9. INTERFACES WITH THE DATA REDUCTION CONSORTIA

This chapter describes the key areas in the Hipparcos operations which required an exchange of information between the control team at ESOC and the various groups of scientists responsible for the data processing. Particular attention is paid to the nominal scientific data distribution to the Data Reduction Consortia. In addition to providing the input and final catalogues, the Data Reduction Consortia were able to supply refined payload calibration and other information which proved crucial for both the safety of the spacecraft and the quality of the final results.

9.1. Introduction

The satellite operating principle and the interfaces with the scientific data reduction consortia is illustrated in Figure 9.1. The satellite was fully controlled by ESOC, at Darmstadt (Germany). Using remote ground stations, all the necessary telecommanding was performed and all the telemetered data was received from the spacecraft at ESOC. The data was divided into several categories such as attitude control, spacecraft housekeeping, and science data. By monitoring this data (in real-time and off-line), it was possible, through ESOC's Hipparcos dedicated computer system, to control and operate the spacecraft in an optimum way. Of primary importance were spacecraft safety, on-board and on-ground systems maintenance, and effective science data return.

The Hipparcos Input Catalogue, as defined by the INCA Consortium, was used by ESOC for routine operations involving the generation of the programme star file, described in Chapter 8. Appropriate subsets of this file were uplinked to the satellite, along with the other telecommands necessary to maintain satellite operations. Typically, a 30-minute buffer of observations was maintained on-board, with observations being made continuously. After the on-board compression of the image dissector and star mapper data, the formatted scientific data was telemetered to ground. The telemetry allowed diagnosis of the performance of both spacecraft and payload, providing feed-back for telecommanding and future programme star file generation.

ESOC was also responsible for archiving all spacecraft data and for pre-processing and distributing the data to the data analysis consortia. Preliminary results from the data reduction consortia processing were then used to refine on-board parameters and the on-ground control. In particular, early observational results were sent to the Input

