer-driven television (TV) displays. The parameters that were available from high-speed data formats at the MCC were placed on computer-driven TV display formats so that only a few display formats had to be displayed at a given time.

TABLE I. - DATA-FLOW FORMAT CONSTRAINTS

Format name	Vehicle format bit rate, bps		
	SLV[a]	CSM	LM
SLV/CSM backup	1075	1075	0
SLV launch	2150	0	0
LM only	0	0	2240
CSM and LM PCM[b] (no OBC[c])	0	950	1150
CSM and LM backup	0	1050	1150
CSM maneuver and LM coast	0	1600	640
CSM only	0	2240	0
CSM PCM only (no OBC)	0	2240	0
SPS[d] burn	0	2240	0
LM maneuver and CSM coast	0	420	1820
Erasable memory dump	0	(e)	(e)
SLV orbit	2150	0	0
CSM only (Program 22)	0	2240	0
OBC data	0	420	1820

[a]Saturn launch vehicle.
[b]Pulse code modulation.
[c]Onboard computer.
[d]Service propulsion system.
[e]Optimum manner of formatting determined by implementing organization.

SELECTION OF TERMINAL DISPLAY DEVICES

Balance of General-Purpose and Special-Purpose Display Devices

The concept of a general-purpose display device such as TV was adopted to allow large variations in display-presentation techniques and to provide access to large amounts of data in a small console area. The limitations of any general-purpose device for special applications were recognized. Therefore, the general-purpose devices were augmented by the use of special-purpose display devices to provide such characteristics as high sample rate, high accuracy, attention getting, and time histories. This concept of a balance between general-purpose and special-purpose display devices was very useful in both the Gemini and Apollo Programs. The choice of what balance to use is subjective and is sensitive to the nature of the program being run and to the level of experience with similar functions. As an example of the effect of the experience level, CSM systems monitoring was very similar to previous manned spacecraft monitoring; therefore, the general-purpose TV displays were used extensively. However, scientific-experiment operation for the Apollo lunar surface experiments package (ALSEP) was new to flight control, and unique special-purpose display devices (i. e., drum recorders, multipoint recorders, and meters) were used for experiment-data presentation. As experience is gained with scientific-experiment operation, an additional category of general-purpose display devices may be added to the current display system.

General-Purpose Display (Television)

The TV display system is the prime general-purpose method of display within the MCC. Analysis of required display characteristics such as clarity and density of data presentation, data sources, distribution of displays, and hardcopying of the data resulted in the choice of the high-resolution TV technique. This selection was based on the ease of distribution and on the types of input information to the display system. Of the five categories of inputs, four were scenic. The inputs are as follows:

1. Computer-driven displays (the only nonscenic type)

2. Opaque televiewers (cameras mounted over tables in remote locations within the MCC and used for such manually prepared information as trend plots, drawings, and Flight Plan revisions)

3. External TV (Kennedy Space Center launch TV and spacecraft TV)

4. Reference slide files

5. Other cameras within the MCC

These sources are routed through a switching matrix to provide outputs to individual console TV monitors, ceiling-hung TV monitors, and large projection group-display monitors. Of these various input sources, the computer-driven displays and the opaque televiewers are the most useful. External TV provided a significant addition for the launch and spacecraft TV camera presentations. The reference slide file, designed to provide rapid access to document storage, was of little use because of the constraints placed on text data (i. e., information could not be taken from existing documentation because special text formatting was necessary for TV presentation).

The categories of computer-driven display formats are alphanumeric tabulations, X-Y and time-history plots, meter representations, and schematic and dynamic digital-data combinations. The alphanumeric tabulations, X-Y plots, and time-history plots have been used extensively and are considered the most adaptable type presentation for computer-driven TV. The meter representations were eventually deleted from the system because of the poor quality of the display formats. Presentation by a schematic that included dynamic digital data was tried on several occasions. This category proved to be satisfactory from a data-presentation standpoint; however, reconfiguration of the category was very costly when compared to the cost for alphanumeric tabulations. Therefore, this category should not be considered as a standard format category and should be used only in special cases.

During the Earth-orbital flights of the Apollo Program, a complement of 28 computer-driven TV channels was sufficient. However, expansion to 36 channels was required for the Apollo lunar-landing missions.

Two control modes were provided for the TV display system. The capabilities are discussed in the following sections.

Display request mode. - An individual console may request a display format; the computer generates the data, formats the display, outputs the data to the next available computer-driven TV channel, and automatically connects that channel to the TV monitor of the requesting console. The concept of a computer-driven channel assignment was based on a "first come, first served" basis as opposed to consigning channels to displays or consoles. Initially, difficulties were experienced when all channels were being used and additional critical displays were needed. To provide positive control, a new display format was added to identify which display format was on each channel and to identify which console had requested the display. Through the use of this display, the flight-control team could determine which display formats to release to the proper channels.

