ACS PERFORMANCE VERIFICATION FOR IRAS - SOFTWARE ENGINEERING AT THE OCC

L P Baldwin

Rutherford & Appleton Laboratories
Chilton, Didcot
Oxfordshire, UK.

ABSTRACT

This paper describes the software engineering approach taken at the IRAS Operations Control Centre to support the In-Orbit Checkout and the Performance Verification and Maintenance of the IRAS Attitude Control Subsystem. The paper begins with a brief description of the IRAS mission indicating those aspects which impose constraints on the ground-operations software system as a whole. Attention is then given to operations related to the in-orbit checkout and the performance verification and maintenance of the Attitude control subsystem, indicating the effect of these operations on the engineering approach and system concepts employed in the relevant parts of the ground-operations software. This effect is drawn out in more detail for the routine attitude-related operations. Some concluding remarks are then made about the quality control procedure and the test and verification concepts employed during the development of the system.

Keywords: Software Engineering, ground operations, attitude-related support, quality control, testing concepts.

1. INTRODUCTION

The Infra-Red Astronomical Satellite (IRAS) comprises a three-axis stabilised spacecraft supporting a cryogenically cooled, 60 cm., infra-red telescope (see Fig. 1). Its primary mission objective is to produce an unbiased all-sky survey of discrete sources in the form of sky and source catalogues. The survey will be made in the infra-red region of the spectrum using four broad photometry channels in the wavelength range 8 to 120 microns. The additional mission objectives are; to perform low-resolution spectroscopy in the survey mode, to perform a survey of the diffuse infra-red background flux in the four primary photometry bands, and to perform spatial and spectral studies of selected galactic and extra-galactic sources.

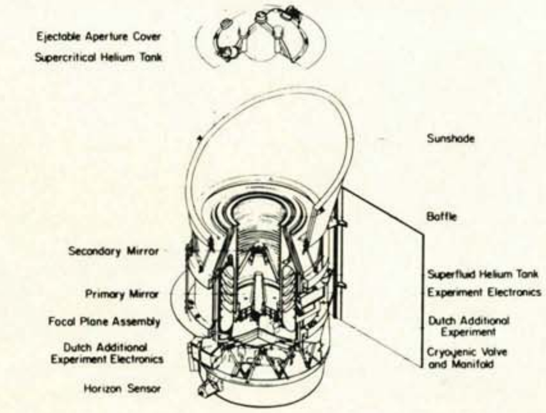

Fig. 1 The Infra-Red Astronomical Satellite

The nominal mission comprises; an initial period of up to four weeks of in-orbit checkout, followed by up to one year of science-data collection. The first two weeks of in-orbit checkout will be with the telescope aperture cover in place, and will be assigned for satellite engineering purposes and verification of initial operations. The next period of in-orbit checkout will be up to two weeks with the telescope aperture cover deployed, and will be assigned, in addition, for calibration and verification of the end-to-end information system. With the exception of the cryogenic subsystem, the satellite design will be based on a minimum lifetime of one year but in such a way as to not preclude eighteen months of operation. The cryogenic subsystem will be designed for one year of orbital operations with as much lifetime margin as the system will permit.

For about the first 30 days of science data collection, the survey will be given the highest priority. Following this period, a significant fraction of the time, nominally 40%, will be available for special observing programmes. This allocation will be divided equally between the American and Dutch/British astronomers. Throughout the mission, a small fraction of time will be allocated to special observations required for the verification and maintenance of satellite performance. All these non-survey observations will be planned so that they do not jeopardise achieving the reliability and completeness criteria of the final infra-red source catalogue. The Observation Planning and Scheduling Facility provided for this is described in Reference 1.

