The Prospero satellite

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[Plates 4 and 5]

The Prospero satellite is described briefly both in terms of the experiments that were conducted and the on-board systems for servicing those experiments that were tried for the first time in this spacecraft. Mention is made of the supporting equipment on the ground and, in particular, the first use with a British spacecraft of computer controlled test equipment and the first use of a British control centre to service a satellite in orbit. Finally, attention is drawn to the use that has been made of Prospero designs and operating experience in subsequent spacecraft projects.

1. Aims and description of Prospero

The Prospero project had four objectives:

(i) To help maintain the competitive position of the British space industry.

(ii) To perform experiments, mainly of a technical nature. When this requirement had been met, there remained some spare payload which was offered to the S.R.C. This led to the choice of the Birmingham micrometeoroid experiment.

(iii) To develop new systems to support the experiments (e.g. for data handling) in forms that could be adapted for subsequent projects, with the aim of reducing the cost of those projects.

(iv) To introduce new facilities on the ground that could be used again in future projects.

The main physical features of Prospero are shown in figure 1. The top and bottom surfaces are octagonal; eight triple-faceted modules of aluminium honeycomb are hinged to the edges of the upper octagon to provide access to internal equipment, and eight fillets are used to complete the external surface. Four of the modules carry power-generating solar cells on their upper, lower and equatorial facets. The other four modules have them mounted on their upper and lower surfaces only, to leave room, on two diametrically opposed equatorial facets, for experimental solar cells and Earth and Sun sensors. Four of the eight fillets carry calorimeters for the thermal control surface experiment and the port to admit micrometeoroids to the Birmingham experiment can be seen on the upper octagon. The spacecraft has four aerials for telemetry and command mounted at the base and these were cranked to avoid folding them in the heat shield of the rocket. Internally, a central box structure supports the bulk of the equipment. Two large rectangular holes in facing panels accept a substructure on which all

the components of the data handling system are mounted and this complete assembly is known as the data tray.

The spacecraft is 1.1 m diameter and 0.7 m in length with a mass of 72 kg. It was launched from Woomera, South Australia, by the British Black Arrow rocket on 28 October 1971 into an orbit whose elements were almost exactly those predicted beforehand (table 1). It is spin stabilized about the axis of symmetry; the initial spin rate imparted by the rocket was 175 rev/min but this has since decayed due to induced eddy currents reacting with the geomagnetic field.

TABLE 1. ORBITAL ELEMENTS OF PROSPERO

	predicted	initial orbit achieved
orbital inclination/deg	82.06	82.06
nodal period/min	106 ± 1	106.53
semi-major axis/km	7415	7443
perigee height/km	556	547
apogee height/km	1570	1582
orbital eccentricity	0.067	0.069
argument of perigee/deg	327	329

2. THE EXPERIMENTS

2.1 The solar cell experiments

Experimental solar cells and assemblies are carried on Prospero that are quite distinct from the conventional cells which power the satellite. There are two parts to the experiment.

The first part consists of ultra-lightweight solar cell assemblies of the type needed to satisfy the much greater power requirements of future spacecraft. A good deal of work has been done in the U.K. and elsewhere on thin solar cells, methods of attaching such cells to thin plastic sheets, suitable interconnexion techniques and mechanisms for deploying large arrays from spacecraft. Figure 2 shows such an array that has been developed at the Royal Aircraft Establishment. The plastic sheets carrying the solar cells are folded in concertina fashion and stowed in a small box-like structure before being erected by a pneumatically operated mast. Prospero carries small solar cell assemblies of this type to assess


DESCRIPTION OF PLATE 4

FIGURE 1. Drawing of the Prospero satellite in a partially dismantled condition. a, module; b, fillet; c, experimental solar cells; d, Sun and Earth sensors; e, one of the calorimeters for the thermal control surface experiment; f, port to admit micrometeoroids to the Birmingham experiment; g, data tray; h, hybrid experiment.

FIGURE 2. A lightweight 280 W solar cell array shown fully deployed.

