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MICROPROCESSORS IN SPACE INSTRUMENTATION

by

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Microprocessors in space instrumentation

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Abstract

The current level of integration of microprocessors with space instrumentation is reviewed. Their inclusion provides the benefits of improved measurement resolution, improved reliability, a more efficient use of limited spacecraft resources, and further provides control for the latest complex instruments. In the past microprocessors were limited to just controlling instruments and simple buffering of the data produced for the spacecraft telemetry system. Already microprocessors are being relied on to perform mission critical calculations while future uses involve increased on-board intelligence and even on-board expert systems.

1) Introduction

Space instrumentation is continuously evolving with the latest generation of instrumentation types ever more complex than the last. However the amounts of spacecraft provided utilities available to support instruments has not significantly increased.

For example each of the four European Space Agency (ESA) Cluster spacecraft(1) due for launch in 1993/4 as the first ESA 'Horizon 2000' cornerstone mission will have similar payload mass and power to the ESA GEOS satellites(2) launched sixteen years earlier in 1977 & 1978. Both of these missions are concerned with magnetospheric and space plasma studies and the scientific aims and range of scientific measurements, and thus the number and types of instruments supported, make them very similar. However the Cluster experiment telemetry allocation will be only 17kbps while GEOS experiments had 98kbps and yet the aim of the Cluster mission is to study phenomena in greater detail than ever before.

If experimenters are to develop new instrumentation designs for more efficient and effective measurements but remain within these limiting constraints almost all electronic circuits must be highly integrated, with as much as possible implimentated in CMOS for low mass and low power. The use of CMOS microprocessors becomes mandatory. Requirements for electromagnetic compatibility (EMC) also usually dictate CMOS technology. Often the sensor head of the instrument cannot be shrunk in size but must be physically large for high geometric factor considerations (e.g. in particle detectors and astronomy telescopes). In these cases mass savings can only be achieved in the experiment processing electronic circuits.

Some space missions require microprocessors to make critical decisions on-board the spacecraft. For example the recent ESA Giotto encounter with Comet Halley (3) lasted about 20 minutes, of the same order as the return radio propagation time to earth and so autonomous functions were required.

In the sections below the application of microprocessors to space instrumentation will be reviewed for their use in control, on-board data handling, on-board intelligence, and on-board expert systems. Particular reference is made to spacecraft used by european research groups in one research field, space plasma studies, but the discussions are equally relevant to other types of space instrumentation.

Traditionally advances in spacecraft hardware have lagged behind equivalent applications of microprocessors to ground-based instruments. There are two reasons for this: (i) there is a the long delay between product availability in commercial components and availability of the high reliability component versions required for space instrumentation ; and (ii) there is a long lead time between design freeze and spacecraft launch.

2) General Instrument

A space instrument has the general form illustrated in figure 1. A sensor head accumulates data on the phenomenum of interest in a given range of measurement parameters. The sensor can be in one of a variety of forms: particle spectrometer, wave analyser, magnetometer, telescope, radiometer, camera e.t.c. An associated electronics package, sometimes variously termed a Dedicated Processor Unit, Digital Processing Unit, or Data Processing Unit (DPU), has the dual task of (a)controlling the measurement parameter range and (b)preprocessing the data. DPU activity is commanded via the uplinked telecommands from the ground station either instantaneously or via time-tagged commands previously uplinked and stored in a central spacecraft computer(4). Processed data and housekeeping data from the DPU are input to the spacecraft telemetry system and downlinked to the ground station. Data are usually digital with all analogue to digital conversion occurring at or near the sensor head.

The ground data handling system is a dedicated computer of mini-computer size that stores the data and performs simple real-time algorithms on it. Data are checked for transmission errors, instrument malfunction, and general instrument health. Some simple scientific parameters are also calculated in real-time but detailed data analysis is usually done at a later date on the minicomputers and main frame computers at the various research institutes involved.

The importance of the role of the DPU can only be assessed in the wider context of the overall instrument to experimenter system illustrated in figure 2. The DPU is only one part of the man-machine loop.