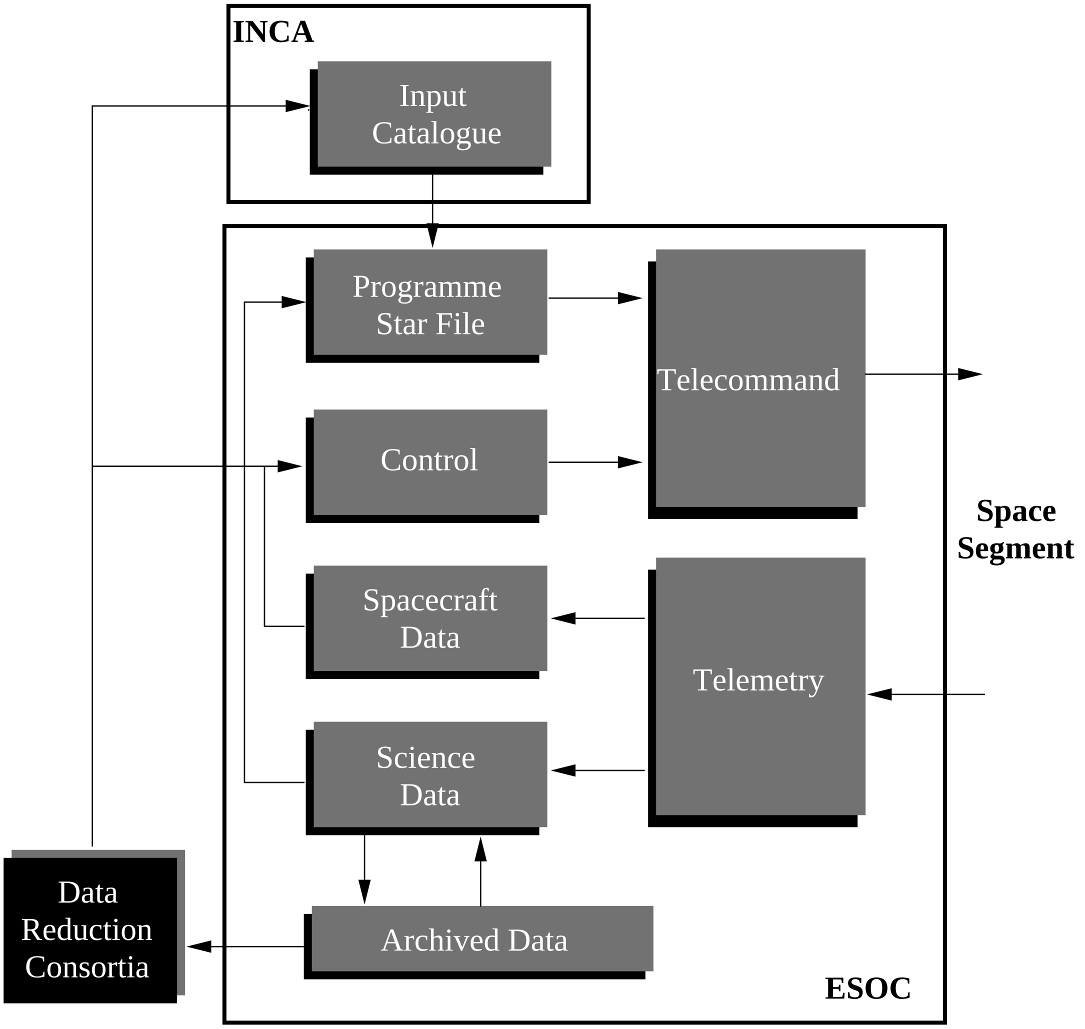

Figure 9.1. *Ground segment operating principle and data distribution. The Hipparcos Input Catalogue, constructed by the Input Catalogue Consortium (INCA), was the basis for the scientific observations and for the satellite attitude control. Data from the Input Catalogue were extracted in the form of the Programme Star File, uplinked regularly to the satellite. Scientific data from the satellite were formatted and archived at ESOC, and despatched to the data reduction consortia. Improved star positions were introduced into the operational scheme as the mission progressed.*

Catalogue Consortium for incorporation into an updated input catalogue for use in the programme star file, thereby improving the reliability of future observations through improved on-board attitude determination using the updated positions, improved detector pointing, and optimised assignment of observation times through the incorporation of improved magnitudes for large-amplitude variable stars.

A full description of the operational interfaces between ESOC and the Input Catalogue Consortium is given in Chapter 8. This chapter describes the interfaces between ESOC and the other Hipparcos scientific consortia, i.e. the FAST and NDAC Consortia, jointly (and in parallel) responsible for the analysis of the main mission data leading to the construction of the Hipparcos Catalogue, and the TDAC Consortium, responsible for the analysis of the star mapper data leading to the construction of the Tycho Catalogue.

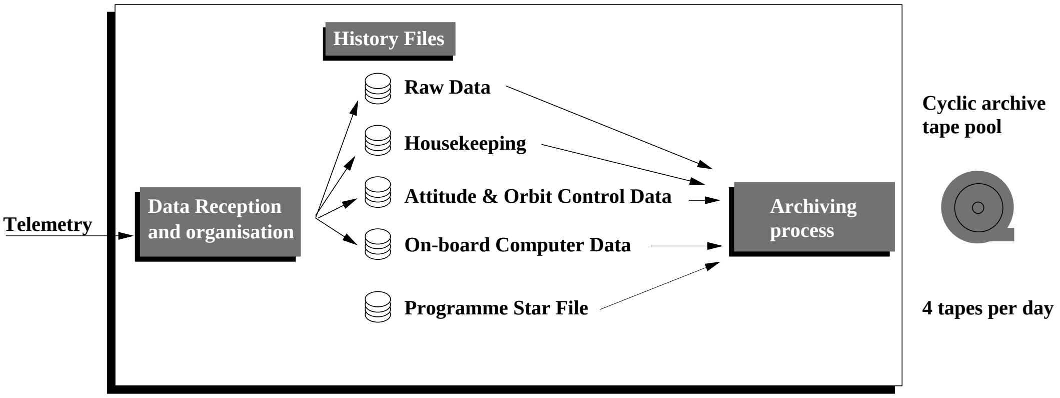

Figure 9.2. *Organising of the data archiving at ESOC. The various data streams from the satellite were merged with orbit data determined on-ground, and information from the programme star file, and despatched to the scientific consortia on magnetic tape.*

