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George H. Ludwig
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ABSTRACT

At the present time we are processing data from 16 scientific orbiting spacecraft at a rate of 160 tapes per day or about 150 million measurements per day. The present on-board data handling systems are now quite complex and capable. The data are being processed on the ground with second generation equipment, and third generation equipment is coming into use in some cases. Increasing amounts of real time data relay from the ground stations are being used for operations reasons. The evolutionary process toward higher data volumes and higher raw information rates from the basic sensors is continuing, as the experiments are designed to conduct more and more detailed measurements. This is necessitating a careful look at the next generation data systems which are expected to include general purpose on-board computers for pre-transmission data processing, automation of data acquisition stations, more extensive real time data relay to the control centers, and more easily usable ground facilities for providing dynamic display of the space measurements to the experimenters for more rapid analysis.

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INTRODUCTION

Since the first spacecraft, the information system capabilities have expanded greatly to meet the needs of the experimenters for more complex and discriminating measurements. The number of spacecraft launches has increased steadily, and the average experiment payload weight has also increased. In addition, the average operating lifetimes of the individual missions has steadily increased. As a result, we are now receiving a very large volume of space data.

The goal of all the data handling activities is to permit the experimenters to reach conclusions about the phenomena being measured by their instrument sensors. All on-board processing, coding, telemetry, decoding, and ground processing are intermediate steps to that goal. But, because of the distant location of the sensors and the data volume, these data handling operations pose complex technical and operational problems.

This paper attempts to indicate the present trends of the evolutionary process for information systems. The present discussion is restricted to the NASA managed and operated space sciences satellites. Department of Defense, applications (weather and communications), and deep space craft have their own interesting but unique sets of problems and are not discussed here.

The daily data volume from these GSFC space sciences satellites is summarized in Figure 1, both in terms of tapes produced by the data acquisition stations, and the number of measurements telemetered. For the purposes of this discussion, a data point is a measurement of some quantity such as voltage, current, number of pulses in a given time, etc., and is usually taken to equal 10 binary digits (bits). Even if we assume the number of launches per year to remain nearly constant, and if the average telemetered data rate per mission remains constant, we may still expect a steady increase in the daily data volume. This results from the increasing spacecraft operating lifetimes. Making the above assumptions, and assuming that the average lifetime per mission will double during the next six years, then we may expect an increase in data volume to over 500 million data points per day by 1973. Not only must we be able to handle this increased data volume in the future, but we must do it more effectively in terms of fidelity, convenience to the experimenters, and economy.

THE GENERALIZED INFORMATION SYSTEM

To define our subject, an information system is shown in generalized form in Figure 2. It consists of the experimenter's sensors and all elements necessary to transfer information (as distinguished from data) from those sensors to the experimenters in a conceptually meaningful form.[1]

The sensors convert physical qualities and quantities under investigation into electrical quantities. These electrical quantities are processed to varying degrees on the spacecraft and transmitted to the ground, where they are received and decoded. Partial processing in the real time control centers permits decisions about the future operation of the spacecraft and experiments which are implemented by transmitting commands through the command link to modify or otherwise control the sensors and spacecraft subsystems.

More complete processing in the Central Processing Facility (CPF) provides the best estimate of the original raw data entering the spacecraft encoder before noise was added in the transmission processes, and establishes the correlation of the data and time. Further processing ultimately reduces these raw data to the tabulations, charts, photographs, motion pictures, etc. which the experimenters use for final analysis. This additional data reduction occurs partially in the central facility, but mostly in the various experimenter's laboratories.

These information systems are progressing through a continuing evolutionary process. Although the remainder of this paper attempts to indicate the present trends for each of these subsystems separately, it should be remembered that the demands for better integration of the entire information system are increasing because of the increasing interrelationships between the subsystems necessary to provide greater system performance.

ON-BOARD PROCESSING

Early spacecraft employed very simple on-board systems to provide high equipment reliability and high confidence in our abilities to interpret the results after flight. As we have progressed from the early Explorers and Vanguards to the present spacecraft, the on-board processing capabilities have increased to accommodate the more complex experiments. A number of special purpose processors have been flown and are presently being built to give better telemetry bandwidth utilization and greater experiment capability, including floating point counters, auto-correlation computers, and statistical distribution computers. A number of arguments now exist for developing general purpose, in flight programmable computers for space flight to provide greater adaptability and greater capacity for data compaction and pre-transmission analysis.[2,3] These include considerations of the problems of ground processing huge volumes of data containing highly redundant and non-essential information, the capability for significantly increasing the information gathering capability, and the present state-of-the-art of computer and miniaturization technologies which make these computers possible. A number of on-board computer projects are under way, including several at the Goddard Space Flight Center (GSFC), and projects at the Electronics Research Center in Cambridge, Massachusetts, the Jet Propulsion Laboratory in Pasadena, California and the Ames Research Center, Sunnyvale, California.

The computer project underway within the Information Processing Division at the GSFC is illustrative. It employs a data bus as illustrated in Figure 3, with a variable number of memory modules (up to eight) and Central Processing Units (CPU's) (up to three) to provide a multi-mission capability. The Input/Output (I/O) provisions are also modular to adapt the basic computer to a large variety of experiments and spacecraft. The memory modules are woven, plated wire, random accessed, and true non-destructive readout. They will each provide 8,192, eighteen bit words of storage with a two microsecond cycle time. The CPU's employ a full parallel adder and parallel transfer at register and I/O interfaces. It uses automatic scaling for binary point bookkeeping and hardware multiply/divide. Add and multiply times will be about six and forty-five microseconds respectively including operand fetch. The I/O design will be customized for each application, but will have an over-all capability exceeding the requirements of any single application. It has a cycle steal capability for rapid exchange of data with memory, priority interrupt for entry of data by external control, and external request scanning for entry of data by program control. It has the capability of being used as a multi-processor and digital tape decks may be added when they become available.