Channel attach mode. - In the channel attach mode, a console requests a given TV channel and receives whatever data are on that channel. This concept of sharing TV channels has been very workable and has resulted in the need for significantly fewer channels.

A hardcopy subsystem was included as part of the TV display system. The requirements for this subsystem were the same as for TV display (i. e., hardcopy of both data and scenic-type displays). This subsystem has been unsatisfactory because of poor legibility. Experience gained during the Apollo Program has proved that only computer-driven data displays need to be hardcopied and, therefore, that the scenic hardcopy requirement could be eliminated. This would make possible the use of many existing direct computer printout/plotting devices instead of the current TV photographic-hardcopy subsystem.

Special-Purpose Display Devices

Event modules. - The event module is a special-purpose display device used extensively on consoles. Initially, events were grouped 18 and 36 events per module. The initial concept was to provide only those events on event modules that were applicable to all mission phases; all other event displays were to be provided by the use of the computer-driven TV system because these displays can be released when not in use. However, experience showed that few events met this criterion; therefore, the evolution of the use of event modules during the Gemini and Apollo Programs resulted in the current concept that the prime method of event display is the use of event lights. This concept change caused a significant increase in the size of the event-display hardware and software, including the development of 72-event modules for high-density event display. Because the original system was designed for expansion, no significant problem was encountered. Event-light modules are used extensively, both in the mission operations control room (MOCR) for prime-parameter monitoring and in the staff support rooms for detail-parameter monitoring. The two sources of event drives are the real-time computer complex (the same computer that drives the computer-driven TV channels), which is required for parameters that must be processed or limit sensed at a rate no greater than once per second; and a pulse-code-modulation (PCM) ground station, which is required for high-sample-rate event displays. In the early phases of the Apollo Program, event displays directly from the ground station (i. e., bypassing the computer) were also desired because of a lack of confidence in inline computer systems.

Analog strip-chart recorders. - The analog strip-chart recorders were used primarily for detailed analyses of system parameters (especially those requiring high sample rates); therefore, the recorders were in the staff support rooms. These recorders also bypassed the computer and were driven directly out of the PCM ground station. Two strip-chart recorders used in the flight dynamics staff support room (SSR) were an exception because they were used to display guidance parameters that had to be processed by the real-time computer complex. These two strip-chart recorders were viewed by TV; the pickup cameras viewed the strip-chart recorders directly. This TV method of display was very useful and was extended to ALSEP scientific parameters (i. e., X-, Y-, and Z-axes of the lunar seismometer). More extensive use of TV for the display of analog parameters as a function of time is anticipated. The two methods of TV presentation of analog display investigated for the remainder of the Apollo Program were the use of TV-viewing strip-chart recorders for high-sample-rate presentation and the use of computer-generated time-history plots.

Analog meters. - Experience in the use of analog meters as an end-display device has been interesting, and several conclusions can be made. Initial attempts were made to depict meter-type displays on the computer-driven TV displays. As mentioned in the TV discussion, this method was unsatisfactory and, because proportionately large amounts of computer capacity were required, the method was discontinued. The use of hardware meters increased immediately after the elimination of meter representations on computer-driven TV displays. These hardware meters were driven directly from the PCM ground stations by digital-to-analog converters. A common rationale was used regarding the hardware meters, the event-light panels, and the strip-chart recorders. Initially, the users had little confidence in computer-driven displays; therefore, meters driven by the PCM ground station provided a backup to the computer-driven displays. As confidence in the computer displays increased, the number of hardware meters was reduced. The change in meter number and location as the Apollo Program progressed exemplified this increase in confidence. For the AS-201 mission in February 1966, which was a Saturn-IB (S-IB) launch-vehicle-only mission, 30 meters were in the MOCR. For the Apollo 5 mission in January 1968, which involved an S-IB launch vehicle and an unmanned LM, the number of meters had increased to 49. For the Apollo 6 mission in April 1968, which involved a C5 launch vehicle and an unmanned CSM, a maximum of 68 meters was reached. At this time, a strong trend developed to move the meters from the MOCR to the staff support rooms. By the time of the Apollo 13 mission in April 1970, only 43 meters were left when all vehicles were required.

In summary, the following conclusions can be made about meters. Early in the Apollo Program, heavy reliance was placed on meters because of lack of confidence in computers. As the number of vehicles increased during the early missions, the number of meters increased proportionally. Midway through the program, a shift was noted; most of the meters were relegated to the staff support rooms for detail analysis. This shift represented an increase in reliance on the computer-driven TV displays. Finally, a reduction in the number of meters occurred as the staff support rooms relied on the computer-driven TV displays. The last prime use for meters in the Apollo system was for the detailed monitoring of the Saturn launch vehicle, a short-lived, highly active system.

