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APOLLO EXPERIENCE REPORT - REAL-TIME AUXILIARY COMPUTING FACILITY DEVELOPMENT

by Charles E. Allday

Manned Spacecraft Center

Houston, Texas 77058

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16. Abstract

The Apollo real-time auxiliary computing function and facility were an extension of the facility used during the Gemini Program. The facility was expanded to include support of all areas of flight control, and computer programs were developed for mission and mission-simulation support. The scope of the function was expanded to include prime mission-support functions in addition to engineering evaluations, and the facility became a mandatory mission-support facility. The facility functioned as a full-scale mission-support activity until after the first manned lunar-landing mission. After the Apollo 11 mission, the function and facility gradually reverted to a nonmandatory, offline, on-call operation because the real-time-program flexibility had been increased and verified sufficiently to eliminate the need for redundant computations. The evaluation of the facility and function and recommendations for future programs are discussed in this report.

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APOLLO EXPERIENCE REPORT

REAL-TIME AUXILIARY COMPUTING FACILITY DEVELOPMENT

By Charles E. Allday
Manned Spacecraft Center

SUMMARY

The Apollo Real-Time Auxiliary Computing Facility, which was an expansion of the facility used during Project Mercury and the Gemini Program, provided support for all aspects of flight control. Mission support, mission-simulation support, and engineering evaluations also were included in the scope of the facility, and computer programs were developed specifically for those areas. The organization, management, and control of the facility were given to a special group of trajectory analysts. The analysts, who had experience in facility activities, had the responsibility for the development of the facility to provide complete mission-support capability. The existing computer programs were used as the basis for the software; however, strict control was placed on the input and output formats and on the program interfaces and verification.

The real-time auxiliary computing function and facility were developed to perform unexpected real-time trajectory computations and evaluations of trajectory problems that developed during the missions. The facility also provided the capability to perform computations that were beyond the time-limited constraints of the real-time program and the capability to use programs that were too large and cumbersome to be used in real-time computations. Requirements that were established too late in the real-time-program development were accommodated by the facility. In addition, the facility provided the flight controller the opportunity to evaluate programs and displays in a real-time environment before implementing them in the real-time system. By the use of the facility, existing available programs and personnel were used to provide an almost unlimited real-time capability for problem solving.

INTRODUCTION

The Real-Time Auxiliary Computing Facility (RTACF) evolved from the trajectory planning and contingency analysis in support of Project Mercury. Real-time support activities were the result of trajectory-related problems that developed during the Mercury mission simulations. The RTACF was expanded during the Gemini Program to include engineering evaluation support for all areas of flight control. Computer programs were developed specifically for mission and mission-simulation support.

The scope of the function was expanded further for the Apollo Program to include prime mission-support functions in addition to the engineering evaluations; thus, the RTACF became a mandatory mission-support function.

In planning for the Apollo Program, a special group was formed to organize, manage, and control the RTACF. This group was staffed with trajectory analysts who had participated previously in the RTACF activities. One of the prime responsibilities was to expand the RTACF computer system to provide a total mission-support capability. The responsibility for providing the mission-critical computations created the demand for the implementation of configuration control over the offline computing software. This goal was accomplished primarily by means of specific offline software verification and a common data base that could be used by all offline programs. The RTACF functioned as a full-scale mission-support activity until after the first manned lunar-landing mission. After the Apollo 11 mission, the facility gradually reverted to a nonmandatory, offline, on-call operation because the real-time-program flexibility had been increased and verified sufficiently to eliminate the need for redundant computations.

The RTACF for the Apollo Program was developed because of the need to perform unexpected real-time trajectory computations and engineering evaluations of trajectory problems that developed during the mission, as well as during mission simulations. The RTACF was expanded to perform the following functions.

1. Computations requiring multiple ephemerides and trajectory planning beyond the time-limited capability and flexibility of the real-time program

2. Computations using large and cumbersome programs with running times too slow to be feasible for real-time computations

3. Computations to satisfy requirements established too late in the real-time-program planning cycle to be satisfied by the real-time system (Normally, these computations were absorbed by the real-time system during later missions.)