With a fully reprogrammable capability it will be possible to accommodate a wide range in on-board processing, to permit use of simple programs early in the flight or at times of questionable equipment performance, and increasing in complexity as the experimenter's confidence in the equipment and in his knowledge of the phenomena being investigated increases.

The single memory module, single parallel CPU, average I/O version of this computer is expected to weigh approximately 12 pounds and have a volume of about 0.25 cubic foot. It will consume from 3 watts (idling) to 13 watts (400,000 word per second memory exchange rate). It will be ready for missions in the 1969 - 1970 era.

DATA ACQUISITION

The scientific spacecraft presently employ the Space Tracking and Data Acquisition Network (STADAN) depicted in Figure 4. This coverage is expected to remain essentially fixed during the next five years. In addition to continuous improvement of equipment performance during this period, the largest single change is expected to be in much greater automation of the stations. Figure 5 indicates the utilization of the Santiago station for 29 March 1966, assuming that all spacecraft in view of that station were operated. In actual fact, the load is leveled somewhat by scheduling, but this will not help as much in the future as the number of spacecraft to be operated increases. We have the option of either installing more links (a link is an antenna, receiver, auxiliary equipment, and recorder string necessary for acquiring data), or of utilizing our present ones more effectively. The latter option is preferred, and will be implemented by decreasing the setup time for each pass indicated by the open areas in Figure 5. By using a computer and additional control and checkout equipment we expect to decrease the setup time for each pass to a few minutes, thus providing the capability indicated by the solid areas.

Beyond the immediate five year period, it appears that orbiting data relay satellites may come into use. This concept of three satellites at synchronous height for relay of data directly from spacecraft to a few central ground terminals, with ground or satellite relay from those terminals to the control centers, looks attractive for several reasons. It will provide full time coverage at data rates higher than achievable by on-board recorders. The development of this capability will be accelerated by a full time data recovery requirement for low-altitude manned flights. In addition, the greater on-board processing capability in both the manned and unmanned flights will demand extensive near-real time processing at the control centers in order to control the progress of the experiments.

GROUND CENTRAL DATA PROCESSING

At the present time, central data processing is done within the various Operational Control Centers (OCC's) and the large scale Central Processing Facility. The data are processed and displayed in the OCC's in real time and near-real time to the extent necessary to operate and control the spacecraft and experiments. The CPF provides expanded processing capability to the OCC's during critical operating periods. Its primary role, however, is to provide pre-processed raw data to the experimenters, usually some period of time after data acquisition. The functions carried out in the CPF are illustrated in Figure 6. The tape evaluation process is completed as soon as possible after receipt of tapes to provide tape quality information for the STADAN. Then the data are converted to digital computer form in the Satellite Telemetry Automatic Reduction System (STARS). In this conversion the signals are separated from the noise as well as possible, bit, word, and frame synchronization are established, time signals recorded on the tapes at the ground stations are decoded, and both data and time are recorded on a computer tape. The rest of the processing is accomplished within general purpose computers.

In the last form (STARS Phase II) a medium scale general purpose computer interfaces directly with the signal conditioners and other hardware to provide automatic equipment setup and to provide some computer processing on the first processing run. Thus, quality and other information are available immediately upon completion of the one operation.

The major changes within the CPF expected in the immediate future are relatively minor. They involve the establishment of better tape evaluation and quality control procedures and changes to provide more convenience to the experimenters, such as merging of orbit, attitude, and data, provision of more convenient tape formats and more frequent quality information, and more dense packing of data tapes. In addition, it will be necessary to develop a high density tape archival system because of the very large number of data tapes which must be stored indefinitely.

The most important change expected by the 1972-1974 era is the move toward much more rapid processing, with the advent of real time data links from the ground stations and, later, the orbiting data relay satellites. It is expected that many of the distinctions between processing in the OCC and CPF will disappear, and that these functions will tend to become merged.

DATA REDUCTION AND DISPLAY

After the data are available in raw form the experimenters are still faced with the monumental task of reducing these data into forms from which they can reach meaningful conclusions about the phenomena being investigated. This function commonly includes reformatting, sorting, merging, accumulation, statistical analysis, and mathematical manipulation of the raw data. It includes some provision for outputting the summarized data in a readable form, such as line printer tabulations, x-y plots, motion pictures, etc. The volume of the data which must be handled, and the complexity of the programs for handling them, vary depending on the intended purpose. The purposes can generally be sorted into four major categories:

1. Data Scanning It is frequently necessary to scan all or a major fraction of the data rapidly and with relatively simple processing to select the most interesting portions for detailed analysis. Dynamic visual displays appear most promising for this operation.

2. Mapping Many experiments require the selection of data from specific and predictable regions or periods of time to provide a mapping in either space or time. In many of these cases only a portion of the data must be processed, but the processing may be relatively complex.

3. Analysis of Selected Events Detailed analysis may be performed on selected special occurrences, such as penetration of the earth's magnetospheric boundary surface, or solar storms.

4. Full Analysis Certain experiments may require full analysis of all data. This is especially true for very slowly occurring phenomena such as micrometeorites or heavy cosmic rays, where all events must be analyzed to obtain statistical significance.

At the present time these analysis programs are usually developed by the individual experimenters, with frequent parallel development of similar subroutines by different groups. To assist the experimenters in their task, several development activities are needed:

1. Basic Computer Programming Techniques for Telemetry Data Manipulation Present programming techniques such as Fortran, Cobal, etc. are rather poorly suited to the rapid development of new programs for data manipulation. New modular programming systems for data manipulation are required.

2. Subroutine Organization Subroutines (modules) for performing specific functions (e.g., scale factor correction) need to be assembled into library systems and made available to the community of users. This subroutine structure needs to be built into the program structure discussed in 1 above.