9.2. Data Distribution from ESOC to the Consortia

Scientific Data Distribution

ESOC archived all data coming from the satellite, and also took care of production and distribution of data tapes to the data reduction consortia. As a first step, archive tapes were produced on the Hipparcos real-time machine (VAX 8650) every 6 hours, without interfering with real-time operations. Each tape contained raw science data, housekeeping parameters, attitude and orbit control telemetry, on-board computer telemetry, and star information. The approximate volume of data on each tape was 100 Megabytes (see Figure 9.2).

The exact time spans of individual files contained in each of the master tapes of archive telemetry were held in an Oracle data base on the VAX. The running of a sequential tape production task caused the VAX data base to be queried and all new records to be transferred to the ESOC mainframe computer.

Two cartridge copies were made from each original archive tape: one going directly to a back-up store, and the other one was used to generate the scientific tapes. The off-line Comparex 8/96 machine was used for this second processing step. The archive cartridges were read to produce a set of disk files, where the derivation of the scientific data streams took place.

The recipients of the master set of data were situated at four sites in Europe, corresponding to two specific branches in the data reduction chain. Copies of the main mission data (i.e. data from the image dissector tube and selected data from the star mapper, ultimately leading to the Hipparcos Catalogue) were sent to the Royal Greenwich Observatory (RGO) for NDAC and to Centre National d'Etudes Spatiales (CNES) for FAST. Copies of the complete star mapper data records (ultimately leading to the Tycho Catalogue) were sent to two disinct institutes within the TDAC Consortium, the Astromisches Rechen-Institut in Heidelberg, and the Astromisches Institut in Tübingen.

From these four starting points the data were further distributed to groups contributing to the overall reduction and processing chain within the NDAC, FAST, and TDAC Consortia (see Volumes 3 and 4 for further details). In addition, subsets of the data were sent to the FAST Consortium's 'first-look' facility at SRON, Utrecht, for rapid but in-depth appraisal of the scientific data quality (see Section 9.3).

The Hipparcos tape production system for the data reduction consortia ran on the mainframe computer at ESOC. It consisted of six main components as follows:

(1) Tape Read: this read data from cartridges of archived telemetry into disk-based files. The files were organised as keyed sequential circular, and provided the input for the stream derivation task described below;

(2) Interactive Task: this provided a menu-driven interface allowing the user to configure the system for a single processing run and then to initiate processing by starting the Main Control Task or the Copy/Print Task. The different run types, 'First-Look', 'Sequential' and 'Ad Hoc' were all controlled at this level;

(3) Main Control: this acted as a scheduler for the following tasks. The status of the individual tasks was monitored by main control which could then spawn successive 'Read', 'Stream Derivation' and 'Write' operations depending on the return codes from the previous task;

(4) Tape Write: this wrote the reformatted telemetry onto magnetic tapes. The data was written when the system had sufficient data in its disk files to fill an output tape. The last tape written ended on the last full catalogue period present in the processed data. For sequential processing, two master tapes were produced, for the FAST and TDAC (Tübingen) groups;

(5) Copy/Print: this produced copies of the data reduction consortia tapes for the other groups (NDAC and TDAC Heidelberg) and printed tape labels and dispatch forms;

(6) Stream Derivation: this reformatted the telemetry in the format defined by the Hipparcos 'Data Delivery Interface Document', while performing quality checks and filtering the data. The main part of the processing was carried out in this task. Synchronisation of the various data streams to ensure that all streams covered exactly the same time intervals and removal of any spurious data was carried out here. Once the data had been checked for bad quality and valid satellite configuration, the remaining span was then divided into catalogue periods.