4. Computations performed to provide a real-time testing ground for future Real-Time Computer Complex (RTCC) programs (This capability provided a means of evaluating a computer program in a real-time environment before the program was implemented in the real-time program.)

5. Computations to provide unlimited real-time flexibility as to the type of problem that could be resolved by the use of the engineering analysis programs by the personnel who were involved in all phases of the mission planning

To accomplish these functions during Project Mercury and the Gemini Program, each engineer coordinated his own computing requirements, maintained his own programs, and established his own procedures. Because of the relative simplicity of the RTACF function for Project Mercury and the close relationship of the people involved, this procedure was acceptable. The procedure extended into the Gemini Program and worked well for the early missions. However, as the program matured and became more complex and as the mission-control operations were transferred from the NASA John F. Kennedy Space Center (KSC) to the NASA Manned Spacecraft Center (MSC) Mission Control Center (MCC), this procedure became unworkable. Many conflicts arose in the use of available equipment, in addition to the always present problem caused by the use of incompatible or wrong inputs, and resulted in confusion and the use of incorrect data for mission-control decisions. Also, much redundant programing occurred as the requirements increased for the later Gemini and early Apollo missions. To resolve these problems and to avoid future problems, the following actions were necessary.

1. Creation of an organizational group responsible solely for the RTACF function (This function included assessing requirements, controlling hardware and software, establishing operating procedures, and acting as the point of contact with outside organizations.)

2. Development of the necessary computer facility to include communications with the MCC

3. Assembly and coordination of the development of the required software, including documentation, verification, and establishment of the necessary data base

ORGANIZATION AND MANAGEMENT

Because of the change in mission-control operations from KSC to the Mission Control Center at MSC and the increased requirements for the later Gemini and early Apollo missions, the establishment of an organization responsible solely for the RTACF function became necessary. The major problem that occurred in the formation of this group was that, if the complement of personnel assigned to this element was to have the capability of fulfilling all the requirements, the group would have to have included most of the Mission Planning and Analysis Division (MPAD) engineers assigned the task of Apollo mission planning. (The MPAD personnel had overall responsibility for the RTACF function.) Thus, a decision was made to establish only a small group composed of engineers who were familiar with most aspects of mission planning and mission operations. This group was assigned the responsibility of organizing and managing the overall RTACF function. The group also was responsible for assessing the requirements for feasibility, assigning the requirements to appropriate individuals within MPAD, establishing hardware and software control procedures, establishing operating procedures, coordinating the RTACF activities, and acting as the single point of contact with outside organizations.

To keep all personnel involved informed of the RTACF procedures, requirements, and schedules, a formal documentation procedure was established and followed by the RTACF organizational group. The documents, which were published for each mission, established the RTACF management structure; maintained the current description of the RTACF requirements, software, and data base; and maintained a description of the current procedures. The management structure and requirement processing procedures were contained in the operational support plan. A flight annex to this document was published on a mission-by-mission basis to describe the RTACF software capabilities. A work-plan schedule and the data base also were published on a mission-by-mission basis.

The activities of the organization were different for the prelaunch mission-planning phase and for the simulation and real-time mission-control activities. During the prelaunch mission-planning phase, the assigned personnel were engaged primarily in deciding what requirements could be accommodated, assembling the proper computer programs, verifying exercises, developing operating procedures, developing and coordinating work schedules, assigning other personnel for specific support, and developing the required data base.

During the simulation and real-time mission-control activities, the personnel of this organizational group were supervisors and partial staff for the Flight Dynamics Staff Support Room (FDSSR) and the Auxiliary Computer Room (ACR). These personnel provided a central point of contact in the FDSSR and in the ACR, thus eliminating the conflicts that had arisen during previous methods of operation and establishing a single data-flow channel. The lines of communication and data flow for this period of activities are shown in figure 1. Handbooks were published for each mission, detailing the coordination procedures between the FDSSR and the ACR and the program setup procedures for the ACR.