The future trend is for an upstream movement of the location of processing activities. For example, in real-time operations the ground station computer has to produce high quality 'quick look' data (a duty previously associated with the institutes' computers) to enable experimenters to optimise instrument operation(2,5). Data from several dissimilar instruments needs to be displayed with the same timescale on a common display(5). Similarly the calculation of some scientific parameters and instrument/data checking (duties previously associated with the ground computers) are being performed by the on-board DPU. In the future extension of these trends it will become commonplace for instruments to be controlled by on-board intelligence using the data gathered to make the decisions. The ESA Giotto(6) and USSR VEGA(7) missions have already incorporated similar techniques to acquire the images of comet Halley (see below).

3) Instrument control

Microprocessors are used in instrument control to (a) simplify the operation of a complex instrument, (b) to maximise the amount of time spent taking meaningful measurements (i.e. optimise detection efficiency), and (c) to maintain sensible instrument operation when 'out of sight' of the ground station. They also allow for flexibilty and effect a saving in the use of logic circuits.

Present instruments often take measurements simultaneously in three, four or more dimensions of scientific measurement parameter space. For example ion spectrometers(8) are required to determine, for each ion detected, the energy, mass, charge, and pitch angle (direction of travel with respect to the earth's magnetic field) of the ion, and to further sort ion detections as a function of time. Detection efficiency is vastly improved if the instrument can be controlled to scan only those ion species (mass & charge) to be expected in the space environment. In this example the DPU would need to know where each ion species is to be found in instrument parameter space (e.g. voltages on deflecting plates). Note that the DPU has to transpose between scientific parameter space and instrument parameter space. This transposition algorithm needs regular updating to account for drifts of calibration with instrument ageing or temperature, e.t.c. This algorithm may ~~either~~ be stored in a simple look-up table.

Most instruments have typically several operating modes. Some have vast numbers potentialy available. Usually these modes are to provide a choice of different trade-offs between parameter resolutions. The most common choice being between coarse measured parameter resolution at good time resolution, and fine parameter resolution at poor time resolution. In order to set an instrument into a particular mode many instrument operation values have to be changed. A DPU can use command look-up tables to simplify mode changes to require the receipt of only a single telecommand from the ground. In pre-microprocessor days when each value to be changed required a separate telecommand, the GEOS satellites (2) needed typically 1000 telecommands per hour when operated in real-time. Error checking and resending of failed commands placed a high overhead on the ground system and often resulted in instruments operating for short periods in non relevant 'illegal' modes.

The nature of geophysical phenomena is such that studies of them may be enhanced by using different combinations of instrument resolutions, i.e. different modes. It is a simple task for a microprocessor to regularly switch instrument modes for optimum phenomena coverage.

Once in orbit the experimenters soon acquire the knowledge of where in geophysical space and where in instrument parameter space phenomena are located. It is usually found that studies are improved at one part of the orbit if more resolving power is applied to one part of the sweep of a swept (or stepped) instrument parameter, e.g. electron or ion energy(9,10) or wave frequency(11,12). If the corresponding instrument parameter (e.g. voltage) is directly generated by the DPU (via a digital to analogue convertor) then a microprocessor offers much flexibility in redesigning, after launch, these sweep shapes to best study the phenomena of interest.

When a spacecraft is out of sight of the main ground station or when the station has to service other spacecraft instrument data can still be collected by either tape recording on-board for later dumping to ground(1) or by reception via a passive ground station. During this unattended period the DPU can continuously monitor the health of the experiment and if necessary re-initialise the experiment. Similarly the correct operation of the DPU ,free of software hang-up, can be maintained by regular hardware timer initiated resets or interrupts.

If the experiment has been previously switched off, it is usual to initiate a strict turn-on sequence of operations and instrument health checks. The incorporation of this sequence into the DPU as an automatic self checking switch-on routine saves valuable observing time, especially if the instruments were earlier turned off to conserve power when power is limited(4). It is normal to have the instrument left in a general purpose mode at the end of this sequence, this then covers the possibility that the telecommand facility malfunctions.

4) On-board Data Processing

The DPU provides on-board data processing for (a) data buffering to the telemetry, (b) data compaction and compression, and (c) sometimes for datailed calculations on the data.