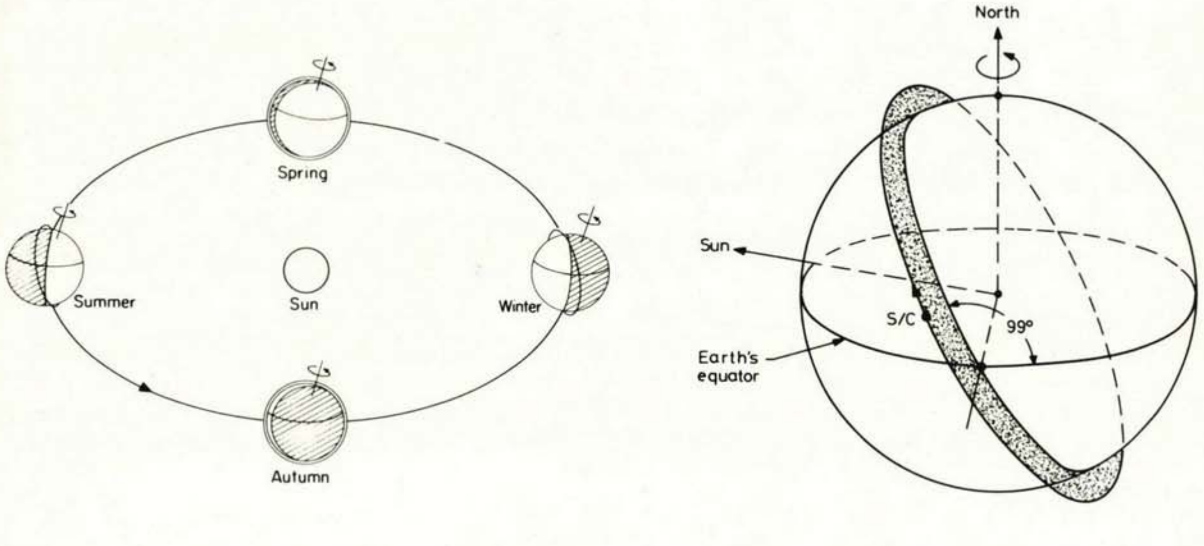

Fig. 2 IRAS Orbital Configuration

The satellite will be launched at dawn in mid-August 1982 from the Western Test Range in California. The launch vehicle will be a two-stage Delta 3910, which will place the satellite, nominally, into a circular, sun-synchronous, twilight orbit, with an altitude of 900 km., a period of 103 minutes, and an inclination of 99^{o} (see Fig. 2). At launch, the line of nodes of the orbital plane will be nominally perpendicular to the earth-sun line, and the direction of motion of the satellite will be anti-clockwise when viewed from the sun side of the orbital plane. The attitude of the orbital plane with respect to the earth-sun line will be maintained by giving it an inclination of approximately 99^{o} with respect to the equatorial plane. The orbital plane will precess around the earth's polar axis with an angular velocity equal to that of the earth around the sun, ie, about 1^{o} per day. For such an orbit, the sun is continually available both as a clear attitude reference, and also as a source of energy via the solar panels, except for short periods when the satellite is in eclipse around the south ecliptic pole.

The IRAS tracking station and operations control centre are co-sited at the Rutherford and Appleton Laboratories at Chilton in the UK (Fig. 3). This site will provide all the tracking, telemetry, command, and data processing capabilities required to meet the mission objectives, with additional facilities to provide interfaces with NASA STDN stations in the event of contingency operations. The IRAS ground-station will acquire the satellite for a period of about 15 minutes on two or three consecutive orbits, at intervals of approximately 12 hours (see Fig. 4). Of these acquisition periods, one will be designated as a 'prime' ground-station pass, and the others as 'back-up' passes. During each of the prime passes an exchange of data will occur; the satellite will dump the science-data collected during the previous 12 hours, and the ground-station will load into the on-board computer the set of commands comprising the satellite observations plan for the next 12 hours. In addition, satellite health and status will be checked and tracking data collected for refining orbit predictions. Any functions omitted during a prime pass may be re-scheduled for a subsequent back-up pass.