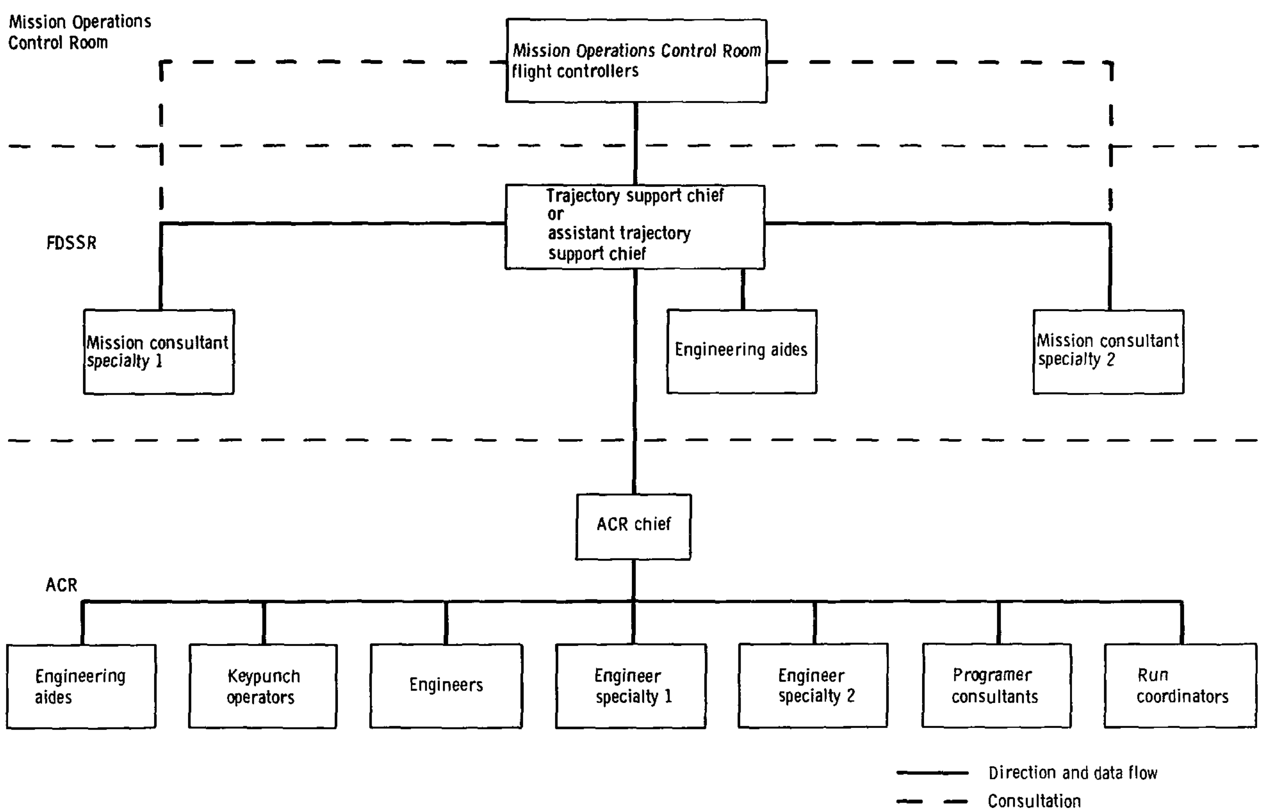

Figure 1. - The RTACF communications and data flow during the Apollo Program.

As can be noted from figure 1, to perform effectively, the ACR required personnel of varied specialties. The RTACF was manned on a three-shift basis for the Apollo Program and was a significant user of available resources. The numbers of man-hours expended for mission and mission-simulation support for some of the Apollo missions, including both computer support and trajectory specialist support, are shown in table I. During the early Apollo missions, the ACR was staffed essentially by the engineers responsible for the premission planning; but, as the mission complexity grew, the requirements for premission planning grew. Eventually, the premission planning engineers could not devote adequate time to the RTACF function. As a result, the permanent staff of the organization had to be enlarged, and the planning engineers were used only as consultants.