Projection-plotting devices. - The projection-plotting devices were implemented during the Gemini Program. Standard, direct-write X-Y plotboards were used as backup devices because the projection-plotting devices were a developmental system. The backup direct-write plotboards were removed early in the Apollo Program after the projection-plotting devices became operational. The projection-plotting devices were used primarily for trajectory displays (e. g., velocity as a function of flight-path angle plots with limit lines). The devices were also used as general-purpose displays to depict the mission progress (i. e., the relative location of the spacecraft during translunar coast).

Event recorders. - Event recorders provided accurate high-sample-rate time histories of events. Initial implementation for the Apollo Program was a 200-event pen capability in a remotely located equipment room. By the time of the Apollo 11 mission, verification of event occurrence in a time-dependent manner became a necessary task of the vehicle systems SSR; therefore, an additional 400-event pen capability was added in the vehicle systems SSR. These recorders were not collocated with the consoles because of floorspace constraints. Recorder utility would have been improved if the recorders and consoles had been collocated; however, collocation was not considered mandatory because most of the events were duplicated on the console event lights and the computer-driven TV formats.

Unique display devices. - A unique cardioscope display module was used for presentation of astronaut heart waveforms. The cardioscope was chosen instead of the TV because of the high accuracy of waveform that was required. The cardioscope paralleled the same information on strip-chart recorders in the medical SSR. Heart and respiration rates were presented on special-purpose digital-read-out modules as part of a unique input-computation system for the flight surgeon. A third category of unique display devices was the event-sequence-override module. The use of these modules was discontinued because many spacecraft systems had different event sequences depending on the mode of system operation. Computer-driven TV was used where event sequences were of interest. The need to override telemetry events diminished as confidence in the spacecraft and ground telemetry systems improved through the use of cross-checking of different parameters.

MANAGEMENT OF GROUND-SYSTEMS CONFIGURATION

As used in this report, configuration requirements refer to the specification of the arrangement of the ground-systems data formats, displays, and controls. Because of the developmental nature of the Apollo Program and the short launch intervals, requirements were levied against the ground systems to provide various degrees of configuration flexibility from mission to mission. Therefore, the configuration requirements were constrained to be within the configuration capability of the original ground system design.

Configuration-Requirement Categories

Configuration requirements were divided into six categories based primarily on the leadtime needed for the reconfiguration of each category.

1. Callup of remote site facilities and interfaces

2. Data-flow format configuration (i. e., the parameters and sample rate in each format, within the constraints given in table I)

3. Special data processing of a mathematical nature (e. g., the determination of the fuel volume from pressure and temperature telemetry measurements)

4. Command-system configuration (e. g., the command-execute panel arrangement and the identification of which commands are to be stored in the remote-site computers for mission execution)

5. Display-system configuration (e. g., the layout of the computer-driven TV display formats and the arrangement of parameters on event panels, meters, and recorders)

6. Intercommunication panel configuration (e. g., access to the various loops and loop arrangement on the panels)

Documentation Method

The method of documenting the configuration requirements evolved from a method of writing the requirements in text form, as was done in Project Mercury, to a hybrid method of computer-generated/manual text preparation. The use of computer-generated documentation was valuable where many configuration changes were caused by a developmental flight program such as the Apollo Program (i. e., early missions had few vehicles and simple mission profiles, whereas later missions included more numerous and more highly developed vehicles and complex mission profiles). Three advantages of the computer-generation method were as follows.

1. The computer could sort the requirements efficiently. (The requirements were prepared according to flight-control function, such as all configurations applicable to the CSM guidance function, whereas the implementing organization preferred grouping requirements by system, such as all data-flow configuration requirements.)

2. The changes from previous mission configurations were identified easily.

3. Maximum use was made of previous mission-configuration requirements without having to retype and check the unaffected configurations. Manual text preparation was still required for the specification of new or modified special data-processing requirements.

Single-Point Coordination, Review, and Approval

Configuration-requirement management was accomplished by one flight-control organization. The responsibilities of this organization were to ensure that schedules were met, policies were applied, requirements were integrated, duplication was avoided, requirements were within the capability of the systems, and late requirements were evaluated from a standpoint of justification and impact.

Schedules

The schedule for submittal of configuration requirements began with the initial submittal 10 months before the mission. Final cutoff dates were spaced between 9 months and 1 month before the mission, depending on the requirement category. (Changes to the data-flow formats were terminated at 9 months premission, changes to special data-processing requirements were terminated at 8 months premission, and all configurations were terminated at 1 month premission.) Generally, these requirement cutoff dates were a result of the leadtime necessary to implement and check out that requirement category; however, the last date at 1 month premission was to ensure that training integrity was not affected by changing the system configuration.