FIGURE 5. Prospero's data tray. a, low speed encoder; b, high speed encoder; c, tape recorder; d, programmer; e, transmitters and command receivers.
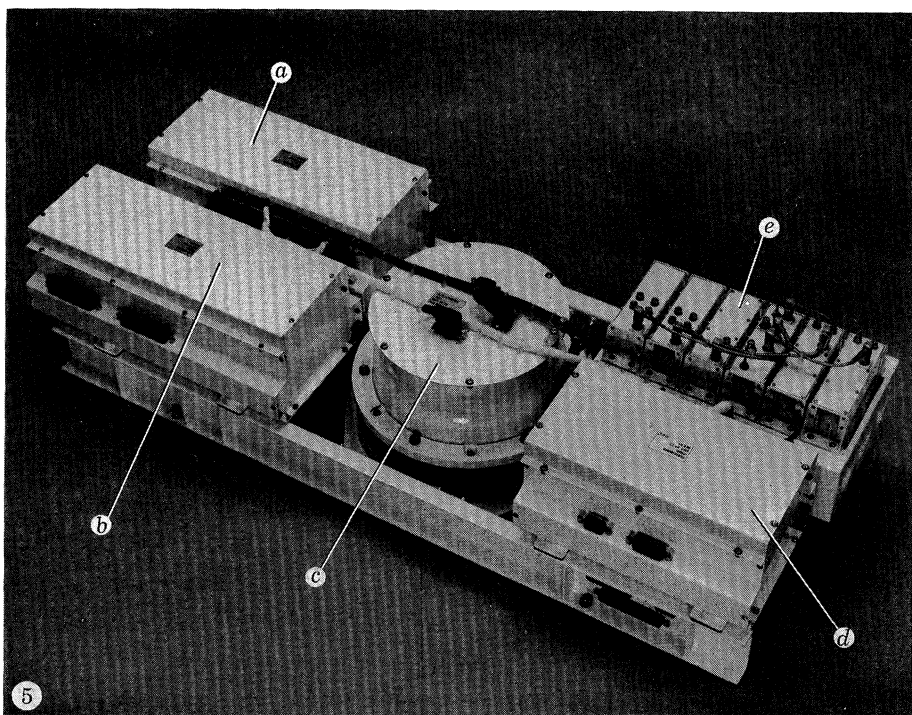