The main on-board data processing application of the DPU is to buffer the instrument data output for acceptance by the spacecraft telemetry system. Often this operates effectively as a simple first in first out buffer to account for the difference between times of data availability from the instrument and the times required for data input to the telemetry (dependant on the position of the data words allocated to the instrument in the overall repeating frame of words from all data sources). Data sampling and processing tasks(13) can be synchronised to the telemetry word frame to ensure that data is available when needed.

Most spacecraft operate on one of a variety of telemetry data rates. The DPU, besides putting the instrument into the most relevant mode, can further average data to optimise time resolution at a given data rate.

Future spacecraft will use packet telemetry where instruments provide data in labelled packets to the spacecraft central data computer, much like other inter-computer networks. The DPU microprocessor is ideal for this type of buffering. Since a packet can correspond to a parameter sweep, (e.g. one wave frequency spectrum or one electron energy spectrum) data is better handled in this way with the label, including other related instrument values.

The DPU also has the possibility of compacting data for more efficient use of the available telemetry. Telemetry systems often use 8 bit data words only allowing values from 0 to 255. Most instrument outputs range in value over many more decades. For example particle count samples and wave intensity values typically range over 5 or 6 decades. When quasi-logarithmic compressions are employed (9,10,11), a wide dynamic range can be compacted into 1 byte with little error. A 4 bit exponent and 4 bit mantissa can reduce 19 bit values to 8 bit values with a maximum percentage error of 3.1% (10).

On-board microprocessors can also perform detailed data calculations of a signal processing nature. For example particle correlators(14) can calculate autocorrelation functions of fast particle samples and thus access aspects of the data that otherwise could not be transmitted to ground in a realistic telemetry bandwidth. This can provide a totally new insight into the nature of a phenomenon (in this case wave-particle interactions).

Some DPU computations are done to relieve the ground computer of laborious tasks, and ensure the computed values are available in real-time. For example the moments of particle distribution functions have been calculated by a particle spectrometer DPU (15) for instantaneous display to the ground experimenter. The experimenter can assess the moments of a complicated distribution very quickly.

Data can also be compressed on-board (as opposed to the above data compaction where no significant data is lost). On Giotto, three dimensional electron distributions were measured(16). Since it is known that distributions are generally symmetrical with respect to the magnetic field, a processor was used to find the direction about which the distribution was symmetric. The information could then be transmitted as a two dimensional distribution with a significant gain in time resolution for a limited telemetry bandwidth. As a byproduct the instrument could furnish a measurement of the magnetic direction as a backup to the magnetometer.

Displays of swept parameter measurements against another parameter such as time can usually be represented in an image. For example particle measurements are displayed as energy versus time and wave measurements as frequency against time with the particle flux or wave intensity as image intensity or colour. It seems that future on-board processors might be employed as image compressors. Simulations of what can be achieved by a DPU using actual geophysical data (17) have shown that savings, typically as much as 4:1 in data quantity, are still acceptable. Although there is some loss of data sensible choices of compression algorithms lead to negligible loss of scientific value. The algorithms used were standard image compression techniques(18) and further improvements are likely.

5) Microprocessors and the space environment

On short duration sounding rocket flights (<20 minutes) the thermal capacity of the payload structure limits temperatures closely to the temperature at launch, and commercial grade components are often acceptable. In contrast the possible wide temperature extremes experienced on spacecraft and the essential reliability required for years of unattended operation demand the use of high reliability components that have been test cycled and inspected (e.g. to military standard MIL-STD-883).

Heat dissipation can be a major problem on both rocket and satellite flights. Even CMOS microprocessors when running at high clock rates can dissipate a few hundred milliwatts. In the convectionless space environment this requires thermally conducting heat sinks to the main structure.

On some missions the radiation damage accumulated by the spacecraft repeatedly traversing the earth's radiation belts is too much for standard devices and only radiation hardened devices can be used. In non-hardened devices radiation can induce(19,20) latch-up, single event upsets, and long term changes in memory access times and voltage logic thresholds related to total dose received.