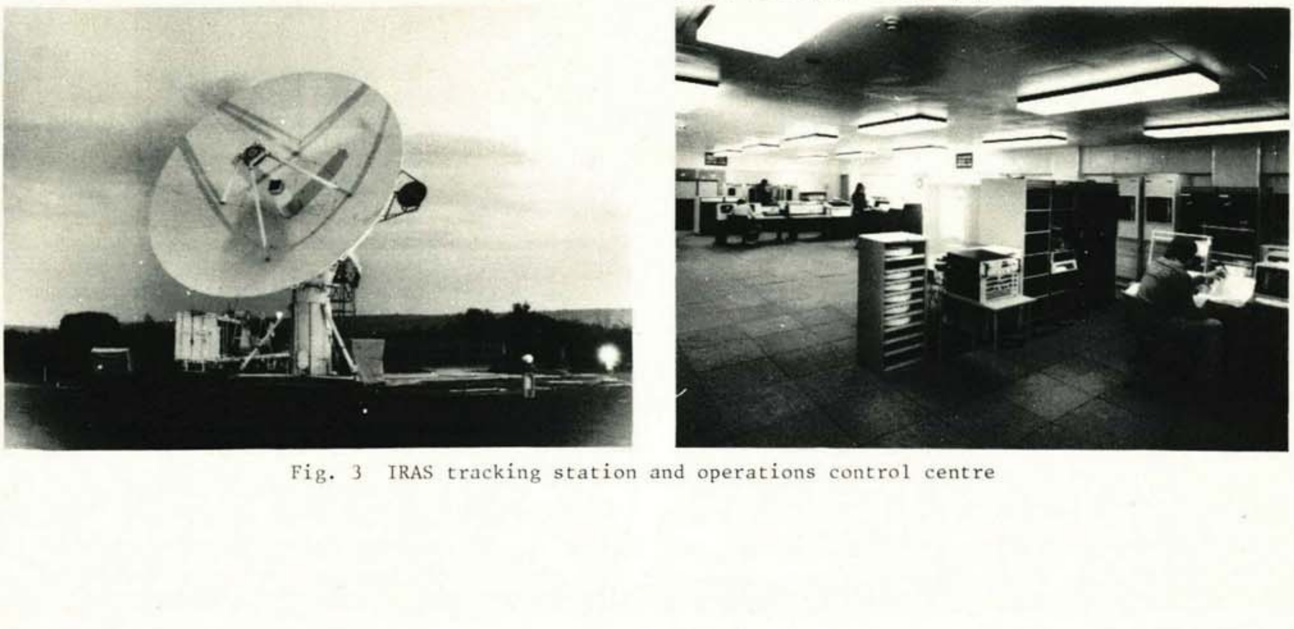

Fig. 3 IRAS tracking station and operations control centre

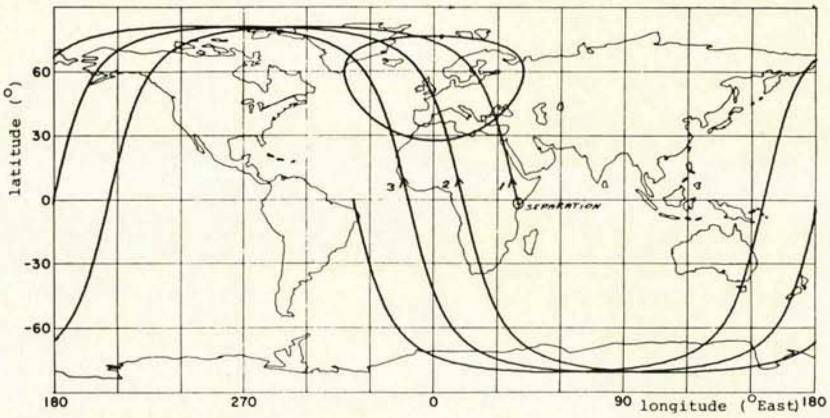

Fig. 4 First three ground-station passes for visibility range above 5° elevation

The ground-station software is distributed over three computer systems, and is organised into three segments around the ground-station pass (see Fig. 5). Thus observation planning and scheduling (Ref. 1), generating the 12-hour satellite observations plans, and generating the task-schedules for the ground-station passes, is performed by the 'pre-pass' software, which is written in FORTRAN and runs on an ICL 2960 under DME (to emulate, for historical reasons, an ICL 1904S under GEORGE 3). Control of the ground-station antenna, real-time control of the satellite, and reception of low-speed and high-speed telemetry is performed by the 'in-pass' software, which is written in Assembler and runs on a DEC PDP 11/34 under RSX-11M. Initial processing and subsequent distribution of the science-data is performed by part of the 'post-pass' software which also runs on this machine, but uses in addition an attached FPS AP120B. Satellite health evaluation and ancillary data distribution are performed by the remainder of the 'post-pass' software running on the ICL 2960. Orbit determination is performed, as required, by software running on the ICL 2960. Changes to the on-board software are handled, as required, by software which has segments on both of the computers mentioned above, and also uses an on-site Phillips P856 as a test-bed.

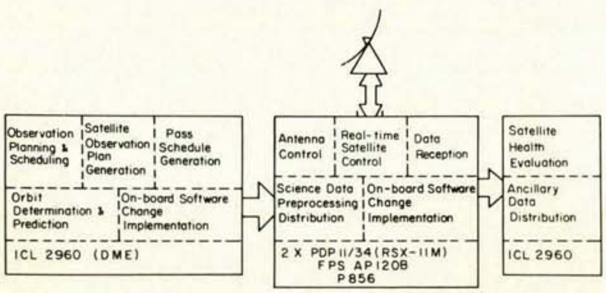

Fig. 5 Ground-Station Data System

The Attitude Control Subsystem (ACS) on-board the satellite is a digital, sampled-data control system based on an on-board computer linked to the following sensors and actuators (see also Fig. 6); coarse sun sensors, fine sun sensors, horizon sensor, magneto-meters, gyros, star sensors, reaction