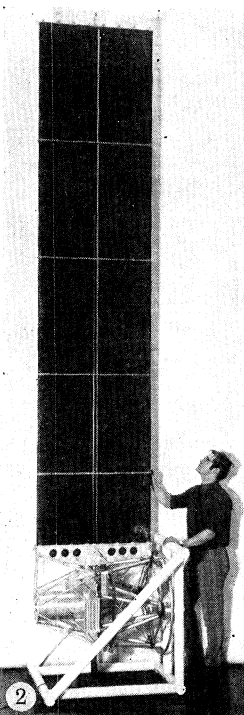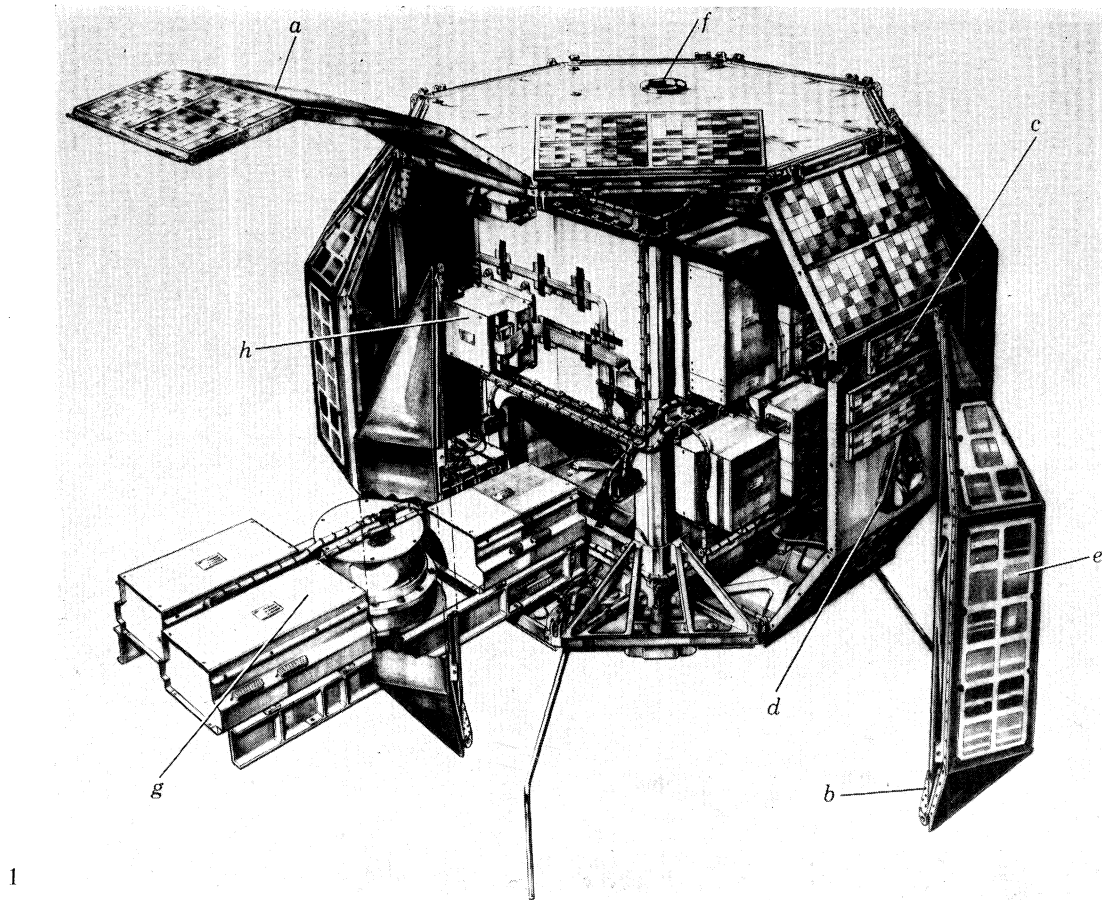
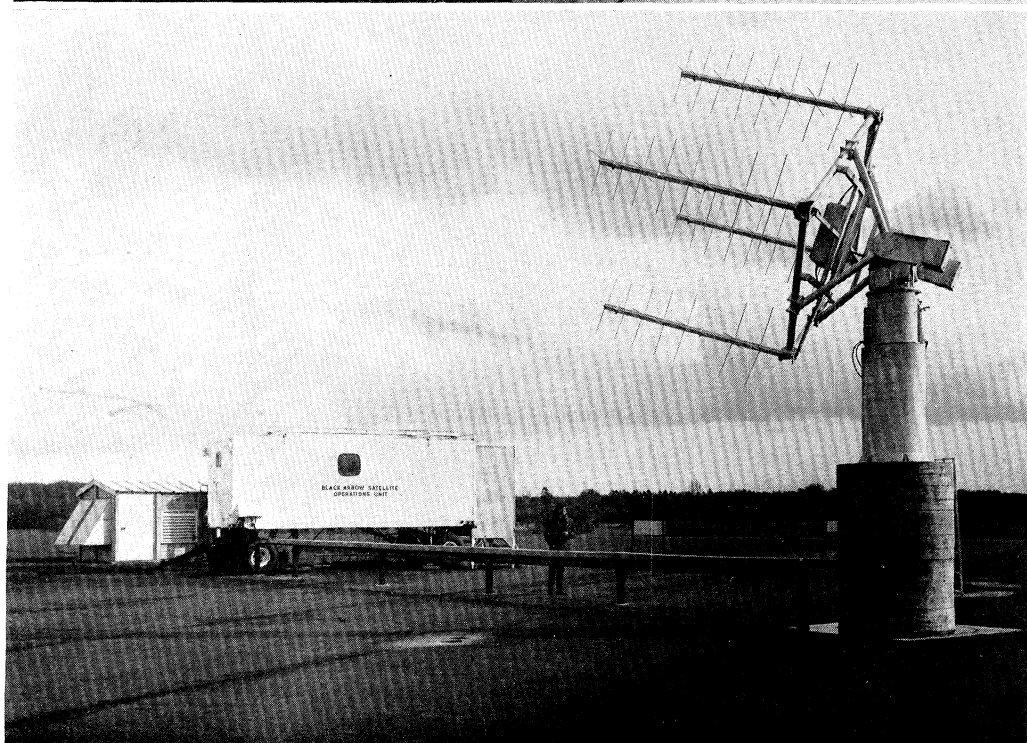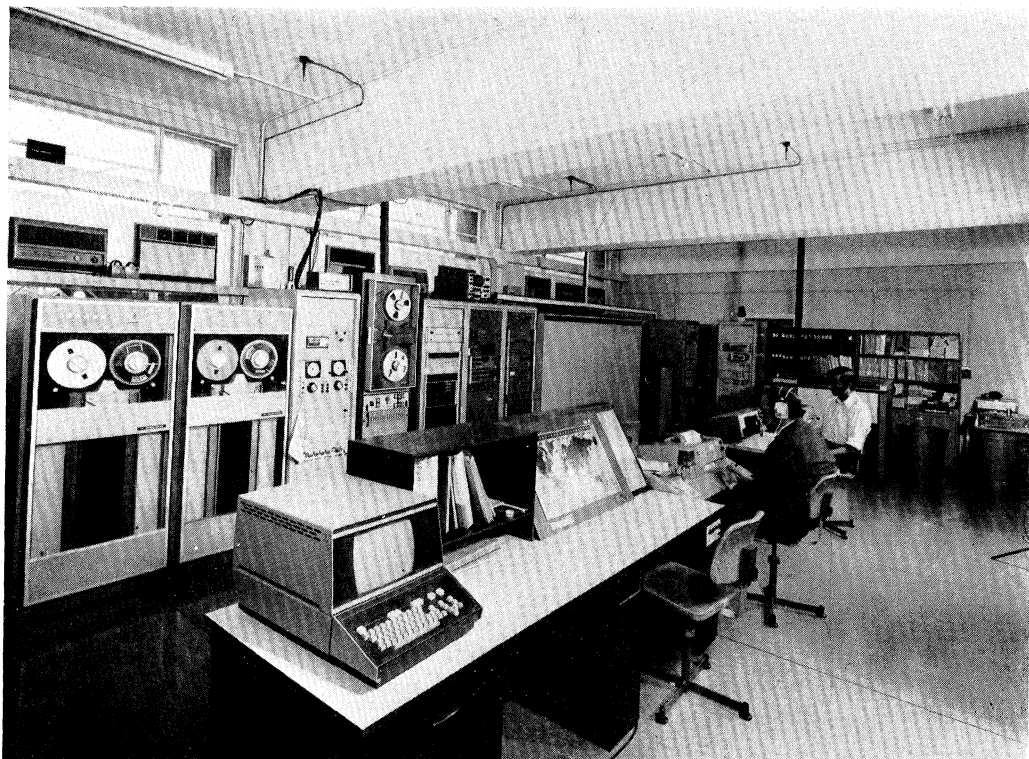FIGURES 1, 2 AND 5. For descriptions see opposite.