Final tapes for distribution to the scientific teams were created in an agreed interface format, specified completely by the Data Delivery Interface Document, which had been defined through dialogue and exchange of simulated data between ESOC and the Consortia well in advance of launch. The final tape contruction also added eclipse, orbit, payload monitoring and coil current calibration matrix files to the scientific streams. The scientific tapes were then distributed to the scientific consortia. Figure 9.3 shows the various steps in this tape production system.

ESOC also responded to specific requests from the consortia during the mission, to provide data tapes covering different time spans, used to evaluate anomalous trends in the behaviour of the payload or to validate specific aspects of the consortia software.

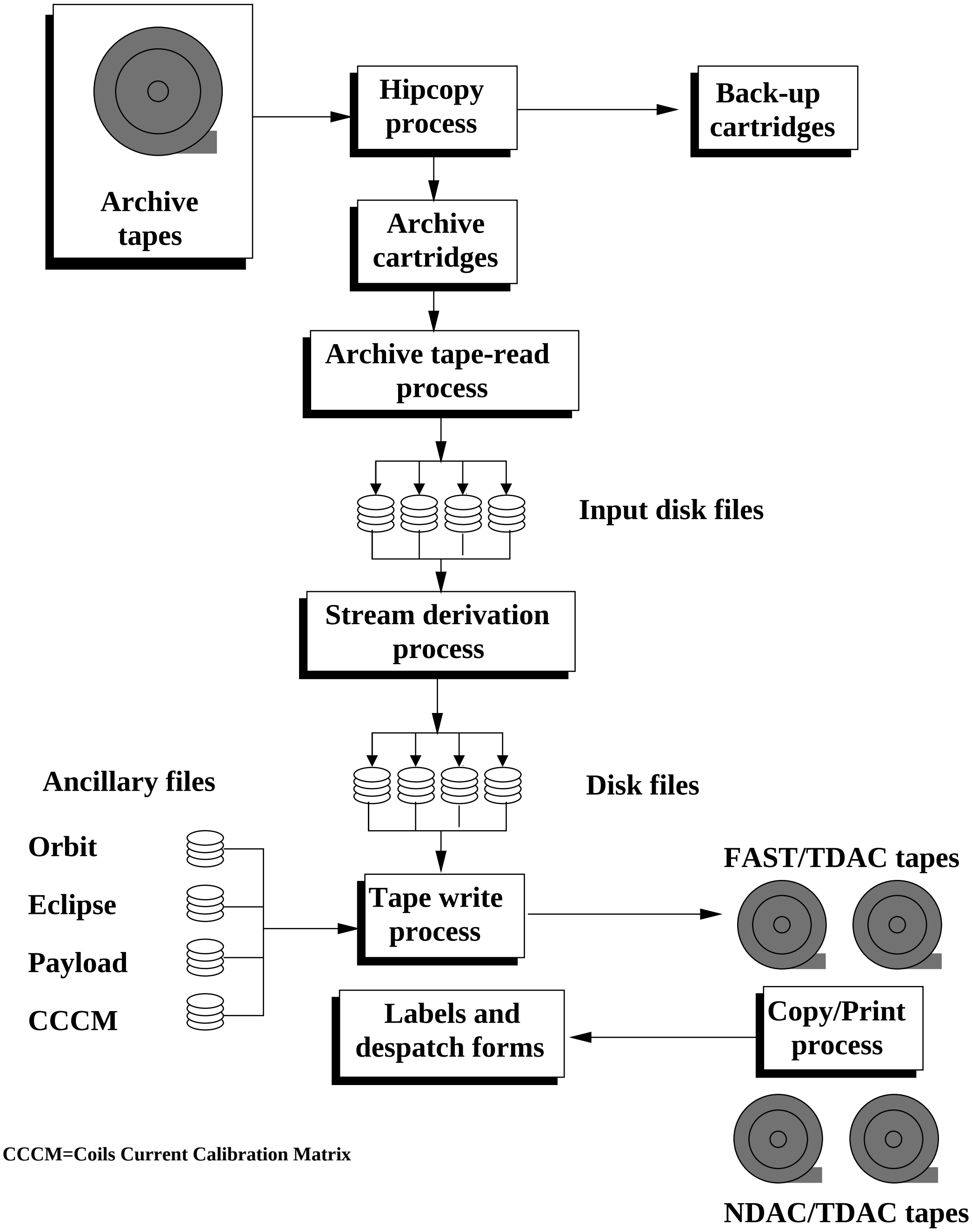

Figure 9.3. *ESOC tape production organisation, leading from the raw data received from the satellite to the magnetic tapes distributed to the data reduction consortia.*

The tape production system was designed with the nominal mission and nominal satellite configuration in mind. Certain changes were introduced as a result of the non-nominal orbit. The failure of on-board components also meant that certain parameters could no longer be reliably extracted from the telemetry. A method of inputting these ‘adjustable parameters’ was developed and extended throughout the mission as each new anomaly occurred. For example, gyro configurations, star mapper and image dissector tube selections plus additional nominal scanning law parameters were all entered. Checks on the satellite configuration were carried out by the stream derivation task. The changing, ‘cross-strapping’, patching and re-routing of the on-board systems demanded constant updates to the model against which the configuration was checked.

Once per week, several off-line tasks were performed to analyze all reports from the payload monitoring software in that period. One product from the analysis was a list of intervals in which the image dissector tube quality flag consistently showed that good scientific data was being collected. A file containing all such intervals over the entire mission was input to the tape production software. The consortia only processed data which was flagged as ‘good’ in this way.