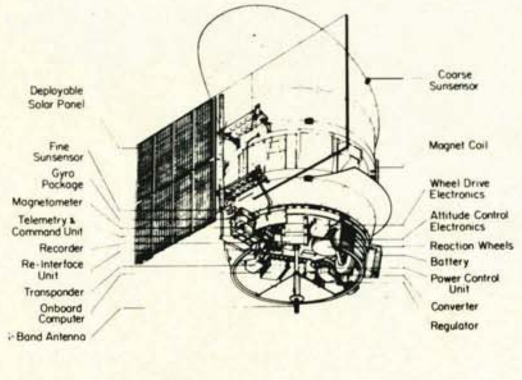

Fig. 6 Spacecraft Equipment

wheels, and magnet coils. It has the following basic tasks; initial acquisition of the sun as a basic attitude reference, maintaining a safe attitude with respect to sun and earth, providing fine attitude control during observations, and executing attitude calibrations to correct the on-board attitude estimate and to support attitude reconstruction on the ground. The sun is acquired initially by rotating the satellite by means of the reaction wheels, using the coarse sun sensors to provide attitude information, until the sun falls within the field of view of the fine sun sensors (Fig. 7). A safe attitude with respect to sun and earth is maintained by rotating the satellite so that the sun remains within the field of view of the fine sun sensors and the earth remains outside the field of view of the horizon sensor (and, therefore, outside the field of view of the telescope). These sensors are thus being used as safety devices. Fine attitude control during observations is maintained by a combination of; the fine sun sensors used as absolute attitude sensors, and the z-axis gyro used to measure the rotation about the sun-satellite line. During periods of eclipse fine attitude control is maintained by the three-axis gyro package. Attitude calibrations are performed as selected visible stars cross the slit-type star sensors embedded in the telescope focal plane (Fig. 8). The results of these calibrations are used; on-board to provide an absolute attitude correction to the z-axis gyro measurement, and on the ground to support attitude reconstruction. Excess angular momentum in the satellite can be dumped by interaction between the earth's magnetic field and the suitably energized magnet coils. The magnetometers are used to measure the ambient magnetic field so that the magnet coils can be energized correctly. A variety of contingency operations is also possible using various combinations of sensors and actuators to meet non-nominal conditions.

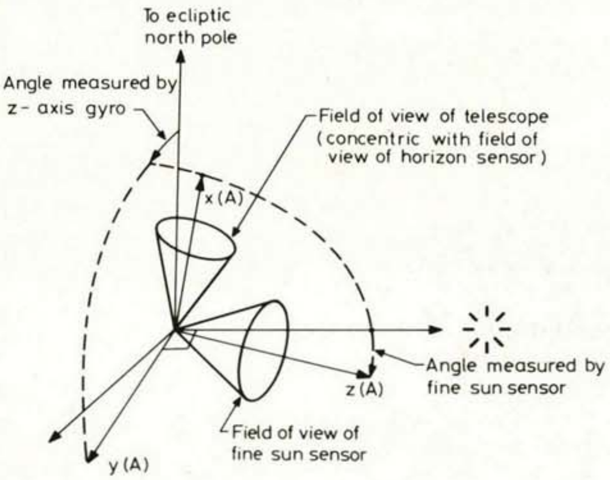

Fig. 7 The control coordinate frame, showing fields of view of fine sun sensors and telescope.

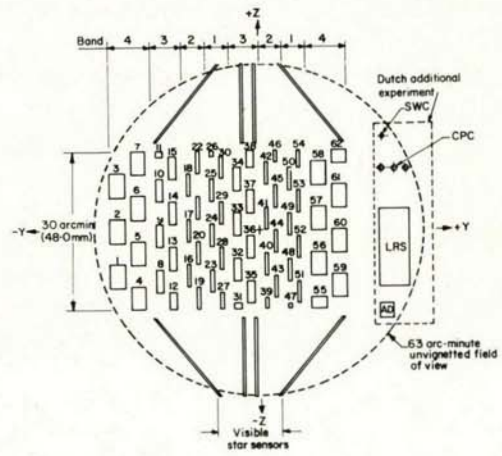

Fig. 8 Focal plane layout showing; the 62 infra-red detectors, the visible star sensors, and the Dutch additional experiment

2. APPLICATIONS DEPENDENCY OF SOFTWARE SYSTEM CONCEPTS

During in-orbit checkout, in-flight calibration will in general be required for the following characteristics of each of the ACS units; transfer function, misalignment and geometrical calibration, alignment stability, and sensitivity. In specific cases, some of these characteristics have to be actually determined in orbit, while for others it is sufficient to verify that their pre-launch values are valid. The division between these two cases depends mainly on the following factors; the required accuracy of the calibration, the accuracy obtained from pre-launch measurements, the uncertainty in the effect of the launch environment, and the feasibility of in-orbit calibration.

The in-flight calibration taking place during in-orbit checkout will in general be a 'one-off' determination of ACS unit characteristics. In most cases, this will require special calibration sequences involving non-nominal spacecraft operations which will not be repeated again during the mission. Some of these sequences, used for the in-orbit checkout of the gyros, are described in Reference 2. Budgetary constraints prohibit the provision of an automatic ground-software system for performing the analysis of these calibrations. A limited set of software will be used to provide the spacecraft engineers with attitude-related data obtained during the relevant calibration sequences, and the determination and verification of ACS unit characteristics will then proceed with the aid of a desk-top calculator.

Throughout routine operations, and in some cases during in-orbit checkout as well, it will be necessary to verify that certain ACS performance characteristics lie within their expected range, and to ensure by corrective measures that they remain so. The performance characteristics being verified may be divided into: a 'prime set', which directly influence the scientific results, and comprise control accuracy, and limit cycle; and a 'secondary set', which affect the general control of the satellite, and comprise angular momentum unloading, and accuracy when using the horizon sensor. The verification procedure will involve the re-determination of certain of the ACS unit characteristics, and corrective measures may require the updating of some of the associated parameter values held in either or both of the on-board and ground-station software.

The periodic monitoring of these ACS performance characteristics will be carried out automatically within the ground-station software. In most cases, the software system will extract useful attitude-related data for this purpose from the standard data products associated with the normal observing programme. However, special provision will have to be made for the gyros, which are prime attitude sensors, and which will require special calibration sequences inserted into the normal observing programme. Special attention will also be paid to the horizon sensor, which although it will not require special calibration sequences, it will require more complex analysis because it is a particularly difficult sensor to calibrate pre-launch.