3. Better Display Techniques, Devices, and Programs and Use of these for Developing New Programs Many experimenters still obtain their data outputs as printed tabulations, and then use much manual effort to reduce them to charts, etc. Dynamic cathode ray tube (CRT) displays, motion pictures, the use of color, three dimensional displays, and others can be expected to provide a more rapid means for arriving at the desired processing programs, and a more rapid and comprehensive understanding of the phenomena being investigated.

Several efforts are underway to develop some of these techniques. The Data Reduction Laboratory (DRL), a project of the GSFC Information Processing Division, and pictured in Figure 7, will provide several operator stations with two consoles each. One alphanumeric CRT and keyboard will provide dialog communication with the central Univac 1108 computer for rapid program development. A second CRT will display alphanumeric and graphic data, in either static or dynamic form. It will be possible to add remote communication consoles later, so that experimenters may develop programs from their own laboratories. It will be possible to enter data either in real time via data link from several of the STADAN stations, or off-line from either analog or digital tapes. In addition to its capability for rapid program development, its dynamic display capability will provide operational real time or near-real time data presentation for the support of experiment and spacecraft operations, especially during critical operating periods. The basic DRL is scheduled for completion in early 1969.

Although the DRL is an attempt to begin some of the required work, a great deal of industrial support will be necessary before it will be possible to process and display data with the desired ease. An interesting analogy has been made between software and hardware development. Hardware development has evolved from circuit development by the use of basic components such as resistors, to module development from basic circuits such as integrated logic circuits, to subsystem development from basic modules (as was discussed above in connection with the on-board computer). Software development for data manipulation is still frequently done from the basic elements, machine language instructions. A rather commonly accepted average program writing rate is 10 machine language instructions per day, fully debugged.[4] Many programs use 3000 of these instructions, requiring about one man year of effort. Modules for data manipulation are needed to speed the program designers efforts.

SUMMARY

All portions of the information systems are undergoing a very active evolutionary process. Present activity is in the direction of more on-board processing, data acquisition station automation, real time or near-real data relay to the operating and data processing centers with the attendant fading of the distinction between real time and final data processing, and the development of new data processing programming and display techniques.

These efforts are necessary if we wish only to maintain our present experiment timetable in the face of increasing experiment capability and data volume. A typical timetable for a large number of the space sciences experiments presently being flown on the Explorer and Observatory missions is shown in Figure 8. Experiments are selected from two to three years before launch and data analysis often continues for five years after launch. Further acceleration of the above efforts can help to shorten this time scale. The on-board computers can be expected to shorten instrument preparation time by providing many functions by computer program rather than by hardware. Other of the activities listed above will provide the data to the experimenters more rapidly. And the computer program and display efforts will permit the more rapid development of processing programs and assimilation of data by the investigators.

The activities described in this paper are essential if we are to avoid an even larger mismatch between our capability for gathering data and our ability to process and interpret those data.

FIGURE CAPTIONS

Figure 1. Data volume from space sciences earth orbiting spacecraft. The quantities are averages for the years indicated.

Figure 2. Diagram of a general space information system.

Figure 3. Basic organization of the on-board computer being developed by the GSFC Information Processing Division.

Figure 4. The NASA Space Tracking and Data Acquisition Network

Figure 5. Data acquisition coverage of the Santiago, Chile station for a representative day, March 29, 1966. The closed areas indicate actual satellite visibility times, while the open areas indicate the present preparation and evaluation times.

Figure 6. Data flow within the GSFC Central Processing Facility of the Information Processing Division.

Figure 7. Artists drawing of the GSFC Data Reduction Laboratory. The three operator positions can be seen, as well as the (clockwise) computer interface equipment, supervisor's console, tape decks, hard copy processor, and line printer. The Laboratory is designed to interface with a Univac 1108 computer.

Figure 8. Representative experimenter's timetable for typical Explorer and Observatory missions, from the time of experiment selection to the publication of the last major papers.

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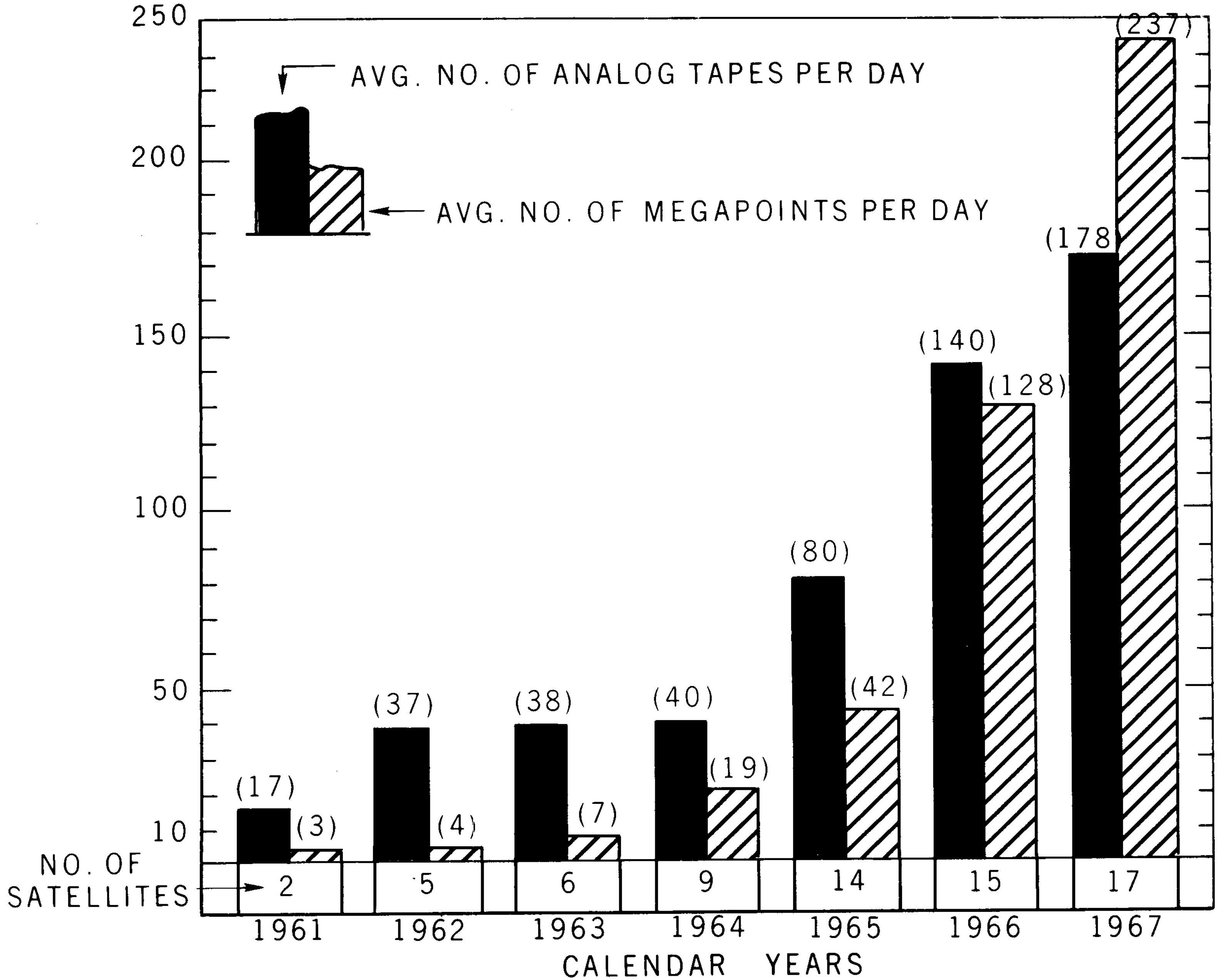