The original raw telemetry was sorted and merged as follows: (i) decommutation into ‘floating streams’ corresponding to image dissector tube, star mapper data, housekeeping, attitude and orbital control system, and on-board computer data; (ii) association of telemetry reports from on-board computer streams with their corresponding data samples; (iii) extraction of star mapper data from the full star mapper data stream for transits of a magnitude-limited selection of programme stars; (iv) addition of orbit data and eclipse data; (v) addition of other ancillary data (payload monitoring results, coil currents calibration matrix data); and (vi) derivation of a data catalogue which described the payload and on-board computer status and identified periods of unchanging status. The files were transferred from ESOC to the consortia on magnetic tape.

The magnetic tapes were recorded at 6250 bytes per inch with a 7-bit ASCII character set. The maximum allowed blocksize in any file was fixed at 28 800 bytes and the maximum number of logical records were packed into each block. Each tape was self-contained and self-describing, with no multi-volume data sets.

There were two independent sources of timing information given on the tapes: the spacecraft (on-board) time and the ground station time. The ground station times had a resolution of 0.1 μs, but an absolute error of ± 1.0 μs which included a quantisation error of ± 0.2 μs associated with the clock. All telemetry frame times were retained and stored in compressed form with the attitude and orbit control system data stream. For each record of every stream only the initial ground station time and mean frame duration were stored in the telemetry header. The initial ground station time was not corrected for spacecraft-to-ground station propagation delay, nor for the internal ground station delay (these corrections were subsequently made by the data reduction consortia). The on-board time was stored in some records either as a 24-bit format counter or a 32-bit on-board time counter.

The structure of each tape was determined well in advance of satellite launch, following an extended period of dialogue between ESOC and the data reduction consortia, also involving the provision and analysis of simulated data, and leading to a complete specification of the tape structure and contents in the form of the Hipparcos ‘Data Delivery Interface Document’.