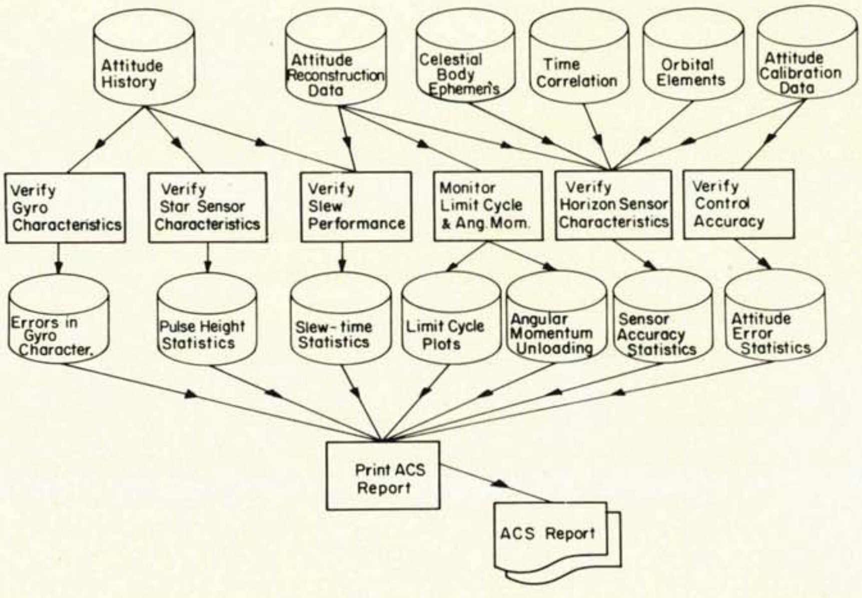

Fig. 9 ACS Analysis Software

3. APPROACH FOR ATTITUDE-RELATED ROUTINE OPERATIONS SUPPORT

The routine performance verification and maintenance of the ACS requires that the following items be monitored once per week, each item being verified over all of the 12-hour satellite observation periods from the preceding week; control accuracy, attitude calibrations, limit cycle, slew-times, angular momentum unloading, horizon sensor accuracy, spacecraft-telescope misalignment, and star-sensor sensitivity. In addition, the z-axis gyro transfer function is to be re-determined at intervals of two weeks, and misalignment between the gyro and the ACS control coordinate frame is to be re-determined at intervals of eight weeks. The results of the analyses are to be printed, and distributed to the interested parties. Modifications to parameters in either or both of the ground-station and on-board software systems are to be made as required, on the basis of previously agreed criteria.

The emphasis in the software engineering approach to supporting these attitude-related routine operations has been to provide a smoothly operating, automatic,error sensitive (but not error prone!) software system. This emphasis has derived from two major factors in the IRAS mission. Firstly, the performance of the ACS has a critical effect both on the quality of science-data collected during observations and also on the accuracy of the final source catalogue. Secondly the IRAS lifetime is strictly limited by the performance of the cryogenic subsystem (which is monitored elsewhere), so that poor quality data or satellite unavailability could have a serious impact on the success of the mission.

The analysis software designed to meet these requirements is shown in Figure 9. This software forms part of the 'post-pass' software, and is written in FORTRAN to run on the ICL 2960. Some items are not shown here. The monitoring of the spacecraft-telescope misalignment is covered during verification of control accuracy, and the statistics on successful and failed attitude calibrations is already handled by the satellite health evaluation software.

The analysis software will be run, with the rest of the 'post-pass' software, after each ground-station prime pass, ie. twice daily. The ACS Report would, however, normally be printed from the accumulated analysis data only at the end of each week. This procedure is preferred to running a major ACS job once per week for a number of reasons. Firstly, the rest of the software is set to this twice daily cycle, and, although the GEORGE 3 command language contains powerful facilities for user-instructed program scheduling, it was considered that the preferred approach produced a system that would be simpler both to use and to maintain. Secondly, twice daily processing would smooth out the work-load on the machine. The ICL 2960 is a medium-range machine, and it is expected that there will be competition for resources particularly with the Observation Planning and Scheduling Facility (an on-line system for astronomers, described in Ref. 1), and with the Preliminary Analysis Facility (a quick-look, 'post-pass', science-data evaluation system, not described in this paper). Thirdly, twice daily processing avoids the need for archiving and retrieval of the Attitude Reconstruction data. This data-set, which occupies approximately 1 Megaword of disk space for each 12-hour period, is used, within the ground-operations software, only for this ACS analysis. For weekly processing, maintaining a one week, on-line, data-base would be impractical, and an archiving and retrieval system would require additional tape operations throughout the week. Lastly, although the software will, in general, be monitoring gradual degradation of ACS performance characteristics, twice daily processing will permit the detection of sudden anomalies as soon as they occur. A 'pre-issue' of the ACS Report may then be printed automatically to provide the operations personnel with immediate access to the analysis results.