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150
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AVG. NO. OF MEGAPOINTS PER DAY
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(3)
(37)
(4)
(38)
(7)
(40)
(19)
(80)
(42)
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(237)
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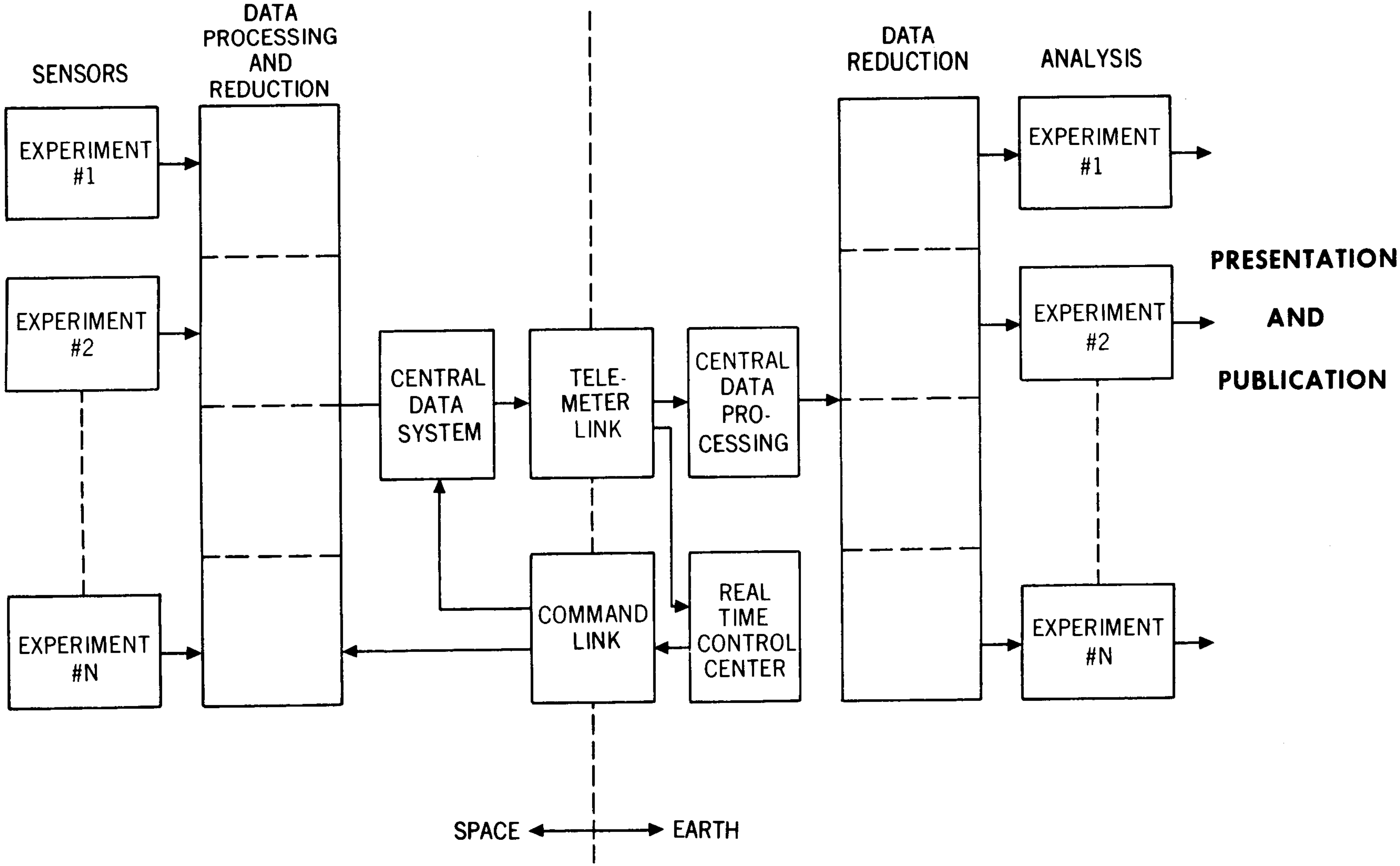
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EXPERIMENT #N
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REAL TIME CONTROL CENTER