FIGURE 7. The satellite control centre.

FIGURE 8. The Lasham ground station.

their space-worthiness. For each of the three types of cell carried, the short circuit current, open circuit voltage, current near the maximum power point and cell temperature are measured. Using information from the attitude sensors, the results are corrected for angle of incidence of the sunlight after readings taken at a greater incidence than 20° and readings taken when radiation from the Earth falls on the cells are eliminated. Further corrections are made for cell temperature and time of year (which affects the solar constant). In this way the voltage–current characteristic can be reconstructed for standard conditions. The orbital results have fully confirmed the techniques used in preparing these solar cell assemblies.

The second part of the experiment is concerned with cover slip behaviour. The main reason for cementing a glass cover to a silicon solar cell is that the effective emittance is about doubled; this allows the cells to run cooler and hence their conversion efficiency is much improved. The aim of the experiment was to compare the British cerium oxide doped cover with the more complicated conventional cover which typically consists of fused silica with a multilayer ultraviolet filter to protect the underlying cement. The covers to be tested were used on cells which had previously been irradiated with about 10^{16} electrons cm^{-2} at 1 MeV, the idea being that the performance of the cells would not change perceptibly during the life of the satellite due to the natural radiation environment and so any observed change could be attributed to darkening of the cover. In practice, these cells degraded in an unexpected manner. The effect is thought to be photon induced and it has been seen recently in the laboratory, particularly in silicon cells prepared by the float-zone process such as those in Prospero (Crabb 1973). A continuing watch is being maintained on the Prospero real time data in view of the general interest in these cells and a further experiment on this topic is being prepared by R.A.E. for the U.S. Navy's Timation 3A satellite.

2.2. *The hybrid experiment*

The second of the technological experiments is concerned with proving the space-worthiness of hybrid electronic assemblies made up from thick film resistors, chip capacitors, and unencapsulated active devices mounted on alumina substrates carrying conductor patterns. Such assemblies offer important advantages for spacecraft use. The technique enables a higher standard of quality control to be applied when a relatively small number of equipments is required. The alternative approach of buying transistors and integrated circuits in cans and attempting to detect badly made specimens by subsequent electrical test is unreliable since devices screened in this way that subsequently fail are often found to be poorly made when the can is removed. With hybrid electronic assemblies it should be possible to buy unencapsulated components and select the best by careful visual inspection and electrical testing. They could then be assembled at contractors specializing in the manufacture of electronic equipment for space use who would then, for the first time, be able to ensure that the same standards of quality control

were applied to all the assembly processes. Additional reliability is obtained by enclosing a large number of circuits in one can, since the number of series connexions is reduced, and a further advantage is the much smaller mass, which may be one tenth that of more conventional equipment.