Control accuracy is, perhaps, the basic performance characteristic of the ACS. It is influenced by a wide variety of factors, including; satellite hardware characteristics, satellite attitude history, calibration-star position accuracy, and software computation accuracies. During the normal observing programme attitude calibrations will be performed at regular intervals as suitable calibration stars pass over the star-sensor slits (see also Fig. 8). This will enable the on-board software to regularly update its on-board attitude estimate on the basis of the attitude errors derived from the calibrations. A statistical analysis of these attitude errors, performed by the ground-station software, can then be used to monitor the control accuracy achieved by the ACS. The weekly ACS Report will contain the statistical data in a tabular form for each satellite observation period of the week. The data will be based on all successful attitude calibrations of each period. The spacecraft engineers will then be able to use the data both to monitor trends in control accuracy over longer periods of time, and also to monitor the spacecraft-telescope misalignment which affects the attitude error about the spacecraft y-axis (see also Fig. 7).

During any twelve hour observing period, the satellite will usually need to slew from the end of each observation to the beginning of the next, as very few observations will begin when and where the previous observation ended. To check that the satellite always achieves the required stable attitude within the allocated slew-times, and also that the allocated slew-times are not unnecessarily long, a statistical analysis will be performed on the difference between the allocated slew-times and the actual slew-times required to achieve stable control. The results of this analysis will only be required for one satellite observation period during each week. The processing will, however, be performed for each such period, and the slew-time statistics file overwritten each time. Should an anomaly be detected, either by the ground-operations software or even by the Preliminary Analysis Facility, the latest set of data will always be available for inspection by the operations personnel. Also, the ACS Report, printed weekly, will always contain the latest statistical information on slew-times.

The characteristics of the gyros will be verified at intervals of two weeks (for the transfer function) and eight weeks (for the misalignment). Special calibration sequences will be required in each case, and the analysis software has been configured to handle these events automatically. Firstly, of course, the calibration sequences have to be introduced into the normal observing programme as special observations. The Observation Planning and Scheduling Facility (Ref. 1) will allow ACS personnel initially to generate these observations interactively, and then to store the observations on the system so that they can be used by operations staff to schedule the special calibration sequences as they are required throughout the mission. Each of these observations will be uniquely identified as a special gyro calibration sequence, and the ACS analysis software used to verify the gyro characteristics will check through the attitude history data for each satellite observing period to look for these observations. On those occasions when such observations are present, so that verification of the gyro characteristics may proceed, the printing of the ACS Report will be triggered automatically, irrespective of the weekly cycle, so that the results of the gyro-related analysis will be available immediately.

The horizon sensor is basically used as a safety device, but can also be used to provide attitude data for certain contingency slew and scan modes. It is however difficult to calibrate this sensor pre-launch so the sensor characteristics will be modelled in correspondingly greater detail by the analysis software. Measurements made by the horizon sensor will be checked against the satellite attitude obtained from the results of attitude calibrations. During the in-orbit checkout phase, while the telescope aperture cover is still on, these calibrations will be performed with the magnetometer. During the remainder of the in-orbit checkout period, and throughout routine operations, these calibrations will be performed with the visible-star attitude sensor as part of the normal observing programme. Routine performance verification requires that the sensor accuracy be monitored by means of a statistical analysis of the differences between the measured and expected sensor outputs obtained at attitude calibrations. Early in the mission, however, it will be necessary to characterise the horizon sensor transfer function, so a facility will exist to provide the spacecraft engineers with additional information on; the position of the earth relative to the horizon sensor coordinate frame, and the actual values of the measured and expected sensor outputs.

The limit-cycle performance of the ACS during each satellite observation period will be monitored by plotting data taken from the basic attitude sensors during a normal survey scan. The data, which will be obtained from each of the fine sun sensors and the gyros, will be plotted at a frequency of once per second and will cover a period of approximately two minutes. The OCC has a variety of graphical facilities, driven directly by the ICL 2960, for producing high-quality graphical output. However, given the 'monitoring' nature of the attitude-related software it was considered that the lower-quality plotting capability of the standard line-printer would be quite adequate, so that the limit-cycle plots could be included as part of the normal ACS Report. The software was thereby simplified.

The visible-star attitude sensor comprises eight slits and associated electronics mounted in the focal plane of the telescope (see also Fig. 8). The slits are used in pairs of one skew and one perpendicular slit to perform attitude calibrations as suitable visible stars pass through the telescope field of view. As a star image crosses each slit, a pulse is generated, and from the pulse timings