Ionising radiation can produce photocurrents that activate latch-up, a low impedance, high current path from power supply to ground operating like a silicon controlled rectifier (SCR). This current is sufficient to fuse the thin wires connecting integrated circuit chips to the chip carrier. In low radiation environments this damage in non-hardened devices has been avoided by the inclusion of fast bi-stable resettable fuses on the power lines (14). Single high energy particles can in hitting some locations produce voltage transients sufficient to invert the state of a memory cell (a single event upset). Corruption of memory in this way can at least be detected by software calculated memory checksums(21) and appropriate action initiated such as restoring default values. Parity checks and the use of error correcting coded memory extends this possibility.

If after all reasonable attempts to shield from radiation, the predicted orbit dose is such as to produce total mission device doses greater than a few kilo-rad, then radiation hardened devices are necessary to avoid the longer term deterioration. Luckily most of the commonly used support devices in the standard 4000 series logic family are available in radiation hardened form. However there are only a few radiation hardened microprocessors and memory types(20,22), severely restricting design choice.

A further design problem is caused by some radiation hardened microprocessors (e.g.S3000, CDP1802) requiring to be operated at 10V supply in order to fully appreciate their speed and remain radiation protected. As all memory devices run at 5V fast voltage level convertors are required on the data, address, and control lines. These devices are also expensive and have complex procurement procedures.

Although there are now many CMOS microprocessors on the market, the satellites presently operating were restricted to those microprocessors available some years ago. Instrument designs are frozen several years before launch to leave sufficient time for the necessary environmental testing and interference checks between spacecraft packages. Designers cannot rely on stated manufacturers future product release dates. Table 1 lists some of those CMOS microprocessors that have been used to date. CMOS types are preferred because of their low power, high imunity to noise spikes, the relative ease with which they can be radiation hardened(20) and they generally have low stray e.m. emissions.

Some idea of the rate of incorporation of microprocessor technology can be learnt by listing the missions launched and planned in the field of space plasma physics. The mission launch dates and processors used were: ESA GEOS1 & 2 1977,1978 (no on-board processor) (2); Franco-Soviet ARCAD3 september 1981 (a single central spacecraft processor in hardware) (23); three US/UK/FRG AMPTE satellites august 1984 (many CDP1802 & NSC800); USSR VEGA 1984 (NSC800 +?) (7); ESA Giotto july 1985 (many CDP1802 &NSC800) (3); Swedish VIKING 1985 (HM-6100 & NSC800) (24); ESA Cluster 1993 & 1994 (HS-80C86(1) and Inmos T414 Transputer). It is a sobering thought that by the launch of the ESA Cluster mission in 1993/4, many personal computers of the IBM PC type will have used a similar 8086/8088 CPU for a decade. At least space instrument designers have the advantage of well developed software development tools!

In the above discussion about space environment effects on microprocessors it should be noted that microprocessors themselves affect the space environment. Sensitive wave spectrum analysers flown as instruments on space science missions are easily able to detect(11) the many high frequency emissions generated by microprocessor electronics boards. Although the number of interference lines produced can be reduced by locking all microprocessor clocks together there is still considerable variation of the emissions. Each microprocessor, executing its own program, continuously changes in a nearly arbitrary manner between the different timing cycles e.g. memory read, memory write, I/O access, and operation codes. EMI

6) Microprocessor implementation and processing power

The hardware and software implementation of a space instrument microprocessor is similar in many ways to other imbedded microprocessor applications. However special attention must be paid to (i) continued processing free of software hang-ups, (ii) the certainty with which the microprocessor can be commanded, and (iii) the ease with which a majority of the program can be changed from the ground.

Continued program operation can be checked by special arrangements of software and hardware that reset the processor if necessary or, more simply, cause regular automatic resets. It is possible to include 'error traps' in the code (21) to reset the processor if an unexpected program branch occurs ,say as a result of an error in reading or writing the program address register. In this quest for continued uninterrupted operation, the processor must still be made certain of responding to ground commands. The simplest method is to use non-maskable interrupts for ground commands(14), but these have the disadvantage of immediate interruption of what might be a time critical process already taking place. It is better if the command response is included as part of the software/hardware system for continued operation checking with the system making regular checks to see if a new command has been received.