At the start of every tape was a ‘volume header’ which gave a unique identifier to this tape, followed by a ‘tape header’ file which identified the tape as a Hipparcos tape, recorded the date of production and described the structure and contents of the rest of the tape. Every tape then consisted of a series of files, each preceded by a header whose purpose was to identify the consortia for whom the tape was made and to describe the type of file. The end of each file was marked with an end-of-file record which would list the number of blocks in the preceding file. All subsequent files fitted into this structure in a systematic way, no matter which combination of data streams was written to a particular tape. The tape contents generally consisted of the data catalogue, and science and ancillary files. The latter consisted of the image dissector tube file, star mapper file, raw housekeeping (including derived parameters), Tycho data file, attitude and orbit control system data, orbit data, eclipse data, coil currents calibration matrix and payload monitoring results.

Data catalogue file: The data catalogue file was a catalogue of payload status changes derived from the application of an algorithm to the housekeeping data stream. The aim of the data catalogue was to provide a log where the sequence of payload operations was available in a convenient form, and to aid direct access to parts of the data from a tape after it was transferred to disk. A catalogued period was defined as a period containing an integral number of consecutive telemetry formats during which no significant status change occurred. For each such period one record was added to the catalogue.

Telemetry header: All files which were pointed to by the data catalogue had records with a common header containing timing, datation and quality information. All timing information in the header referred to the start of a record. If part of the information for a particular record was missing from the telemetry stream, the timing would still be defined as if the record had been of perfect quality.

Image dissector tube file: Each image dissector tube record was formed by merging an image dissector tube observation report, its associated photon counts and relevant information from the Hipparcos Input Catalogue (in particular the details of the star observation strategy, described in Chapter 8, could be derived from this file). The file also included data received during calibrations of the grid reference marks and internal star pattern assembly (see Chapter 2), in which case the appropriate calibration reports were used. A flag in the image dissector tube header indicated which of the possible alternatives (i.e. normal image dissector tube, or calibration report) was contained in a particular file. Observation reports were merged into the image dissector tube reports without modification.

Counts were integrated over 1/1200 s and were compressed on board in one of two ways, depending on how the star was observed. In the analogue mode (for stars of magnitude brighter than 1.5) counts were 8-bit integers, with nominal quanta of 250 counts per sample period for image dissector tube number 1 and 220 counts per sample for image dissector tube number 2. For stars with magnitude fainter than 1.5, the photon counting mode was used in which counts were expressed as a 3-bit exponent (E) and a 5-bit mantissa (M). For N counts ($0 < N < 8159$), with $J_{\mathrm{I}} = 32(2^{\mathrm{I}} - 1)$ ($0 < I < 7$), if $J_{\mathrm{I}} \leq N < J_{\mathrm{I+1}}$ then $E = I$ and $M = (N - J_{\mathrm{I}})/2^{\mathrm{I}}$. Any fractional part of M was truncated. To reconstitute the image dissector tube signal the algorithm was applied in reverse, with appropriate allowance for the effects of truncation and a non-linearity correction factor. This encoding method was also used for data samples in grid reference marks and internal star pattern assembly observation frames. In practice the analogue mode was never used (see Section 3.1).

Star mapper file: The star mapper file contained selected parts of the Tycho stream covering the calculated crossing times of selected programme stars merged with associated information from the programme star file. Crossing times were calculated for only one of the star mappers, whichever one was operational. For each transit 200 star mapper sample pairs (comprising B_T and V_T samples) were needed. To simplify the subsequent use of these records they were aligned on telemetry frame boundaries and contained 10 consecutive (i.e. separated by $0.04166\ldots$ s) frames centered around the calculated transit ($T_{\rm calc}$). Star mapper records were stored in chronological order, and stars with $B > 10.25$ mag were disregarded. The transit in a given star mapper record occured at sample number $[(T_{\rm calc} - T_{\rm start}) \times 0.25] + 1.625$ within the record, thus the 200 samples of B or V could be extracted from the 250 samples in each record. The constant 1.625 was the delay between the accumulation of a sample and its appearance in the telemetry. The star mapper samples were encoded with the same semi-log compression law as for the image dissector tube photon-counting mode. There was no corresponding analogue mode for bright stars in the case of the star mapper data.