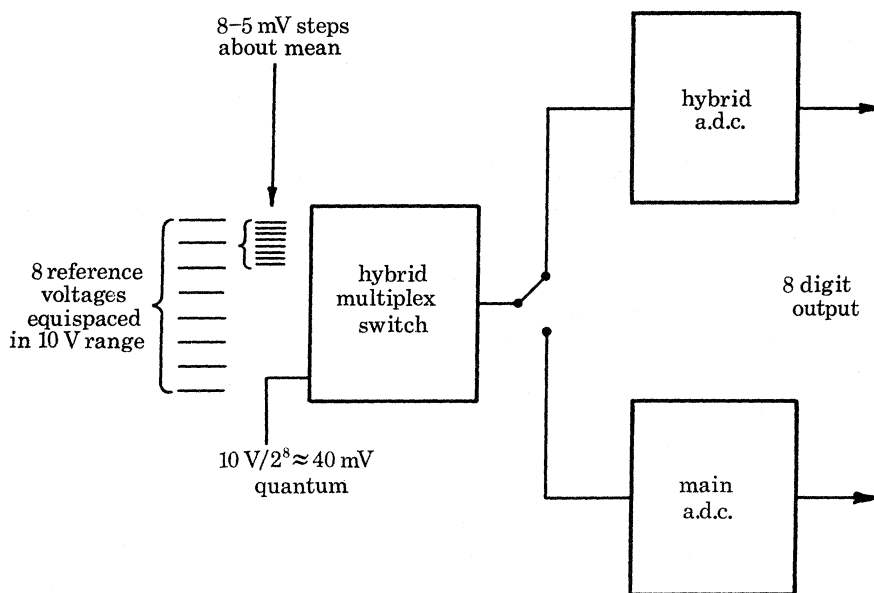The subsystem chosen for the experiment consisted of a voltage to digital

FIGURE 3. Block diagram of the hybrid electronic experiment.

converter and an eight input multiplex switch used to select calibration voltages from a potential divider (figure 3).

The output from the mutiplex switch was applied either to the experimental 'hybrid' voltage-to-digital converter or to the voltage-to-digital converter of more conventional construction that forms part of the satellite's data handling system. Signals representing the voltage applied to the potential divider and the outputs of the two converters are transmitted to the ground in order to monitor the behaviour of the hybrid experiment. The eight input voltages to the multiplex switch are equispaced in a 10 V range and each of these voltages is varied, in a suitable sequence, in eight 5 mV steps about the mean value. In this way a sensitive in-orbit check has been made on the stability of the characteristic of the 'hybrid' voltage-to-digital converter.

The hybrid assemblies for this experiment were made at the Royal Aircraft Establishment. After two years in orbit the experiment is still operating correctly. The very small changes that have occurred are completely consistent with the measured changes in temperature of the equipment.

2.3. *Thermal control finish experiment*

The most common method of influencing the temperature of a satellite, or a part of a satellite, is by the application of suitable surface finishes. For example, in the simple case of an isothermal sphere in continuous sunlight at the Earth's distance, the temperature of the body could be lowered by about 200 K if the surface finish were changed from polished metal to white paint. It is thus a matter of some practical importance to establish a range of surface finishes that show little deterioration of the desired thermal properties with time in orbit.
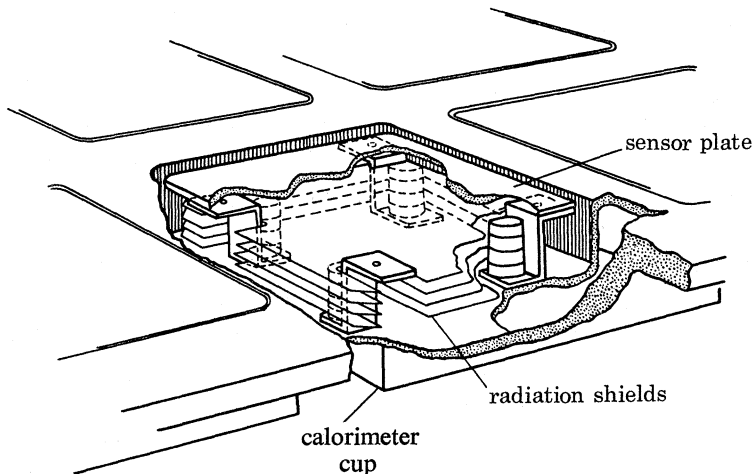

FIGURE 4. Calorimeter for the thermal control finish experiment.