TABLE I. - MANPOWER EXPENDITURE FOR THE RTACF

Mission	Mission type	Manpower, man-hr[a]	Approximate mission duration
Apollo 5	Unmanned LM[b], earth orbit	6375	6 hr
Apollo 6	Unmanned CSM[c], earth orbit, high speed entry	3426	12 hr
Apollo 7	First manned CSM, earth orbit	NA[d]	11 days
Apollo 8	Manned CSM, lunar orbit	3783	6 days
Apollo 9	Manned CSM/LM, earth orbit	9246	10 days
Apollo 10	Manned CSM/LM, lunar orbit	4880	8 days
Apollo 11	First manned lunar landing	7644	8 days
Apollo 12	Second manned lunar landing	894	10 days

[a]Includes both mission and mission-simulation support.

[b]Lunar module.

[c]Command and service module.

[d]Not available.

FACILITY

The interfaces of the RTACF within the mission-control operations and the MSC Central Data Facility are shown in figure 2. The RTACF provided a centralized work area (the ACR) with voice links to the Mission Control Center FDSSR and to the RTCC. Data lines connected the ACR to the computers located in the Central Data Facility. Data generated in the ACR could be transmitted by means of video to any area within the MCC. The RTACF used the general-purpose computing hardware that was used by the trajectory analysts for premission design work. Special priority arrangements were coordinated with the Computation and Analysis Division for immediate access to the computers during simulation and real-time support periods. A diagram of the computing hardware used by the RTACF is shown in figure 3.

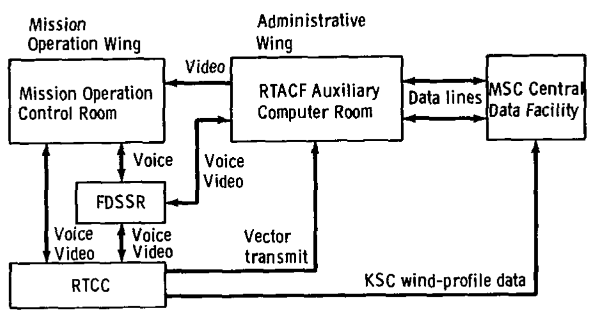

Figure 2. - The RTACF interface within the mission-control operations.

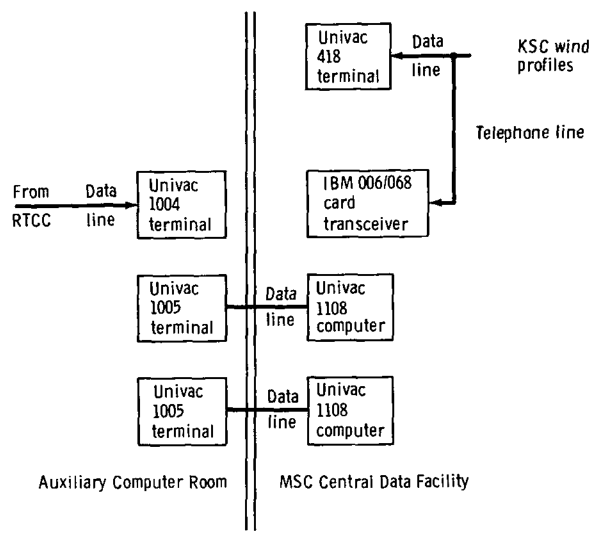

Figure 3. - The RTACF computing-hardware configuration.

As shown in figure 3, several different pieces of hardware were required to operate the RTACF. The KSC interface was redundant because of the mandatory requirements of the data received from KSC. The two interfaces with the MSC Central Data Facility were required to accomplish all the tasks in the proper time, as well as to provide redundancy. The RTACF had the capability to support the activities in both Mission Operations Control Rooms in the MCC. Each Mission Operations Control Room is located on a separate floor in the MCC. Voice and video communications were established between the ACR and the FDSSR on each floor and between the staff support rooms on each floor.