Sometimes the on-board program is found to be in need of modification. This may be as part of a general software improvement as the instrument characteristics become known in orbit. It may also be necessary to respond to errors discovered late in the software, or to replace a part of memory permanently damaged by radiation. However the processor still expects to find reset and interrupt vectors in a specific address area in memory. It is usual to incorporate hardware switching of memory banks in case of corruption of this area of memory. Perhaps two versions of the pre-flight program are stored in Programmable Read Only Memory, PROM. One PROM is selected initially as starting from this area and using part of its program copies itself to Random Access Memory,RAM. This RAM is subsequently switched in to start at the reset address. Facilities must also be included to enable ground commands to write directly to RAM. It is difficult to design systems that will cope with all eventualities but systems designed in this way will in general provide useful service for longer. A generalization is that it is best to have a rather simple shell program with the ability to add into it by uplink later.

Since the choice of flight microprocessors is limited, high processing powers (that would on the ground be achieved using state of the art Digital Signal Processors, DSP) can only be realised by groups of microprocessors. The tasks can be spread between processors and in principle some degree of redundancy is introduced.

Many of the Giotto and AMPTE mission instruments used such groups of microprocessors each with its own memory and isolated data bus(6,15,16,21,25). Usually the first processor handles commands and provides control over the overall instrument and control over the other processors in a master - slave configuration(15) (see figure 3a). The second processor would handle the main data processing, while a possible third (or more) processor provides a specialised complex data calculation. In the absence of space qualified DSP chips this third processor and probably the second processor will usually require their own external hardware multiply/ divide circuits. With each processor having its own specific function defined by its unique hardware interface there is usually little redundancy ahieved in practice. Most of the tasks of any one processor could not be performed by the other processors.

In an attempt to improve the reliability of microprocessor groups it has been proposed to have a number of processors each with identical complete instrument software and hardware interfaces on one of the experiment proposals for the ESA Cluster mission in 1993/4(26) (see figure 3b). At any one time the tasks are distributed between the different processors to provide in effect complete redundancy. A hardware arbiter monitors the activities, checking for correct operation and redistributing the tasks according to the continued health of the processors.

Further into the future the Inmos transputer promises to overcome many of these problems. Transputers can be connected in arrays to provide high performance with a minimum of external support circuitry(27) (see figure 3c). Transputers are interconnected by simple high speed serial links and each has some internal RAM memory for its program and data. Many applications will require the addition of fast external RAM since the internal

RAM is at present only 2 to 8 kilo-bytes. Only a few of the transputers in the array need their own external PROM program memory since the others can obtain their programs from those via the links (boot from link).Perhaps most importantly for space instrumentation applications these arrays can be arranged in 'fault tolerant' configurations where a damaged processor is simply bypassed. The software can redirect the flow of calculations via different links to avoid the damaged processor. Preliminary radiation susceptibility tests indicate(28,29) that the transputer will at least be acceptable for some missions. It has been estimated that had the ESA Giotto camera had transputers for image compression it could have sent back ten times more images(28).

7) On-board intelligence

Processor intelligence may be employed to make mission critical decisions on-board the spacecraft. Often these decisions require analysis of data in much the same way as a ground-based data analyst would approach the problem.

For example one of the main purposes of the ESA Giotto mission to comet Halley was to obtain detailed images of the comet nucleus. The Halley Multicolour Camera (6) used the spacecraft spin and telescope mirror movement with respect to the spacecraft to scan the comet. The image detectors were Charge Coupled Devices (CCD) that had the image clocked across their plane at the same speed as the image scanned across them to improve signal to noise (similar to a focal plane shutter camera). The image produced was 292 x 391 pixels in 4 colours stored on-board as 1 byte/ pixel /colour. However the telemetry allocation only allowed the transmission of an image of 98 x 98 pixels.