In the Prospero experiment, 19 finishes were tried, consisting of white paints, black paints, metallic finishes (with low a and e) and so called 'black metal' surfaces (with high a, low e). Each sample is contained in a calorimeter as shown in figure 4. The thermal control surface is carried by a thin sensor plate approximately 4 cm square which is backed by high reflectance radiation shields and the whole is mounted in a cup, in one of the external fillets, by supports of low thermal conductivity. Thermistors are attached to the rear surface of each plate and to each calorimeter cup, and the output from each thermistor is relayed by the on-board data handling system.

The results obtained show the gross way in which the surfaces degrade with time as evidenced by their temperature history. For example, the Ariel 3 white paints, which were flown for comparison purposes, degrade at a significantly higher rate than the more recently developed white paints. However, it was hoped to extract the variation with time of both solar absorptance and infrared emittance; this has proved to be much more difficult than expected, but all hope of doing so has not yet been abandoned.

2.4. *Micrometeoroid experiment*

For a description of this experiment see Bedford (1974).

3. SUPPORTING ON-BOARD SYSTEMS

3.1. *The data handling system*

The data handling system for Prospero was the first pulse code modulation system for space use to be designed in the U.K. It consists of high and low speed encoders to organize the data for real time transmission and recording, a tape recorder, a programmer, and twin transmitters, command receivers and command decoders. The high speed encoder samples analog signals at a rate of 256 samples a second and converts each sample to an eight-bit word in 250 μs. Experimental data already existing in parallel or serial digital form can also be accommodated. All control and timing waveforms are derived from a crystal oscillator operating at 2^{21} Hz and a 23 stage binary divider chain. The resulting serial train of digits at a rate of 2048 bits per second is organized with suitable synchronization codes into 64 groups each containing 64 eight-bit words for transmission to the ground. The low speed encoder is similar to the high speed encoder except that the whole tempo of data organization is slower by a factor of 32, which is the ratio of replay speed to record speed in the tape recorder. This is of the single spool, single track type using an endless loop of graphite-lubricated tape. The v.h.f. system is conventional using twin transmitters, each with an output of 350 mW at approximately 136 MHz, and a twin tone digital command system operating at about 148 MHz which handles the 35 separate commands.

Three features of the data handling system are worthy of mention. First, the whole system was designed to be carried as a unit on a separate data tray (figure 5). This concept led to reduced lengths of interconnecting lead and many fewer plug and socket connexions; also it enabled the whole system to be checked out as a unit with the aid of automatic checkout equipment before it was installed in the spacecraft. Secondly, care was taken in the circuit design to break up the system into small modules of standard form, using wire-wrapped interconnexions, with the twin objectives of making the equipment easily repairable and of creating module designs which could be used again in later satellites. Lastly, the Prospero tape recorder did not fail until it had worked in orbit for 19 months, thus setting a record for a device of this type.

3.2. *Attitude sensors*

In order to interpret the results of the experiments it is necessary to know the spin period of the satellite, the spin position at any instant, the angle between the spin axis and the satellite–Sun line and the angle between the spin axis and the local vertical. The principle of operation of the necessary on-board sensors can be explained with the aid of figure 6.

Let OX be normal to the plane CDEF (which represents a panel on the surface of the spacecraft) and perpendicular to the line AOB (which represents the spin axis of the spacecraft). Suppose a hemisphere lies towards the observer with centre Y given by the intersection of OX and the plane CDEF. Imagine 2 slits in the hemispherical surface, the first, marked 1, being defined by the intersection of a plane containing AB and the point Y with the hemispherical surface and the second,
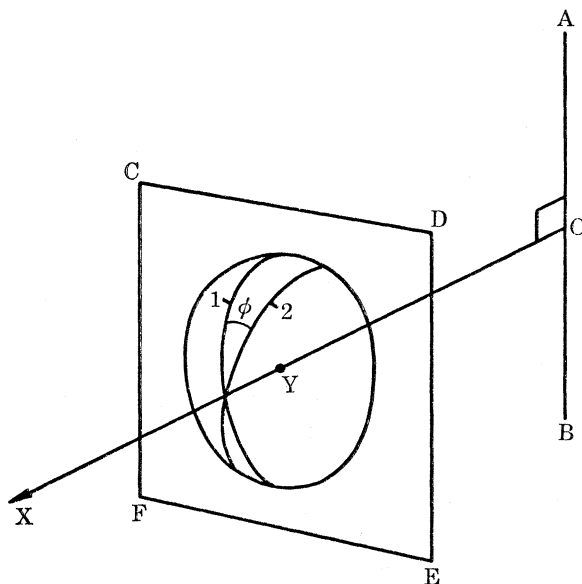