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AND
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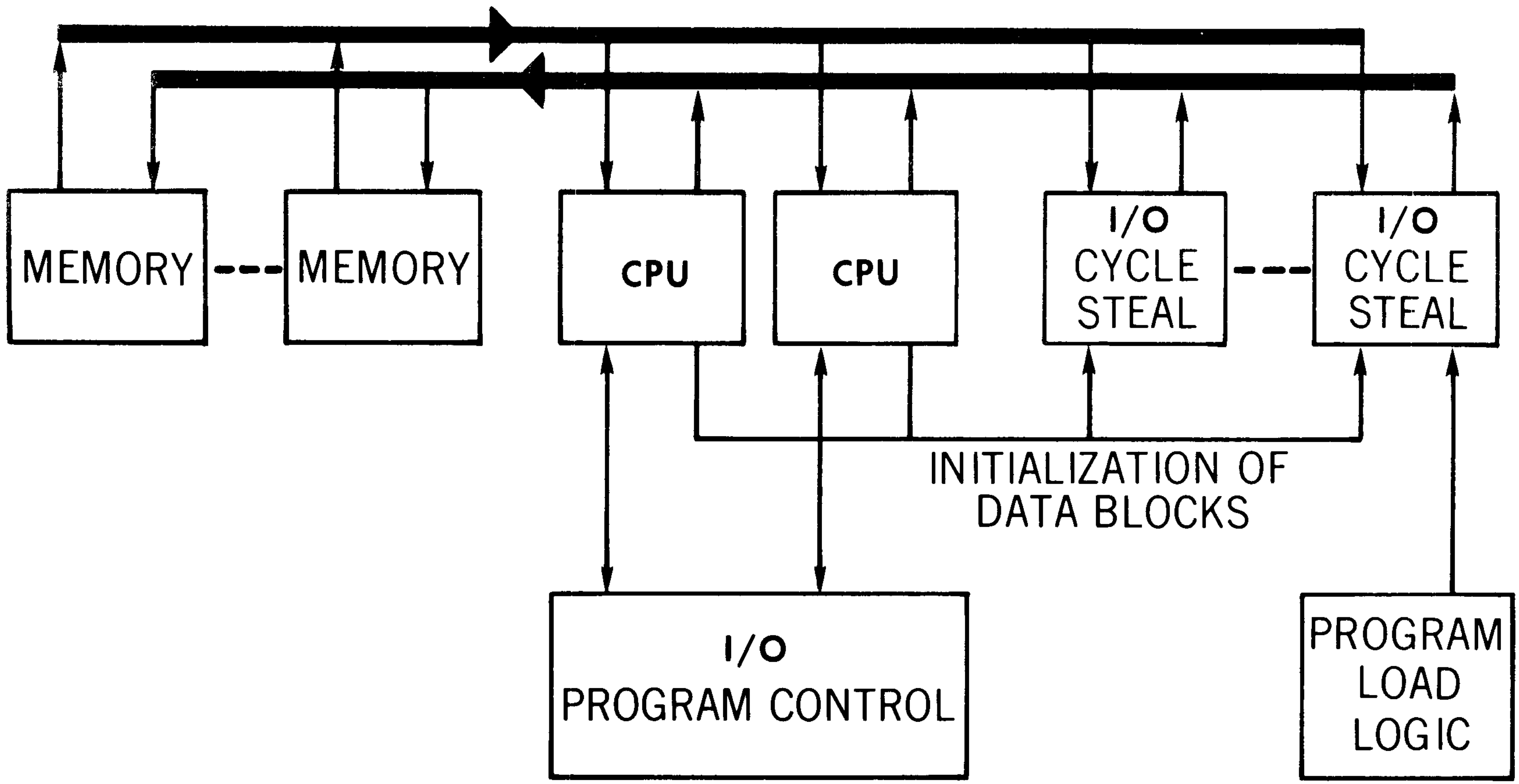
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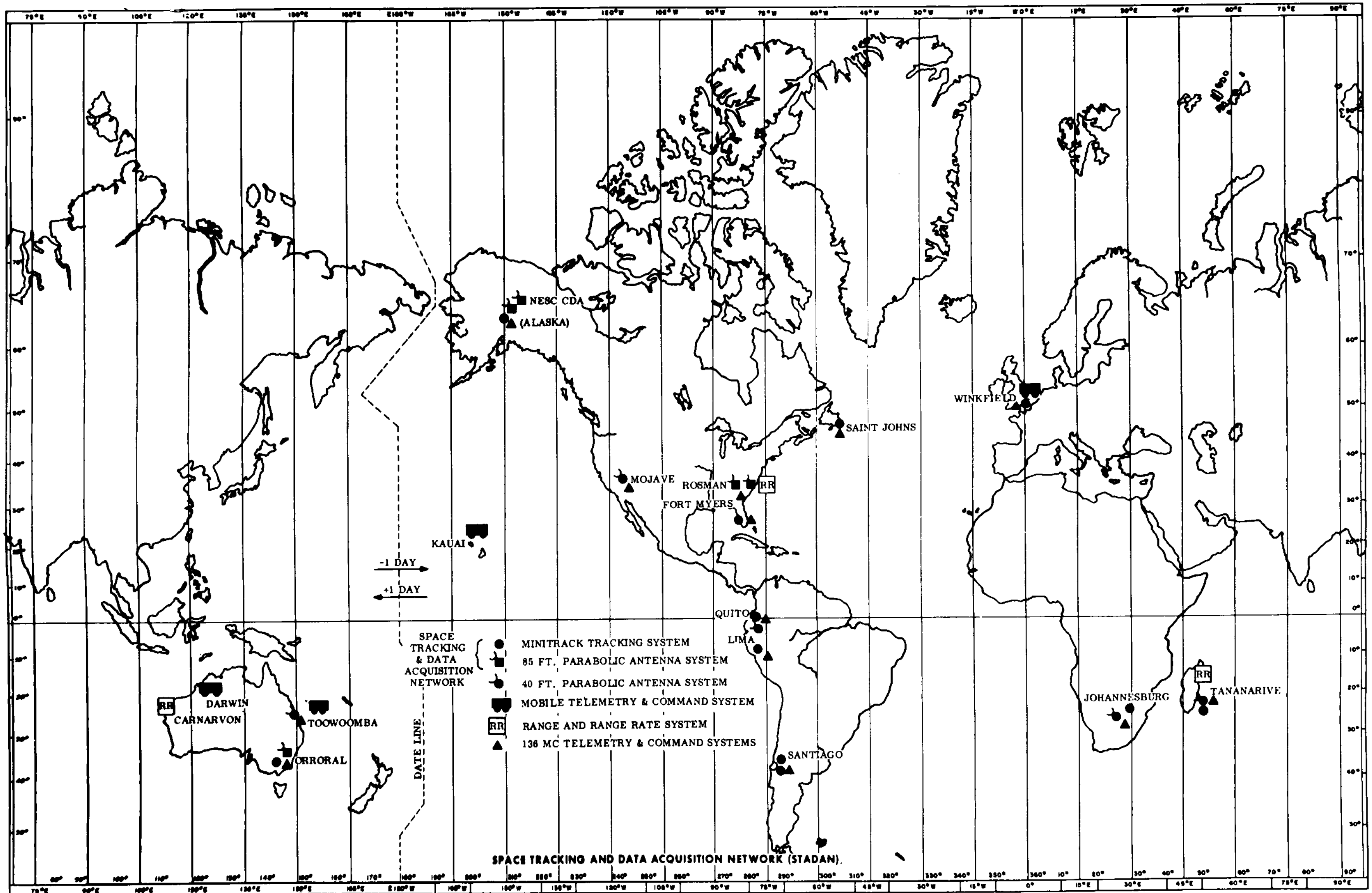
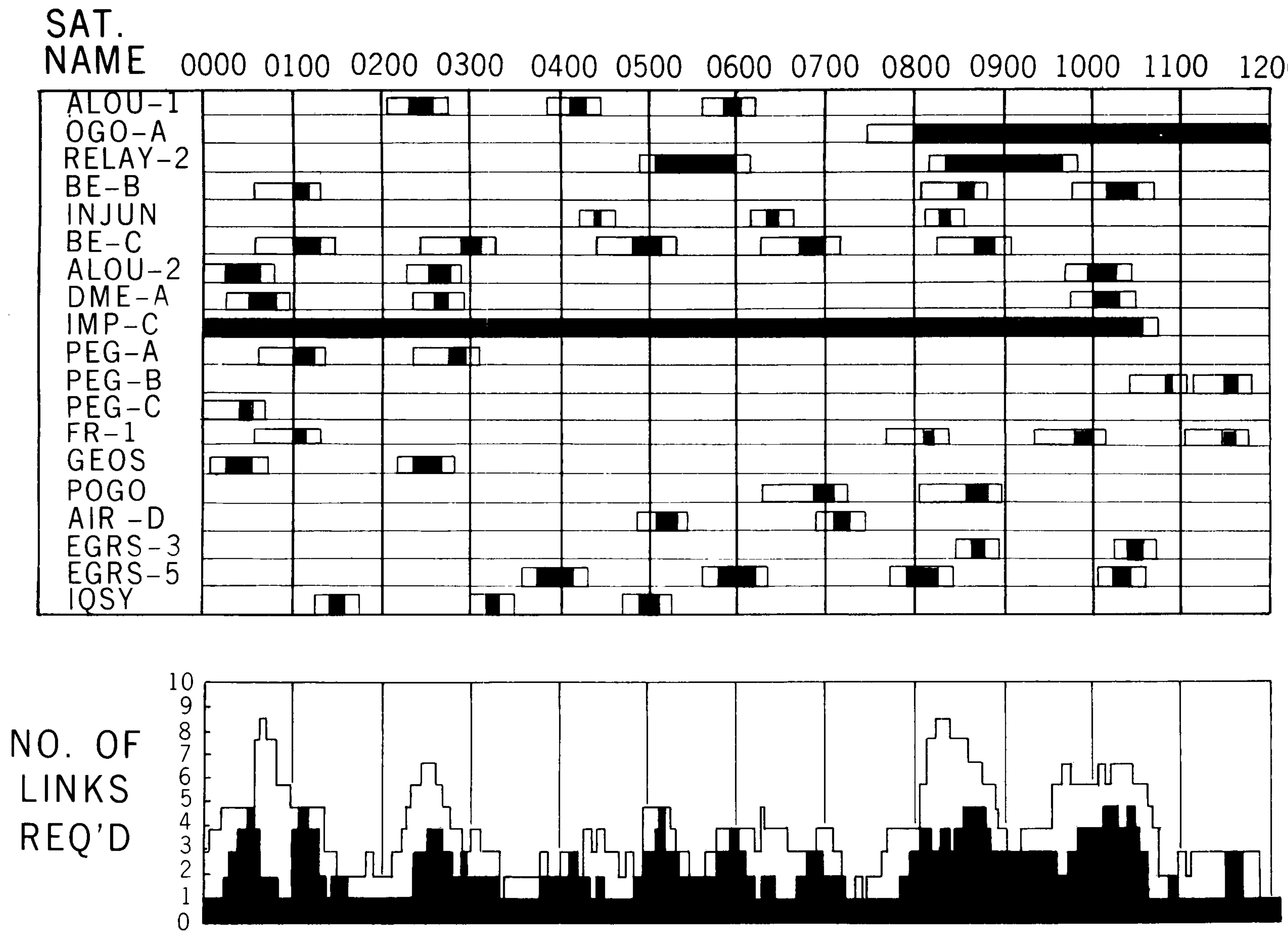