Two of the most important decisions to be made were (i) when to clock the CCD image into memory, and (ii) which part of this stored image to transmit. These decisions had to be made for each image (once per 4 second spin of the spacecraft). The long time for round trip radio communications ruled out any ground decision making. The DPU used a combination of three NSC800 processors corresponding approximately to: (i)providing overall experiment control; (ii)controlling sensor electronics and stepper motors (e.g telescope mirror); and (iii)signal processing. Each of the processors inter-communicated via a 'mail box' system. The third signal processor had separate hardware multiply and divide as well as control over two special hardware processors that preprocessed the data for the important tasks of acquisition and tracking. The acquisition preprocessor converted the data to one bit and effectively operated a pattern recognition algorithm for cometary image detection. This information was then used by the main processors to target the instrument. The tracking preprocessor determined the intensity centre of the CCD image and enabled the experiment control processor to send only that image part corresponding to the comet.

The USSR VEGA TV system(7) passing 'more slowly' at a greater distance from the comet used a similar but simpler system. Two

NSC800 processors were used to (i) control camera orientation, and (ii) provide overall experiment control. Again image recognition and tracking were two of the most important software operations without which the level of scientific return would have been negligible.

A second example of the use of on-board intelligence is in the forthcoming ESA Cluster mission(1) to be launched in 1993/4. The prime mission of these spacecraft is to study in detail the various boundaries crossed separating the different space plasmas in the near earth space or magnetosphere. On crossing a boundary measurements need to be made on timescales perhaps two orders of magnitude faster than at other times. The regions immediately before and after the boundaries are of great interest. To facilitate this increased resolution but keep the data transmission rate low a large on-board burst memory is envisaged. Emptying of the burst memory can occur later at low data rates when the spacecraft is in a region of little measurement interest.

The difficulty is to decide on what constitutes a boundary crossing in real time. Intelligent software will need to analyse data from several instruments to gain enough information in order to make a decision. Data will have been continually stored in the burst memory until a few minutes after the boundary is recognised at which time the contents are frozen. The decision algorithms(26) to freeze memory must resemble those normally used afterwards on the ground by the data analysists selecting data for further detailed study.

A similar situation is encountered if instruments are deliberately designed to take measurements on faster timescales than can be transmitted. Using data compression to then fit within the allocated data rate can offer average time resolution improvements of 4:1 or better(17,26,30). Such a compression relies on some parts of the instrument measurement space having little or smooth variation or being predictable from previous measurements. However the data output rate to the telemetry must remain at a constant rate. Thus a data buffer is needed so that the compression ratio can be varied to enable more detail to be transmitted at times of interesting events when a larger part of the measurement parameter space varies significantly in an unpredictable way(30). The choice of compression ratio to best transmit the data is again one requiring some degree of artificial on-board intelligence.

The approach must be adopted with care. Space science instruments are flown in order to gain knowledge about naturally occurring phenomena. Based on the information from previous missions the approach described above uses on-board intelligence to optimise resources. There is a real danger that aspects of these phenomena, or new phenomena, will remain unobserved. For example, if (as in section 3), ion spectrometers only look in parameter space for expected species, "new" species could not be observed.

8) On-board Expert System

The further extrapolation of the trends outlined above, incorporating more on-board intelligence, is the inclusion of expert systems on-board the spacecraft, probably to be termed smart spacecraft, and smart space instruments. Besides a change of name there is little to distinguish these implementations from those in the previous section which can be thought of as involving 'expert data analyist' systems. In general they aim to improve mission reliability and help maximise the scientific return of a mission. A spacecraft expert system can help make the spacecraft operate autonomously, relieving the ground station of the heavy burdon of continual health checks(31).

Aready one of the Giotto instruments(21) has included artificial intelligence techniques in the operating system of the main instrument control processor. A large part of its operating system was devoted to fault pattern recognition and corresponding correction routines.

Initial ESA studies(31) have shown that expert systems might be applied to spacecraft fault- management, resource allocation, and task scheduling. Health diagnosis and the use of heuristic rules to activate redundant units is similar to the medical areas in which expert systems have been successful historically. In common with most expert system applications, the major problems are knowledge collection and system vallidation.