The number of computer hours used in support of some of the Apollo missions is given in table II. As would be expected, the hours required depended greatly on the complexity of the mission but also depended heavily on the overall confidence in the real-time system.

Mission	Mission type	Computer usage, hr[a]	Approximate mission duration
Apollo 5	Unmanned LM[b], earth orbit	149	6 hr
Apollo 6	Unmanned CSM[c], earth orbit, high-speed entry	154	12 hr
Apollo 7	First manned CSM, earth orbit	565	11 days
Apollo 8	Manned CSM, lunar orbit	630	6 days
Apollo 9	Manned CSM/LM, earth orbit	645	10 days
Apollo 10	Manned CSM/LM, lunar orbit	613	8 days
Apollo 11	First manned lunar landing	256	8 days
Apollo 12	Second manned lunar landing	52	10 days

[a]Includes both mission and mission-simulation support.

[b]Lunar module.

[c]Command and service module.

SOFTWARE MANAGEMENT AND CONTROL

In general, the computer programs used in the RTACF were obtained from the existing mission design/analysis program and were incorporated into the RTACF computer system without change to the basic logic and equations. During the mission, the programs were run in a batch-processing mode, which is similar to the premission planning mode. To establish the proper level of confidence in the RTACF, the software had to be controlled and verified in a manner similar to that in the real-time system.

Software-Configuration Control

The responsibility for providing mission-critical computations and the significant increase in offline computing requirements necessitated the implementation of a strong configuration control over the offline computing software modules, including the module interfaces, inputs, and outputs. The program logic and equations were supplied by the mission-design engineer, and neither was altered by RTACF personnel.

In addition to providing a configuration control over the RTACF software, the program-interface-control concept also reduced significantly both the manpower and the computer time that were required to update the RTACF system. These reductions were accomplished by providing a common format and program location for the mission-dependent constants. Also, job turnaround was improved and human errors were decreased significantly by having the computer transfer automatically from module to module, instead of having the inputs manually keypunched for each individual module.

The trajectory ephemeris tape and the 200-Word Record were the automatic program interfaces that were used during the Apollo Program. The ephemeris tape contained position and velocity-vector data and spacecraft-attitude information for one or two spacecraft. This tape was written by the basic RTACF integrator (the Apollo Reference Mission Program), which had both free-flight and powered-flight capabilities. Other programs, such as optics computations and radiation-dose computations, that contained no integrator also used the ephemeris tape for input. The 200-Word Record was a group of selected quantities (trajectory information, guidance quantities, maneuver parameters, and so forth) that were used to initialize the other programs. This interface record was the basis of the RTACF modular mission-support program. From this record, the RTACF personnel were able to construct computer programs from combinations of the programs that were furnished by the mission-planning engineers. The data deck setup was simplified because the mission-support personnel had to initialize only one program, which in turn provided most or all of the initialization parameters to the other modules. Also, the modular concept reduced redundancy in the RTACF programs because the capability of one program did not have to be implemented into a second program. Verification of the RTACF programs was reduced greatly by the modular concept because each module was a verified mission-planning tool.

Program-Input Control

Primarily, RTACF control of the program inputs was accomplished by the use of a common data base. This data base, located on a FASTRAND drum (as were most of the programs themselves), contained most input data that were required by the trajectory program (that is, launch data, aerodynamic data, center-of-gravity data, thrusts, radar-station locations, and so forth). In addition to providing a tool for ensuring correct program inputs, the common-data-base concept greatly simplified the revision of program input values. Before the data base became operational, RTACF personnel updated and checked each program individually. The data base provided the capability to input the proper values into a single drum file that was available to all programs, thus eliminating the individual program checks.

Program Verification

The RTACF programs that provided backup computations for the RTCC were verified by means of both formal and informal runs with the RTCC. Formal verification involved a set of computations from both the RTCC and the RTACF. The informal verification was accomplished by RTACF personnel during mission simulations by computing selected cases that were run by the RTCC. These computations were coordinated with Flight Control Division personnel. Compatibility with the mission-planning programs provided verification of the computations that were not in the RTCC. Also, checks were made with programs that were used to support earlier missions.

