AN ON-BOARD PROCESSOR FOR OAO-C

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Summary  This paper describes the design of a stored program computer for spacecraft use and its application on the fourth Orbiting Astronomical Observatory (OAO-C). The computer, referred to as OBP-2, is a medium scale, parallel machine and has a memory capacity of 16,384 words of 18 bits each. It possesses a comprehensive instruction repertoire and operates on 45 watts of power (including the DC to DC converter). The machine operates at a 667 KHz rate and executes an add instruction in 7.5 microseconds. The primary function of OBP-2 on OAO-C will be auxiliary command storage, spacecraft monitoring and malfunction reporting, data compression and status summary, and possible performance of emergency corrective action for certain anomalous situations.

Introduction  Designs of future Orbiting Astronomical Observatories indicate a requirement for one or more medium scale, stored program digital computers on the spacecraft. The concept being developed for the advanced OAO system (beyond OAO-C) is that of a centralized computer which can perform functions such as command storage, spacecraft data handling, experiment data handling, attitude stabilization and control, and on-board error diagnosis. A low power computer system, capable of being configured to fit this application, is currently being developed by the Space Electronics Branch of the Goddard Space Flight Center. As a way of qualifying the computer components and computer controlled functions for use on these future satellites, a non-redundant or simplex version of the processor will be flown on the fourth OAO spacecraft, known as OAO-C. The present OAO series was developed to house and support a variety of optical experiments with essentially a standard hardware design. As an aside, the primary experiment on OAO-C will be the Princeton Experiment Package which contains an 833 mm primary mirror and requires slewing to any attitude with a pointing accuracy of 0.1 arc second.

Guidelines for implementing the OBP-2 experiment on OAO-C are that a failure of any computer component will not adversely affect mission life and that integrating the computer to the spacecraft will not necessitate a redesign in any of the existing subsystems. Even with these restrictions, a computer spacecraft system interface has
been designed which will allow the computer to: (1) receive commands from ground
control, (2) send commands to other spacecraft subsystems, (3) receive all spacecraft
telemetry data, (4) send analog control signals to the spacecraft stabilization and control
subsystem, and (5) send information which could include its entire memory contents to
ground control. With such an interface, it is apparent that a wide variety of functions may
be performed by the on-board computer.

The exact details of the tasks to be executed will be defined by project management,
spacecraft engineers, and control center operators. It is pointed out that the computer will
not have access to experiment data since the necessary interface would impact the
existing hardware and therefore violate an implementation ground rule.

**General Description of OBP** Although the OBP will be initially applied to the OAO
series of spacecraft, the computer was designed to have features which would fulfill the
requirements of a variety of future scientific satellites. The system is modular and
consists, in a minimum configuration, of one central processor unit (CPU), two 4096
word memory units, and one input/output (I/O) unit. Figure 1 shows how these units are
connected to a common and redundant data and address bus, with the minimum system
shown in solid line. Several unpowered spare functional modules, shown in dotted line,
can be attached to the bus to extend the life of the system. As previously mentioned, the
specific application presented here is a simplex system, and the modular approach to
redundancy will not be used.

**Central Processor Unit** The central processor, which performs the execution of all
instructions, employs a fully parallel adder and parallel data transfers between registers
and at the data bus interface. Data words and instructions are 18 bits in length with
negative numbers being represented in two’s complement form. Addressable hardware
registers include an index register, an accumulator, an extension of the accumulator, a
4-bit memory page register, a storage limit register which specifies read-only sections of
memory, and a 6-bit scale register which represents the location of the binary point in
fixed point data words.

Instructions are formatted such that 5 bits specify the operation code, 1 bit specifies the
index function, and the remaining 12 bits specify memory address. There are 50
instructions in the repertoire, 30 of which require an operand fetch. The other 20
instructions have a minor operation code in the address field of the instruction word.
With 12 bits of address available, 4096 memory words are directly addressable. Memory
size as large as 65,536 words requires a 4-bit page register which can be loaded and
stored under program control and which is appended as the four high-order bits to the
12-bit address field to form a full 16-bit address. If the index bit is set, the low order 16
bits of the index register are added to the address to form an effective address. A memory
size of 16,384 words is implemented for the OAO-C application; therefore, the low order
14 bits form an effective address in this case. All transfers are indirect, whereas all operand fetches are direct.

A storage limit register is employed to avoid undesirable interaction between independent user programs which may be time sharing the computer operation. This register reserves a block of memory in which the operating program may write. These blocks are in increments of 128 words. To provide this feature, the 18-bit register is partitioned into two 9-bit fields. The two fields represent the upper and lower limits on the nine most significant bits of the effective address for write operations. Any attempt to write in an area outside these limits will cause an interrupt to the master or executive program.