9) Conclusions

There are clearly major gains to be had by the incorporation of microprocessors into space instruments. Indeed, they are necessary for modern complex instruments. Microprocessors are adding to the measurement resolution, instrument operation flexibility, detection efficiency, and reliability.

However there is a real possibility that their use distances the experimenter from the instrument. For example, by making interpretations and subsequent decisions of which the experimenter is unaware. This clearly calls for great care in microprocessor system designs and detailed testing.

It is to be remembered that Van Allen discovered the earth's radiation belts by reinterpreting what had appeared to be the instrument malfunctioning (actually saturating). We have to ask ourselves would the radiation belts have been discovered if Van Allen's instrument had been 'smart'. Of course the answer is yes- but only if the system has been properly designed and tested.

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FIGURE CAPTIONS

FIG 1 General space instrument with Dedicated Processing Unit (DPU).

FIG 2 Overall space instrument, ground computer and experimenter 'man-machine' system.

FIG 3 (a) Typical fixed distribution of tasks in a multi-processor space instrument.

(b) Fully redundant identical multi-processor space instrument allowing redeployment of tasks.

(c) Fault tolerant transputer array in future space instrument.

TABLE1

Examples of CMOS Microprocessors in Space Instruments

Type	Source	No of bits	Clock MHz	Software	Rad-hard	Missions
CDP1802	RCA	8	3.5	1802	+ Yes	AMPTE,1984,GIOTTO,1985
HS-80C85	Harris	8	4.0	8085	Yes	?
S3000	Sandia	8	10.0	8085	+ Yes	CRESS 1991+
NSC800	National	8	5.0	Z80	No	AMPTE,1984,GIOTTO,1985 VEGA,1984
HM6100	Harris	12	2.5	PDP-8/E	No	VIKING,1985
HS80C86	Harris	16	5.0	8086	Yes	Cluster,1993/4

+Radiation Hard only if CPU run at 10V.

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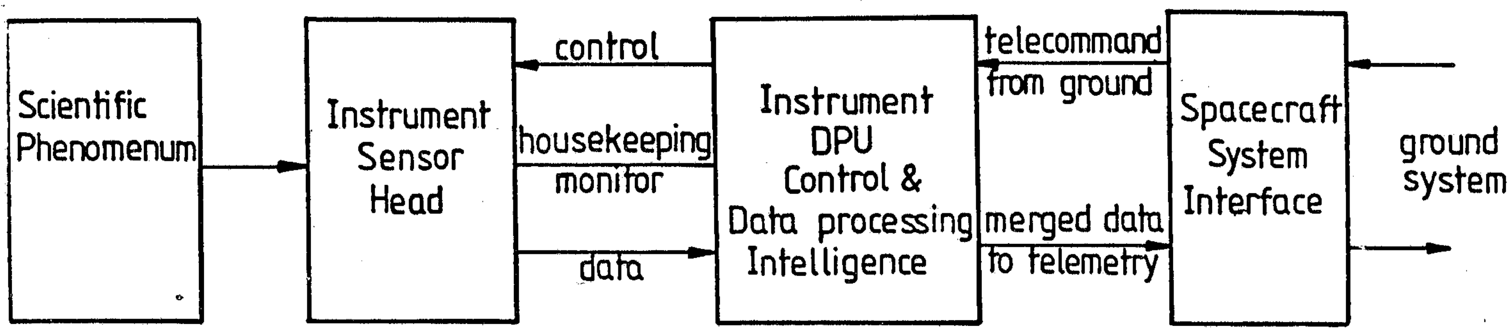
Scientific Phenomenum
Instrument Sensor Head
control
housekeeping monitor
data
Instrument DPU Control & Data processing Intelligence
telecommand from ground
merged data to telemetry
Spacecraft System Interface
ground system