Major Contributions to the Apollo Program

During the Apollo mission-simulation activities, the RTACF provided support for the simulations with the Mission Evaluation Simulator at Downey, California, and with the Full Mission Engineering Simulator at Bethpage, New York, before the RTCC program was ready to support simulations. This type of support provided both flight-crew and flight-controller practice and testing of operational procedures before normal simulation times. Such support was especially valuable in the early development phases of the Apollo Program.

The RTACF also was used to support the Emergency Mission Control Center at the NASA Goddard Space Flight Center. The RTACF programs, which were applied to a system-compatible computer at Washington, D.C., were to be used to guarantee a safe return of the spacecraft and crewmen in the event contact with the Houston MCC was lost for any reason. The programs were tested before each mission, and system incompatibilities were resolved. This mission-by-mission test was required as a result of modifications made to the systems between missions.

Confidence in the RTCC program in preparation for and during the first lunar-landing mission was probably the major contribution made by the RTACF to the Apollo Program. In addition, numerous specific computations that could be performed only in the RTACF contributed significantly to the success of the Apollo missions. The following computations were significant.

1. Earth-resources-photography-experiment support (Apollo 9)

2. Telescope-pointing data (all lunar missions)

3. Mass properties and entry aerodynamics for RTCC initialization (all missions)

4. Launch-pad-abort impact points (mandatory for all missions)

5. Onboard-navigation support (Apollo 8)

6. Passive-thermal-control attitudes (all lunar missions)

7. Pointing data for the Goldstone, California, 210-foot antenna (all lunar missions)

8. Lunar-orbit-insertion crew-chart data (all lunar missions)

9. Optimized translunar midcourse-correction targeting (Apollo 8 and 10)

10. Transearth midcourse correction (Apollo 8)

11. Entry-tracking-ship positioning (all lunar missions)

12. Solar-flare-data reduction (all lunar missions)

13. Powered-descent-abort polynomial coefficients for the lunar module onboard computer (Apollo 11)

14. Verification of all maneuvers performed (all missions)

CONCLUDING REMARKS

The Real-Time Auxiliary Computing Facility provided a level of confidence for the Apollo Program that could not have been practically achieved by any other available means. For the following reasons, consideration of the need for this type of function should be given to any future large and complex undertaking similar to the Apollo Program.

1. To be reliable, computer programs used in real time may have many constraints that will not permit long-range planning or flexibility.

2. Large programs run in real time may be too cumbersome or time consuming to be feasible or desirable.

3. Flexibility must be available to accommodate requirements that are recognized too late in the real-time-program-development activities.

4. This function provides a means of evaluating computational programs and displays before implementation in the real-time systems.

5. This function is an organized method of using available programs and analytical personnel to provide essentially unlimited real-time capability for problem resolution.

A specific organizational group should be given the responsibility for this function if sufficient resources are available. If the resources are not available, at least the overall management and the hardware and software coordination and control should be the responsibility of the group.

The necessary hardware and interfaces must be made available, depending on the complexity of the operation and the mandatory nature of the function.

The software should be assembled and built from existing analysis programs, and strict control should be exercised on input validity, program interfaces, program verification, and output formats. The same computer hardware that is used for the premission analysis should be used for the real-time function.

The assigned personnel should be thoroughly familiar with the real-time-operations procedures, operating hardware, operations personnel, program objectives, and program-planning activities. The personnel should be assigned to the task on a full-time basis.

Consideration should be given early in the development of the real-time system to the possibility or desirability of operating with this type of function. Trade-offs in resources for the different modes of operation should be studied. A well-understood, straightforward operation is most applicable to pure real-time programing; whereas, an activity that is extremely complex and not well understood and that is required to accommodate a great deal of change and flexibility is more applicable to the RTACF type of operation.

Some formal documentation should be established to keep all personnel generally informed, to keep procedures current, to establish work plans, to keep the management structure and data flow current, and to document the available software, including input and output formats.

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