The CPU is comprised of 1100 low-power, DTL microcircuits, occupies a volume of 250 cubic inches, and consumes 5 watts. It operates at a clock rate of 667 KHz and executes an add instruction in 7.5 microseconds. Execution times of multiply and divide instructions are data dependent and average 50 and 100 microseconds respectively. Detailed logic design of the CPU was performed by the Aerospace Division of Westinghouse Electric Company in Baltimore, Maryland.

**Memory** Each memory module has a capacity of 4096 18-bit words and uses conventional destructive read-out (DRO) core as the storage element. The random access memory is produced by Electronic Memories and was designed specifically for use in space environments. The most significant feature of the device is that it is capable of being completely power switched on a cycle by cycle basis and consumes less than 150 milliwatts of power in the standby mode. With this feature, several memory modules may be implemented and randomly addressed without paying the price of a large power overhead. Total memory power requirement, therefore, is not a function of capacity but is proportional to usage. For the OBP-2 system on OAO-C, this requirement has been calculated to be approximately 18 watts. Other interesting features of the memory are that it has an access time of 850 nanoseconds and a full cycle time capability of 2 microseconds. Each unit occupies a volume of 128 cubic inches and weighs 6 pounds. For this OAO-C application, the computer will have 4 memory modules for a total capacity of 16,384 words.

**Input/Output** The I/O unit serves to control the flow of information between the OBP memory and the spacecraft subsystems. One important design feature of the I/O is that it has no direct data connection with the CPU. All data flow between the two units must pass through memory by way of the memory data bus. This serves to minimize the number of connections required between modules and allows the easy interconnection of spare CPU, I/O and memory modules. Also, by use of “cycle-steal” channels, the I/O is designed to operate completely independently of the CPU and any portion of memory can be loaded or dumped even though the CPU is either unpowered or executing a
program. This design philosophy of independently functioning modules is required for the spare module concept of redundancy to work properly.

In general, the I/O unit is organized to efficiently accommodate a wide variety of data rates and channel characteristics. Major components of the I/O are the multi-level priority interrupt system which may be altered under program control and two cycle-steal channels which can be time shared to operate with a number of data channels. This interrupt and cycle-steal capability allows efficient computer operation in the real time application.

For convenience, the I/O package also houses the system clock and the data bus controller which queues requests for memory activity and synchronizes traffic to and from memory. The I/O contains approximately 1000 low power, DTL microcircuits and several discrete circuits for logic level conversion at the interface. The unit occupies a volume of 250 cubic inches and consumes 5 watts. Logic design and fabrication of the I/O unit was performed by the Space Electronics Branch of Goddard Space Flight Center.

**OBP-2 Interface with OAO-C**  Figure 2 shows the specific data interfaces between the various spacecraft subsystems and the computer. Before discussing these interfaces, a brief description of the applicable OAO subsystems is presented.

The Command Receiver receives commands transmitted from the ground at a 1042 bits per second rate. These commands are regenerated and fed with a clock and command presence control signal to the Primary Processor and Data Storage (PPDS). This unit is a special purpose processor which decodes, verifies, and executes the commands. It has the capacity to store 256 commands for delayed execution. The PPDS also serves as the source of all timing signals. The Spacecraft Data Handling Equipment receives analog and discrete data from all spacecraft subsystems. This data is properly converted and formatted into a 1690 bit telemetry frame which operates at a 1042 bits per second rate. All data is then stored on a tape recorder and is later played back on command during passes over selected ground stations. Playback rate is sped up by a factor of 64 to 1.

The Fine Wheel and Jet Control subsystem is apart of the analog stabilization and control system. Normal inputs to this unit, which provides the momentum for spacecraft rotation about three axes, are analog error signals from a star tracker signal processor and an inertial reference unit. There are four gimbaled star trackers on OAO-C which will provide the data for accurate attitude determination. The Power Control Unit serves to control the duty cycle of the spacecraft power regulator and consequently establishes the solar array operating point. The desire here is to operate at a point on the solar array voltage-current curve which allows maximum power utilization by spacecraft loads and battery charging equipment.
With this background, the computer/OAO-C subsystem interfaces can now be discussed. As shown in Figure 2, inputs to the computer are commands from the PPDS and spacecraft data from the Spacecraft Data Handling Equipment. Outputs are commands to the PPDS, 30 bits per telemetry frame to the Spacecraft Data Handling Equipment, memory dumps at 50K bits per second to wideband telemetry, three analog lines to the Fine Wheels and Jet Control, and a single analog voltage to the Power Control Unit.