FIGURE 6. Diagram to illustrate the principle of operation of Prospero's Sun and Earth sensors.

marked 2, being defined in a similar way after this plane has been rotated about OX through an angle ϕ. In practice, the slits 1 and 2 each have a field of view of $1° \times 180°$ and each is associated with a photo-detector. The time interval between successive pulses from the photo-detector associated with slit 1 is equal to the spin period, and the spin position at any instant can be deduced by noting the time at which sunlight enters this slit. The angle between the spin axis and the satellite–Sun line is determined by comparing the time interval between the pulses from slits 1 and 2 with the spin period. Clearly, the pulses from the two slits are coincident if the Sun lies in the equatorial plane of the satellite, the interval between the pulses increases as the Sun moves out of the equatorial plane, and the order in which the pulses occur depends upon whether the Sun is above, or below, the local equatorial plane. A measurement of the angle between the spin axis and the satellite–Sun line indicates that the spin axis lies on the surface of a cone with the satellite–Sun line forming the axis of the cone. An horizon sensor with a field of view of 1° pointing in the direction OX (figure 6) provides the additional information needed to establish spin axis orientation in space coordinates.

The horizon sensor works only when it sees the sunlit Earth and, in some cir-
cumstances, ambiguity in the spin axis position cannot be resolved; for example,
when the centre of the Earth, the satellite, and the centre of the Sun are in line.
However, these limitations are not serious. The direction of the spin axis changes
very slowly and it is only necessary to consider observations taken in favourable
circumstances.

3.3. *Power supply system*

The power supply system in Prospero is fairly conventional. However, the
electronic equipment was again designed in modular form to facilitate re-use of
the designs in later spacecraft, a high measure of redundancy was incorporated,
and all the main loads could be switched individually by ground command to
permit fault finding in orbit.

4. THE GROUND ELEMENT

4.1. *Automatic check-out*

Automatic checkout equipment was used for the first time in a British programme
to exercise and check the Prospero satellite during integration, testing and the
launch phase. Similar techniques were also used to test the data tray before it was
integrated. It is possible to check the operation of a spacecraft by manual equip-
ment but the testing has to be rather superficial if it is to be completed in reason-
able time. With automatic equipment, however, quite comprehensive checks can
be made with the minimum of human intervention. With these advantages, a
thorough test can be made at more stages of the spacecraft's development; thus
any failure is quickly brought to light with a much increased chance of relating a
failure to the immediate cause.

Each checkout equipment for Prospero was built around an EMR 6130 com-
puter. This together with peripheral equipment and suitable software comprised
a system able to carry out all the necessary test sequences automatically using,
in the main, the v.h.f. telemetry and command link with the spacecraft. The design
allowed the spacecraft to be exercised in all its modes of operation through the
command link, while performing limit checks on all the data produced by the
spacecraft within 2 s of its generation. Any item that fell outside limits was
brought to the attention of the operator by print-out of the teletype machine and
the test was automatically halted. If the operator judged it to be expedient to
proceed he could either re-run the preceding phase of the test or override the failure
and continue. The limits themselves could be modified by a particular test pro-
gram or by the operator, for example, to take account of ambient temperature.
At all times during the test the equipment monitored 52 critical currents and
temperatures within Prospero to ensure the safety of the satellite. If any of these
quantities moved outside the set limits, power to the satellite was automatically
turned off and, as a secondary feature, a signal was provided that could be used to

stop any environmental test equipment that was being used. The checkout equipment contained a power source to furnish the satellite with a current limited supply similar to that obtained from the solar cells in orbit, and timers to enable the spacecraft's battery to be charged and discharged in a realistic fashion. The supply could also be varied automatically to simulate the modulation expected in orbit due to the asymmetry of the solar cells on the spinning spacecraft. This facility was used to ensure that such modulation did not interfere with the functioning of the satellite. Where appropriate, the satellite could be stimulated externally to assist in system testing. For example, lamps fixed relative to the attitude sensors could be caused to flash under the control of the computer in such a way as to generate signals corresponding to any attitude of the spacecraft relative to the Sun line. The computer was then used to compare the attitude data transmitted by the satellite with that determined by the flash sequence. Auxiliary functions of the checkout equipment include the ability to store all test data, with the addition of timing information, for subsequent off-line analysis; the ability to compute, in parallel with the testing, simple functions of the data, as selected by the operator; and lastly the equipment can check its own status by means of separate programs and calibrate all analog channels.