STADAN CAPABILITIES MAP

GSFC OPERATIONS SUPPORT OFFICE CODE 530 1/67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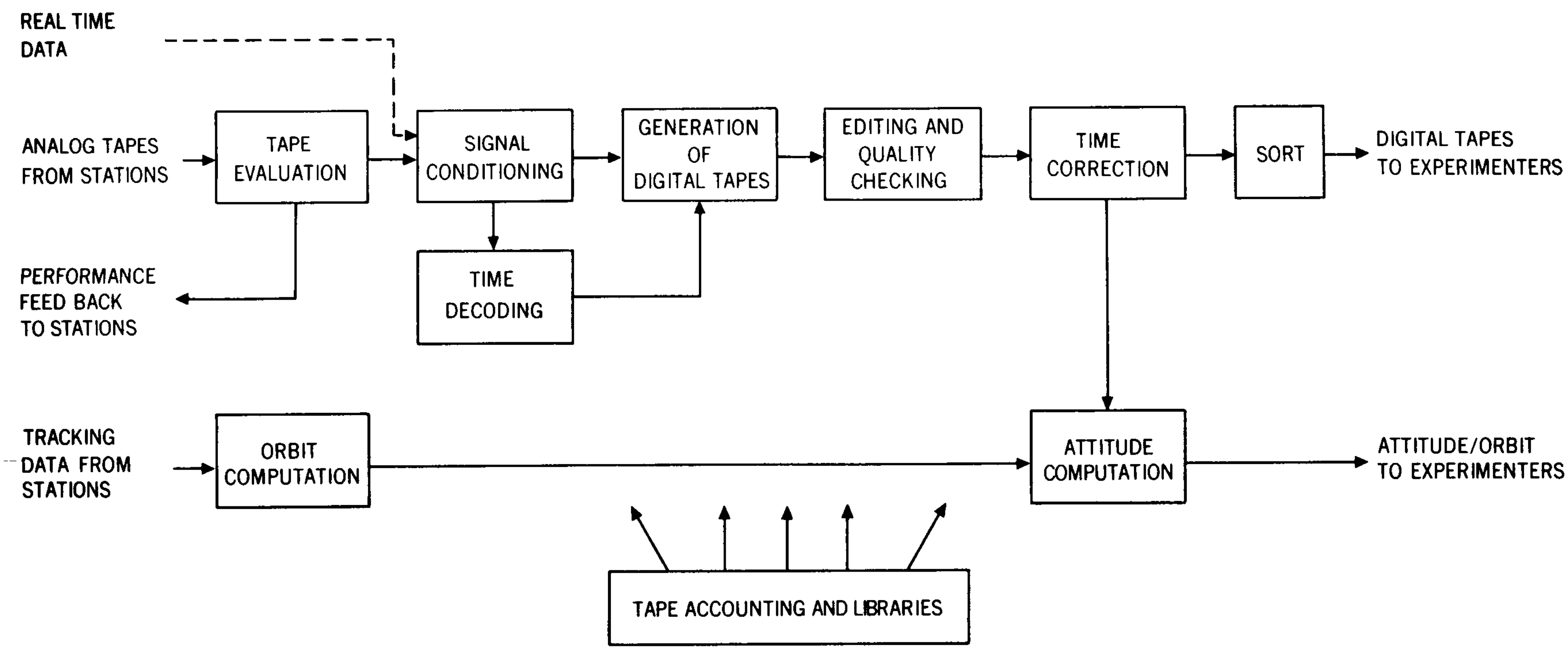
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PERFORMANCE FEED BACK TO STATIONS
SIGNAL CONDITIONING
TIME DECODING
GENERATION OF DIGITAL TAPES
EDITING AND QUALITY CHECKING
TIME CORRECTION
SORT
DIGITAL TAPES TO EXPERIMENTERS