**Command Output**  In more detail, OBP-2 sends commands to the PPDS by simulating the command receiver and outputting the 1042 bits per second command message, clock, and the command presence control signal. With this connection, which is made through a set of relay contacts, the computer can send commands to all spacecraft subsystems and experiments. Those commands which are generated are dependent upon the computer program and there will, of course, be certain commands which will not be allowed in the computer command table. This interface does, however, afford a very powerful capability to a spacecraft controller. As a safety feature, ground control override of this connection is provided by a circuit which causes the relay to assume the de-energized state which disconnects the computer when a command is received from the ground. Redundancy is implemented in this instance to assure a high degree of reliability in the override function.

**Command Input**  The PPDS sends commands to OBP-2 in a serial 32 bit format that can include four different command categories which must be identified. First, there are commands to the computer hardware which either establishes a cycle-steal channel to control a program load, or enables or disables computer operation. Second, there are commands which contain the computer program and, in this case, 18 bits of each command word are written directly into memory. Programs will normally be loaded prior to launch; however, this capability facilitates the reprogrammable feature which could be used in the event a need exists for the computer to do work other than anticipated at launch around certain subsystem failures. The third category is commands which are interpreted by the computer operating program, and can therefore have a variety of definitions. The last category contains commands for other OAO subsystems which are to be temporarily stored by the computer and transferred back to the PPDS at some later time. This function is referred to as an auxiliary command memory and as presently planned, expands the storage capacity from 256 to 1380 commands. This increase in capacity will serve to reduce the required frequency of command loads from 4 or 5 per day to 1 per day which, in turn, means the loads can be transmitted from one ground station instead of several. For this auxiliary command memory function, 4096 locations of OBP-2 memory are required to store the 1024 additional OAO commands. For operation, the 1024 commands are divided into 8 sets, or pages, of 128 commands each, and are transferred from the computer to the PPDS one page at a time. Each transfer of 128 commands is initiated by a command from the PPDS to the computer program (i.e. a category three type command).
Spacecraft Data Input  The 1042 bits per second spacecraft data input provides computer programs with data relating to: (1) thermal conditions of all subsystems, (2) charge and discharge rates of power subsystem, (3) day and night voltages of power subsystem, (4) commanded star tracker gimbal angles, (5) gimbal angle errors, (6) spacecraft aspect from sun sensors, (7) rate information from inertial reference unit, (8) course and fine momentum wheel rates, (9) jet gas usage, (10) magnetometer outputs, and (11) the status of many discrete functions. Some of the possible applications of these data are discussed below.

OBP-2 Status Words to SDHE  The computer outputs a 30-bit status word to telemetry each 1.6 second frame. These bits will be defined in a variety of ways.

One type of message will consist of compressed sensor data. For some sensors, for example, OBP-2 may compute and telemeter the high, low, mean, and standard deviation values for the preceding orbit. For other sensors, data may be telemetered only if their values exceed some predefined limit.

A second type of message will contain predefined information which will verify proper operation of the computer itself. This is accomplished by a special purpose exercise program which will be executed once each telemetry frame.

Memory Dump  For OBP memory dumps, up to 4096 word blocks may be transmitted to ground at a 50K bits per second rate. This output is a 32 bit format, made up of a leading logic 1, 18 bits of data, 12 bits of address, and a parity bit. These data dumps are achieved by the cycle-steal mode of operation and can be initiated by computer program or directly from ground command. This high frequency data link will be used to verify both computer program loads and auxiliary command loads. Another use will be to transmit summary messages which relate to status and usage of various spacecraft subsystems during the previous orbit. For the first time, control center equipment can display historical data almost immediately after acquisition of the spacecraft by a ground station. This is of particular interest to a spacecraft operator in situations where action must be taken to correct an abnormal condition onboard.

Analog Outputs to the Fine Wheel and Jet Control  Outputs of three, 6-bit, digital-to-analog converters are connected through relay contacts to the fine momentum wheels. In this way, the computer can control spacecraft rotation about the roll, pitch, and yaw axes. For safety, the connection of these analog signals can be opened or closed by ground command. Although normal spacecraft operation will not require this interface, the computer may be called on to control spacecraft attitude in event of certain equipment failures in the stabilization and control subsystem.
Analog Output to the Power Control Unit  The output of a single, 6 bit, digital-to-analog converter is connected through a relay to the power control unit. With this connection the computer can control the power regulator duty cycle and thereby influence the operating point on the solar array voltage-current characteristic curve. By considering factors such as sun angle and solar cell temperature, the computer can match load to source at its maximum power capability. This interface may be enabled or disabled by ground command.

OBP-2 Functions  One of the most important functions of OBP-2 on OAO-C is that of auxiliary command memory which was discussed in the previous section. Other of the more significant functional modes which are likely to be implemented on future OAO spacecraft and which can be demonstrated with the hardware available on OAO-C are presented in this section.