The most significant configuration-requirement problem experienced during the Apollo Program was the long leadtime associated with three requirement categories. These categories were the most important ones from a vehicle-systems-monitoring standpoint (i. e., data-flow format configuration at 9 months premission and special data processing and computer-driven TV displays at 8 months premission). The most significant factor causing the long leadtimes was the design approach applied in the ground-systems software programs. Although the design approach provided for mission-to-mission reconfiguration, extensive program checkout also was necessary to ensure reliability. Three additional Apollo Program factors combined with the long leadtime to cause many requirements to be eliminated or delayed until later in the program. These three factors were the short launch interval between missions, the large volume of requirements, and the late changes to the flight vehicles or mission profiles after the ground-system-requirement cutoff dates had passed. As experienced during Project Mercury and the Gemini Program, a large volume of configuration changes occurred. This occurrence is characteristic of a developmental program wherein each successive flight is more complex than the preceding one, and the program includes different mission profiles and vehicles. Generally, the requirements that were eliminated or delayed until later in the program had less than mandatory justification. Late mandatory requirements consumed a large portion of the available manpower and computer-hour resources because of extensive coordination and retesting. Consequently, even more nonmandatory requirements often were eliminated or delayed, and flight-control procedures in turn were changed late in the premission preparation and training cycle.

CONCLUDING REMARKS

The development of both manned and unmanned remote-site computer programs caused an excessive program-development workload. Initially, this excessive workload resulted in deficient program content and reliability. When the communication satellites provided reliable worldwide coverage, the manned remote sites were eliminated; the result was highly reliable and satisfactory remote-site programs. The concept of "display only a few parameters with rapid access to all others" proved to be both feasible and desirable. The amount of data that had to be monitored simultaneously and, therefore, the sizing of the data processing, control, and display systems were proportional to the number of vehicles that were active simultaneously. The number of hardware display devices required to back up the computer-driven displays was inversely proportional to the level of experience the user organization had in using computer systems. A strong trend toward computer-driven displays occurred as experience and confidence were gained. This trend resulted in a significant improvement in the ability to monitor the mission.

The concept of a balance between general-purpose and special-purpose display devices was valid. As the size of the total display system was increased, the balance was maintained with a slight shift in favor of the general-purpose devices. When new mission-control functions were introduced (e.g., scientific-experiment operations), the shift was strongly toward special-purpose display devices; however, as experience was gained, the shift reversed in favor of the general-purpose devices. The choice of television as the general-purpose display system provided excellent flexibility of real-time information-presentation techniques, data sources, and display distribution. An additional type of general-purpose display device oriented toward near-real-time and history-information display (i.e., microfilm) was considered. An evaluation of television display sources indicated that the most useful sources were the computer-driven displays and the opaque televiewer, whereas the reference slide file was unsatisfactory because of unique formatting constraints that were incompatible with standard documentation. An evaluation of television display format techniques indicated that alphanumeric tabulations and plots were most useful. A systems schematics presentation with dynamic digital data was a good presentation technique, but its reconfiguration was costly. Because the meter pictorial technique was unsatisfactory, it was discontinued. The two methods of computer-driven television display access (display request and channel attach) operated well and reduced the size and cost of the display system. The requirement to hardcopy scenic television displays resulted in an unsatisfactory hardcopy system. Experience has shown that the elimination of this requirement is acceptable and facilitates the use of existing high-quality direct computer printout/plotting devices.

The application of computer-generated documentation to configuration requirements was beneficial in the Apollo Program and is expected to be beneficial for any complex developmental flight program. The coordination, review, and approval of configuration requirements by a single-point operations organization was appropriate to a developmental flight program such as the Apollo Program. However, the benefits of computer-generated documentation and the advantages of configuration-requirement management by a single-point operations organization would be reduced greatly for an "all-up" program such as Skylab.

A large volume of configuration-requirement changes should be anticipated in any developmental flight program. The long leadtimes for configuration requirements were a significant problem in the Apollo Program. The leadtime is dependent on the initial design approach. Increased emphasis should be placed on this factor (i. e., rapid reconfiguration, especially in the software systems) during the systems-design phase of future flight programs. Two concepts tried in the Apollo Program are applicable: the modular or table fill-in approach, which reduces or eliminates the need for extensive program checkout after each reconfiguration; and the "universal" design approach, which does not require reconfiguration (e.g., the manual-select keyboard for television display access and the digital-select matrix for the universal command system).

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