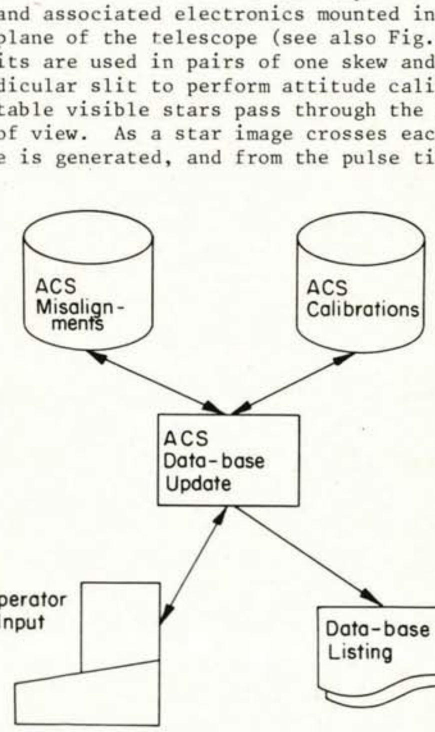

Fig. 10 Interactive updating of the ACS data-base

and the position of the star, a correction can be calculated for the on-board attitude estimate derived from the measurements of the z-axis gyro. Thus the star sensor provides an absolute attitude reference for the gyro. During routine operations, the performance of the star sensor will be monitored for possible degradation of its sensitivity. Such degradation would reduce the number of detectable calibration stars and hence would limit the availability of an absolute attitude reference. The performance will be monitored by performing a statistical analysis on the difference between expected and measured pulse-heights for the calibration stars used in all successful attitude calibrations in each satellite observing period. The weekly ACS Report will contain the statistical data in tabular form, which the spacecraft engineers will be able to use to monitor trends in star sensor performance over longer periods of time.

Various ACS calibration and misalignment parameters are used within; the ground-operations software system, the on-board software system, and the science-data analysis systems. A data-base of these parameters is maintained in the ground-operations software system, and the relevant values are despatched to the other users in various data products. Interactive software has been developed (see Fig. 10) so that the data-base may be initialised and subsequently updated as a result of In-Orbit Checkout calibrations, or as a result of the routine ACS performance verification. The use of an interactive system was preferred to a purely automatic system basically for two reasons. Firstly, human input would be required to initialise the data-base because much of the information would come from manufacturers' documentation. Secondly, much of the analysis, particularly that during In-Orbit Checkout, will require human interpretation to determine whether statistical results or long-term trends indicate the necessity for updating the data-base. The hazards of human interaction have meant that various safeguards have been built into the system. The user enters into a prompted dialogue based on simple English-language commands. The software checks the validity of the response at each stage of the process, and provides a screen-display of updated parameters and a 'help' facility as requested. After each update a printout of the new data-base is produced automatically, complete with a distribution list, so that the update can be verified, in particular by spacecraft engineers. The new data-base would then be made available to all users, after correction if such was required.

4. SOFTWARE TESTING CONCEPTS

The software testing concepts employed within the ACS Performance Verification software-package reflect the concepts employed throughout the ground-operations software-system. Top-down, bottom-up, and thread testing are all combined in an incremental approach to software integration and test (see also Ref. 3).

At first base, bottom-up testing is performed on important, standard, subroutines occupying low levels in component programs. Such routines may be used throughout the software system, or may be used only within this package. It is easier, both technically and economically, to subject such routines to thorough testing at an early stage in the development of the system. They can then be used with confidence as standard items much as computer manufacturer's mathematical functions are used. Top-down testing is applied to the job control procedures written, in the GEORGE 3 command language, for the assembly, package, and program levels. Testing begins at the assembly level, with lower levels comprising dummy procedures, which are replaced in turn. This method enables testing to be performed on command syntax, command functions, procedure interfaces, and operator interfaces, prior to the inclusion (and confusion!) of actual programs.

Software integration into the job control procedure structure then proceeds on an incremental basis, combined with thread testing. Thus, as each program is inserted into the structure, the relevant test-cases can be run to exercise that thread of software within the structure (eg. thread A in Fig. 11). As programs at the same level are inserted, parallel threads in the structure can be exercised (eg. threads A and D in Fig. 11). As programs are inserted at lower levels longer threads through the system may be built up (eg. thread A.B.C. in Fig. 11). In this way critical paths through the system can be integrated and verified independently.

The integration and test process requires sets of test data with which to verify these threads in the software system. These are obtained either from software simulators of the relevant satellite functions, or from the satellite data-system itself. Making use of the satellite itself extends the testing beyond the ground data system alone.

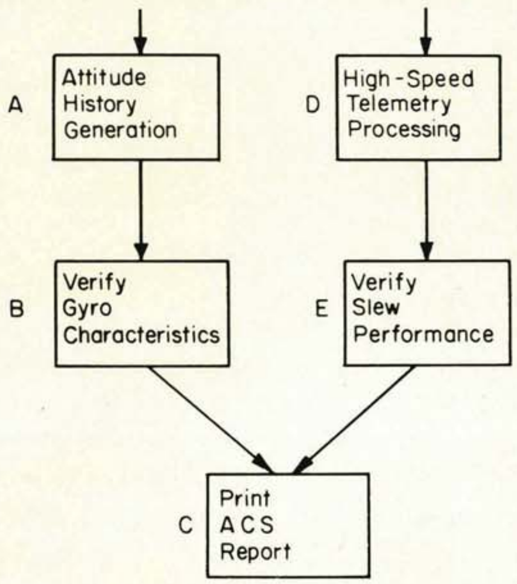

Fig. 11 Thread Testing

5. QUALITY CONTROL OF MISSION CRITICAL SOFTWARE

Two major factors in the IRAS mission emphasise the need for adequate quality-control of the ACS Performance Verification software. Firstly, the performance of the ACS has a critical effect both on the quality of science-data collected during observations and also on the accuracy of the final catalogue. Secondly, the IRAS lifetime is strictly limited by the performance of the cryogenic subsystem, so that poor quality data or satellite unavailability could have a serious impact on the success of the mission.