Even though their implementation is possible, many of the functions shown here probably will not be included as part of the normal operating program since the computer memory capacity is limited. Trade off studies which consider function values and memory requirements are not yet complete. This is a continuing process and even after launch a function may be redefined. This flexibility, in fact, is one of the more important features provided by the computer system. These functions are divided into four major categories: (1) monitor and malfunction detection, (2) emergency action, (3) data compression and status summary, and (4) “workarounds” for failure modes of other spacecraft hardware.

Monitor and Malfunction Detection  This function consists of the OBP acting as a ground station when the spacecraft is not in contact with a station. In one case, it monitors the commands issued by the PPDS and the response of the stabilization and control components and detects possible malfunctions. Among the malfunctions the computer may be programmed to detect are: failure of the PPDS stored command timing, failure of jets to unload wheel momentum, failure of momentum wheel operation, excessive drift of inertial reference unit, star tracker tracking stray light, star tracker losing good star targets, and the sun moving into the experiment’s field of view. In a second case, the computer can monitor spacecraft and experiment equipment temperatures and compare them with maximum limits of dynamic models. Excessive or unexpected measurements can be detected. Finally, the computer can perform energy “bookkeeping” to sense battery rundown or detect failure in other prime electric power system hardware.

Emergency Action  These functions would be actions taken in response to diagnosed malfunctions which, if left uncompensated for a short period of time, could cause mission failure. The general purpose of these functions is to put the spacecraft into a safe
status until ground control can develop a workaround mode. One example of desirable emergency action is for OBP-2 to fire appropriate jets to reorient the spacecraft if the sun is detected moving into the Princeton experiment field of view, since direct sunlight can cause permanent damage to optical sensors in the experiment.

Emergency action should also be taken if the temperature of any subsystem is detected as exceeding a maximum limit. Here, equipment and/or heaters could be commanded off. In case of overheating of experiment optical structures, the spacecraft could be reoriented.

In the case of abnormal battery discharge, the computer could command equipment shutdown and/or spacecraft reorientation to the sunbathing attitude.

Another form of emergency action should be taken if OBP-2 detects that the spacecraft has lost stabilization. For this instance, the computer could perform an initial stabilization mode with jets and momentum wheels by using digital sun sensor and inertial reference unit data.

**Data Compression and Status Summary**  
OBP-2 can assemble special telemetry messages giving a rapid time history of spacecraft system status during the previous orbit. Changes in status would be reported early in a contact so controllers can obtain a “snap-shot” of spacecraft conditions. The malfunctions, if any, would be reported as a part of this quick picture and the emergency action taken, if any, would be indicated. This functions would also report on any telemetry which had exceeded specified limits. Also forming a part of this status summary is a long list of messages relating to data compression performed by the computer for all subsystems, particularly the power subsystem. A very small sample of this list include: number of commands received, number of jet firings, average wheel speed, IRU drift, jitter in the control system, average temperature of equipment bays, end of night voltage, end of day current, battery charge/discharge, solar array capability, etc. In all likelihood, this list will be limited in size by the amount of memory available.

**Failure Mode Workaround**  
There are a large number of failure modes which would leave the spacecraft ineffective if a computer were not on board to substitute an equivalent function. Since failure modes cannot be predicted, the routines required to provide a workaround capability will not be a part of any standard operating program. In fact, any given workaround function can be presently defined only in very general terms. Actual program assembly would not take place until after a failure had occurred and had been thoroughly diagnosed. This backup capability is considered significant, however, since it could have a large and positive impact on the life of the mission.
Conclusion  Although OBP-2 is being flown on OAO-C as an experiment and the actual interface is somewhat limited, one can realize how the computer can make a positive impact on the OAO-C mission. Through auxiliary command memory, 1024 additional spacecraft commands can be executed in the delay mode. Through malfunction detection, emergency action, and failure mode workaround, spacecraft life may be extended. Finally, through status summaries, mission controllers can obtain compressed reports of present spacecraft conditions and a history of spacecraft conditions during the previous orbit.

This application of OBP-2 illustrates a powerful centralized computer performing a variety of functions on a time shared basis. Since it is this same approach to system organization which is being considered for future OAO spacecraft, the overall hardware/software system philosophy will be tested on OAO-C. This centralized computer concept is being applied in contrast to the distributed approach of providing a smaller computer for every function. The reasoning here is that a system with a given overall reliability can be implemented more economically with one machine than with several. This logic is coupled with the belief that a failure of any one function, such as command handling or stabilization and control, will be just as catastrophic to the mission as a failure of all functions.

References


Figure 1 - On-Board Processor, Functional Block Diagram.

Figure 2 - OBP-2 Interface With OAO-C Subsystems.