fig 1

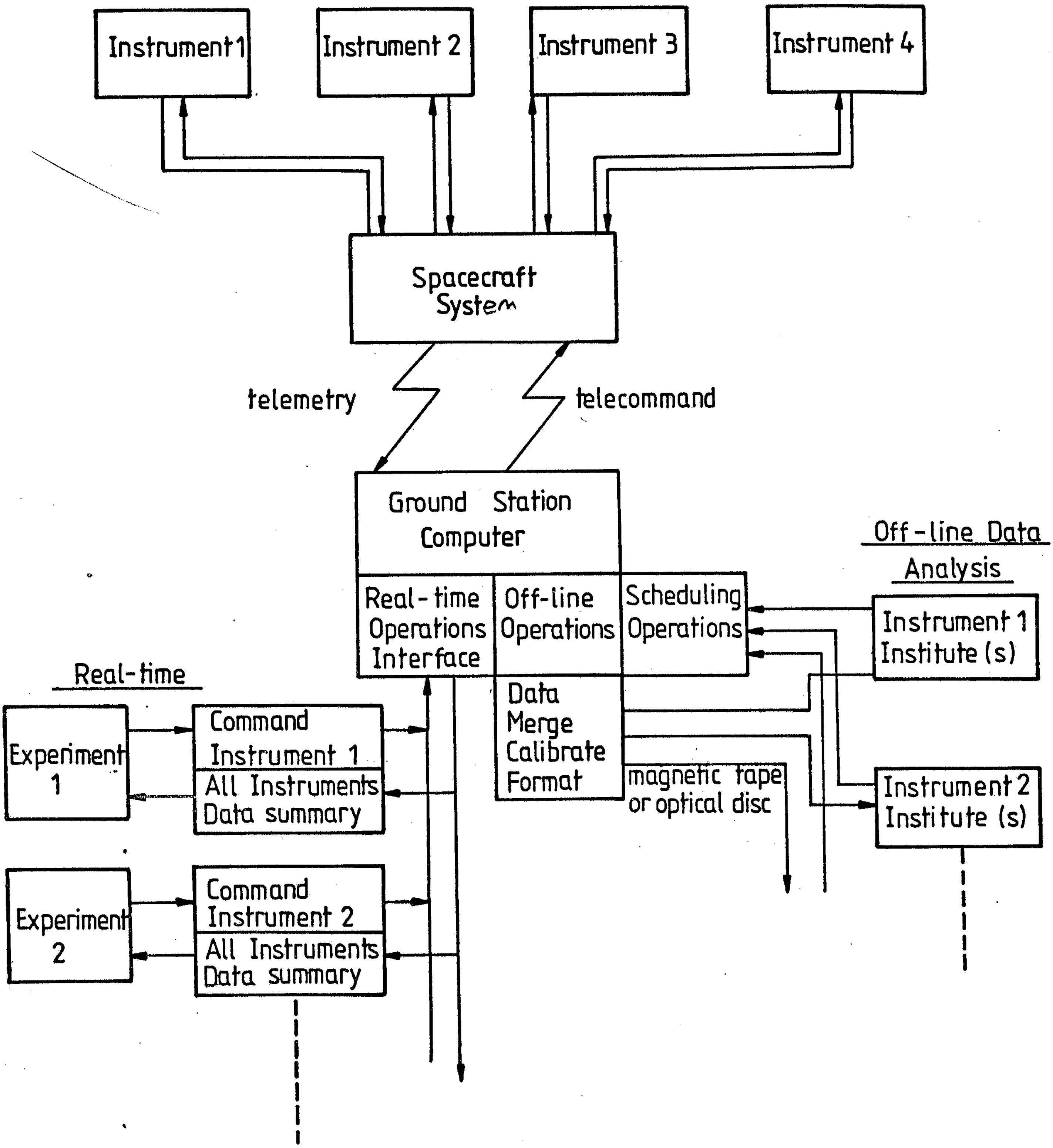
Instrument 1
Instrument 2
Instrument 3
Instrument 4
Spacecraft System
telemetry
telecommand
Ground Station Computer
Real-time Operations Interface
Off-line Operations
Scheduling Operations
Data Merge Calibrate Format
magnetic tape or optical disc
Off-line Data Analysis
Instrument 1 Institute (s)
Instrument 2 Institute (s)
Real-time
Experiment 1
Command Instrument 1
All Instruments Data summary
Experiment 2
Command Instrument 2
All Instruments Data summary

fig 2