Quality control is considered to be a continuous function in the software development process. Its 'active' elements are; design reviews, code reviews and testing. Its 'passive' elements are the procedures and standards used in the design, code, and test processes. The initial design reviews, held on a project-wide basis, reviewed the design specification at subsystem/assembly level in relation to the overall requirements on the ground-operations software. This review process has been continued at package/program level (see also Fig. 12). At this level, detailed design specifications are reviewed in relation to the detailed requirements of the 'customer'. The review process is performed by a small team comprising; software engineers, project management, and the 'customer', in this case being members of the Mission Analysis and the ACS groups in the project. The formal result of these reviews is design approval, which; for the software engineer affirms his design, for the project manager provides evidence of progress, and for the customer gives assurance that this requirements will be appropriately met.

The next step in the process is the code review. In this, the coded, debugged program is reviewed in relation to the procedures and standards applied in the ground-operations software. Opportunity is also provided for checking the implementation of any algorithms specified in the design. This review is an 'in-house' process, performed by a small team comprising software engineers and project management. The formal result of this review is code approval, which; for the software engineer gives the go-ahead for transferring the program into the integration and test schedules, and for the project manager provides further evidence of progress and also assurance that an adequate and maintainable system is being developed.

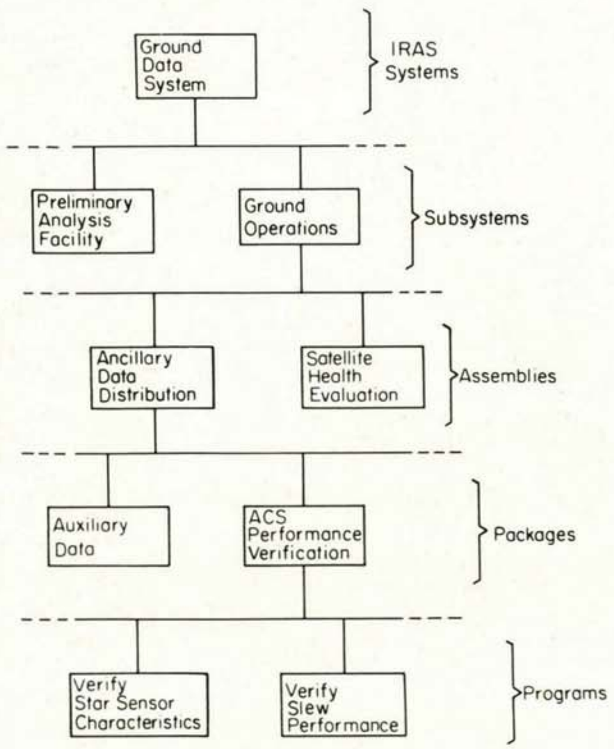

Fig. 12 Ground data system hierarchy

The final step in the process is testing. It is presumed that the program has been debugged, ie. that it definitely runs to a conclusion. Testing then seeks to guarantee that it runs to the conclusion that was intended. The testing process has already been discussed (see Section 4) so only a brief comment will be given here. Program testing will generally begin with individual testing of nominal and obvious non-nominal cases to verify the basic functions of the program. It will then be transferred to the integration and test procedure described above. The final result of the testing process will be acceptance and delivery, concluded in the system test. 'Acceptance and delivery' will include all aspects of the software including technical and user documentation.

The quality control process used here implies an implementation of 'team programming'. This has some important consequences. Firstly, the single-point failure is removed. In the review process design documentation becomes a leading item in the software development, and several members of staff inevitably become at least familiar with each piece of software. This reduces the impact of staff turn-over. Secondly, the 'splendid isolation' common in much programming is avoided. The review process is itself a forum where discussion of software design can become a natural part of the software development. This avoids personal attachment to software with its attendent hazards of defensive attitudes and eccentric methods (see also Ref. 4).

6. SUMMARY

The IRAS ground-operations software system includes packages developed to perform the analysis of attitude related operations both during the initial In-Orbit Checkout phase and also during the subsequent routine operations. Various constraints have affected the development of these packages. Thus, for In-Orbit Checkout, a relatively simple set of software will be used to extract attitude related data from the special observations required for the 'one-off' calibration by spacecraft engineers of the various ACS units. During routine operations, however, a more complex set of software will be used to perform an automatic analysis of attitude-related data, extracted in general from the normal observing programme, for regular monitoring of the various ACS performance characteristics. Standard principles of software engineering have been applied throughout the software development cycle in an effort to ensure the economic production of reliable and maintainable software.

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