4.2. *Orbital operations*

Prospero is the first spacecraft to have its orbital operations controlled from the United Kingdom. A satellite control centre was established at R.A.E. (see figure 7) with the following main functions:

(i) To receive data from the ground stations by teleprinter link and magnetic tape.

(ii) To command the satellite into its various modes of operation.

(iii) To take emergency action in case of faults in the spacecraft.

(iv) To process housekeeping data in real time for the orbital control of the spacecraft.

(v) To produce pass predictions for the ground stations.

(vi) To distribute regular summary reports to the experimenters.

(vii) To produce partially reduced tapes for further analysis by experimenters.

Well over half the passes were taken by the primary ground station at R.A.E. Lasham (see figure 8). By agreement with E.S.R.O., Estrack stations were used during the early orbit phase to cover every orbit that could not be dealt with by Lasham and many real time data were recorded by the S.R.C. station at Port Stanley in the Falkland Islands, particularly in support of the micrometeoroid experiment.

Two features of the control centre are worthy of mention. First, all the operations needed during a pass were defined in advance and incorporated in a suite of monitoring and control programs for the computer. In a sequence that can be pre-selected, the computer sets up the data processing equipment before the pass, tests the telemetry data for freedom from noise, examines the housekeeping data

to assess the state of the spacecraft and initiates the necessary commands. The spacecraft controller and his staff are normally in a monitoring role; they are informed of the progress of the pass by the output of a teletype machine and they only intervene if a fault condition is brought to their attention. In practice they have only been obliged to revert to manual control on two occasions, and both were due to computer failure. Secondly, a determined attempt was made before launch to foresee all possible failure modes of the spacecraft and to develop contingency procedures in computer software for dealing with them. In the case of a fault, the satellite controller would run the computer program appropriate to the symptoms. If this failed to remove the fault the spacecraft would be put automatically into a safe condition pending detailed post-pass analysis. There has been no real emergency up to the present to test these procedures, but they have been tried by simulating spacecraft faults.

Since Prospero was launched there have been only two on-board equipment failures; the calibration flash unit in the micrometeoroid experiment and the tape recorder.

5. INFLUENCE OF PROSPERO ON SUBSEQUENT PROJECTS

As stated previously, one of the aims of Prospero was to develop the supporting systems in forms that could be adapted for subsequent projects, with the intention of reducing the cost of those projects. Table 2 summarizes the benefits to the UK5,

TABLE 2. SCHEME TO ILLUSTRATE THE INFLUENCE OF
PROSPERO ON SUBSEQUENT PROJECTS

	power	data handling	v.h.f.	sensors	
UK5	√	√ ($\approx 60\%$)	√	√	demonstration of command system
UK6	√	√	√	√	
X4	√	√ ($\approx 70\%$)	√		

UK6 and X4 programmes. Although the data handling systems in UK5 and X4 are much more complex than the one in Prospero, well over half the modules are to Prospero designs. UK6 makes direct use of equipment left over from Prospero; this, together with the re-use of elements of the Ariel 4 structural design, should ensure that UK6 is a very economical programme. UK5 depends quite heavily on the ability of the spacecraft to receive, without significant error, sequences of about 130 commands to reset the experiment and attitude control registers. Early in the UK5 programme there was some controversy over whether the Prospero tone digital command system would be adequate or whether a new and more elaborate

command system would have to be developed. The matter was settled by experimental work with Prospero. In one method of checking the Birmingham experiment, a command introduces a pulse at the input to the pre-amplifier causing the micrometeoroid counter to be incremented once, and the state of this counter can be followed on the ground. With the cooperation of Birmingham University, sequences of commands in excess of 10^4 were found to be received without error at normal elevations and so the simpler and much less expensive Prospero command system was adopted for UK5.

The author wishes to acknowledge the work of all those involved in the Prospero project, whether in Birmingham University, industry or the government service.

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