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ORBIT COMPUTATION
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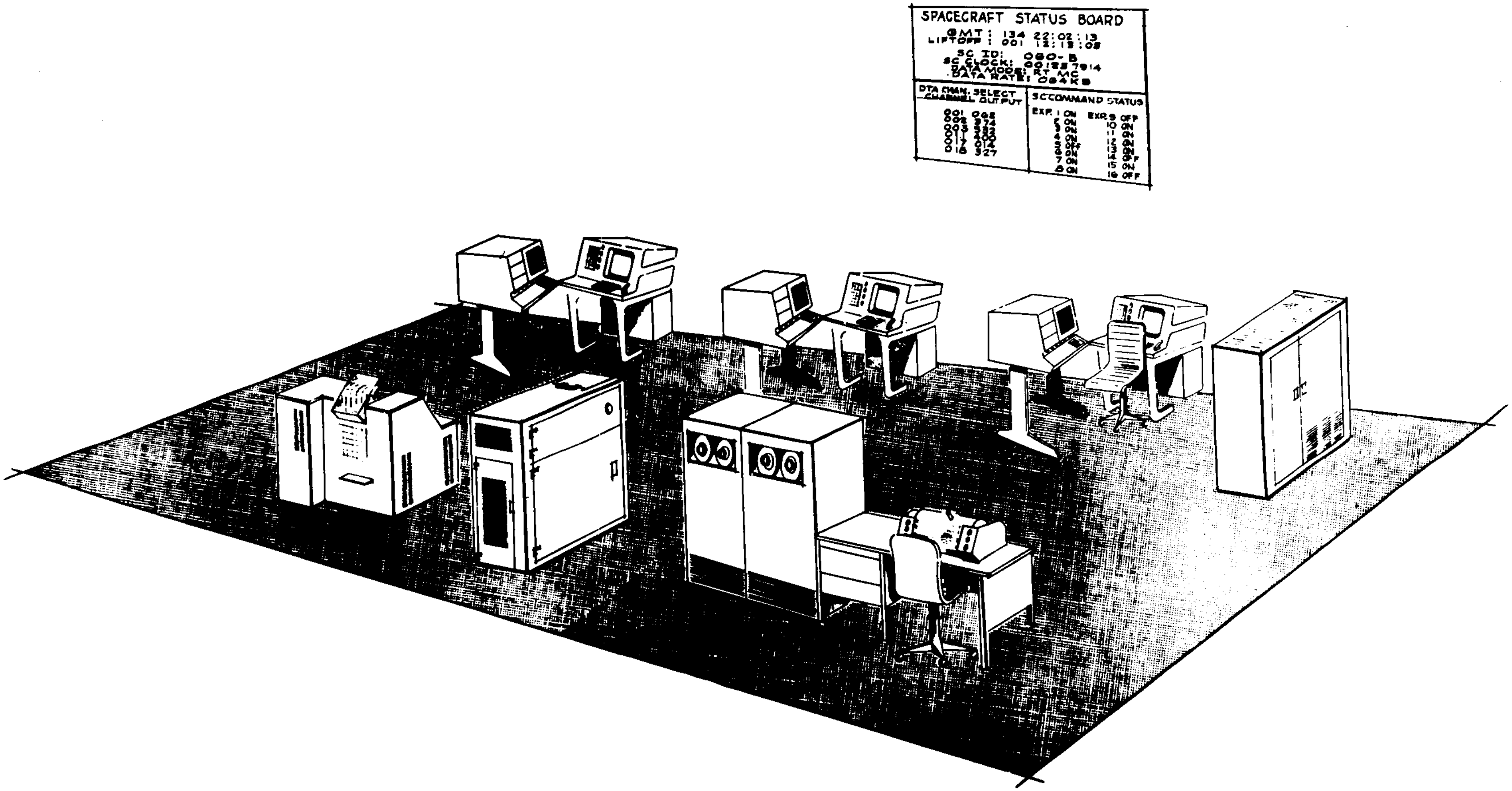
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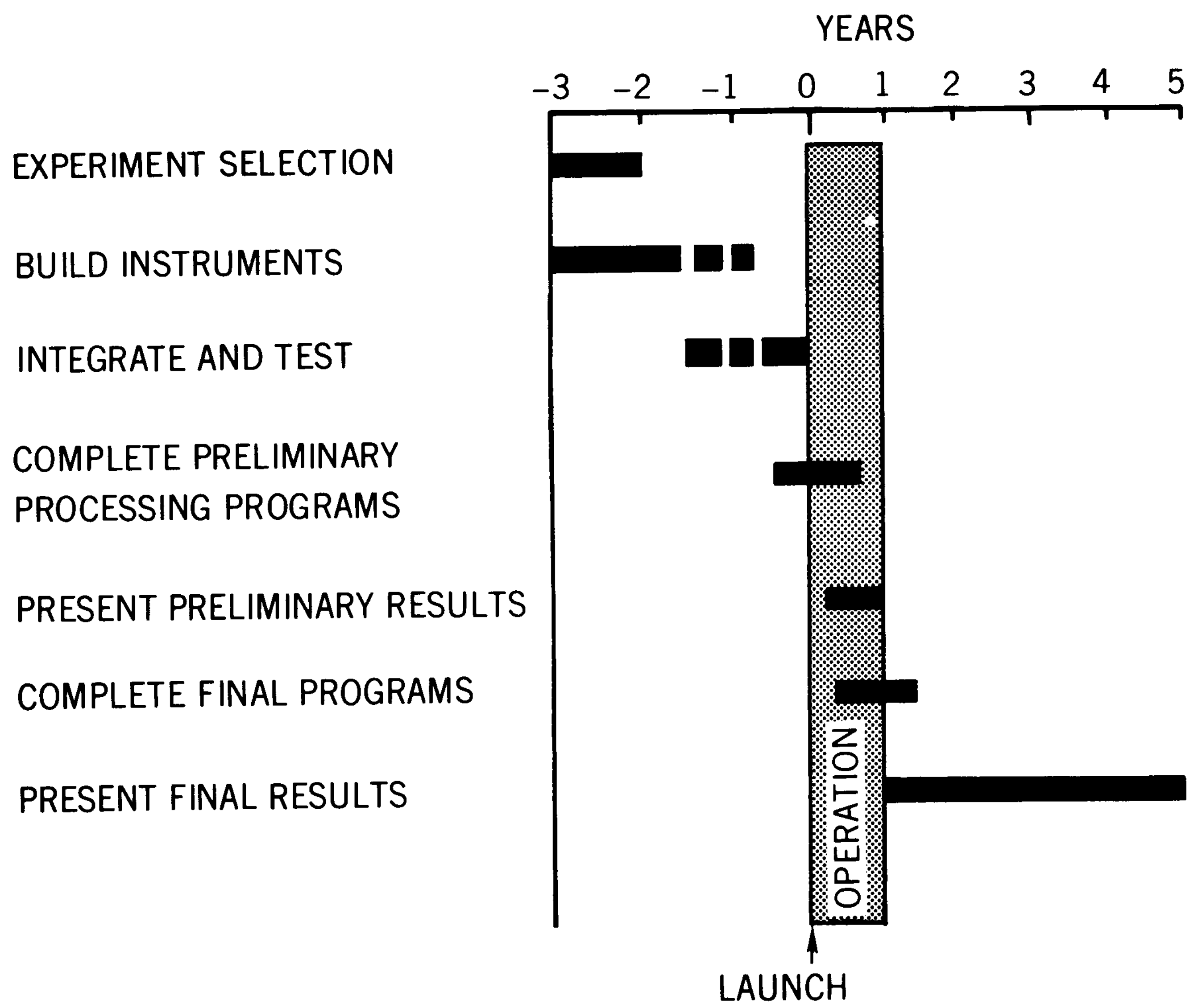
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INTEGRATE AND TEST
COMPLETE PRELIMINARY PROCESSING PROGRAMS
PRESENT PRELIMINARY RESULTS
COMPLETE FINAL PROGRAMS
PRESENT FINAL RESULTS
OPERATION
LAUNCH