Tycho file: Each data record contained data extracted from one high-rate telemetry format, namely: (a) standard telemetry header and (b) the Tycho data stream of interleaved $B_{\rm T}$ and $V_{\rm T}$ star mapper counts, encoded with the same semi-log formula used for the image dissector tube data.

Raw housekeeping and derived parameters: This file contained housekeeping data extracted from the raw frame of the high telemetry format, and included additional information appended by ESOC to each record. There was a one-to-one correspondence between raw housekeeping records and the original raw formats. The contents of any bad or missing formats were set to zero. The additional information consisted of the temperature and powers associated with the 24 payload thermal control cells. The housekeeping data also included the complete spacecraft and payload memory-load-command readouts, along with other parameters which were duplicated in the data catalogue records.

Attitude and orbit control system file: The attitude and orbit control system parameters in each telemetry frame were extracted and stored, without modification, as a separate stream with one record per original format. The telemetered parameters were arranged into two groups: (i) those data expected to be of primary interest to the data reduction consortia, and (ii) housekeeping and status data which was not of primary relevance to the data reduction but may be necessary or helpful for scientific checks which were not foreseen at the time. Parameters associated with missing or bad frames were included and processed, but were tagged with an appropriate quality flag. These attitude and orbit control system files also contained the full datation of all incoming telemetry frames, although this was only expected to be used in the event that the on-board oscillator was unstable. Records were only created when the normal attitude and orbit control system format was being telemetered.

Orbit data: Orbit data were organised into a cumulative file covering the satellite lifetime. There was no relation or precise synchronisation between orbit records and telemetry records, thus the orbit data were not pointed to by the data catalogue, instead a description of the whole orbit file was contained in the first record. The time interval covered by a record was normally about 7–8 hours around apogee, and 0.5–1 hour around perigee.

Eclipse data: The eclipse file was another ancillary file pointed to by the tape header file and not by the data catalogue. It contained details of all eclipses that occurred during the mission.

Coil currents calibration matrix data: Real-time calibration generated one such record each time an internal star pattern or grid reference marks sequence resulted in an update of this calibration matrix.

Payload monitoring results: Payload monitoring generated long-term image dissector tube and star mapper reports, approximately one record per week.

First-Look Monitoring

Every week a special ‘First Look’ tape was sent from ESOC to SRON, Utrecht, a member of the FAST Consortium, for preliminary analysis of the science data. Unlike the main data processing which might only be processed weeks or months after the observations were made, the ‘First-Look’ task processed the data within a few days of delivery to assess the scientific data quality. Through rapid calibration of certain parameters associated with the instrument (e.g. basic angle, grid rotation, and single-slit response) ESOC were informed promptly if unexpected trends or disturbances were observable. ESOC were then able to examine the operations logs around the time of an event to see if there was a correlation with spacecraft activities at that time, and to take appropriate action if necessary. In addition, the ‘First Look’ facility provided payload calibration data to FAST, NDAC and ESOC.

Focus Evolution and Photometry Results

Results from the weekly payload monitoring analysis included an averaging of the intensities and grid modulation coefficients contained in the image dissector tube and star mapper reports. This gave an evaluation of the photometric degradation of the payload due to, for example, radiation darkening of the optics, or temperature instabilities. The best focus position evolved continuously throughout the mission, primarily due to moisture release. The refocusing calibration was performed every week throughout the mission (or more regularly in the case of anomalies) to monitor the best focus position and when necessary to change the actual focus position on-board. Details of the focus evolution and photometric degradation were communicated to Matra Marconi Space for further evaluation. A discussion of both phenomena is presented in Chapter 10.

9.3. Data from FAST to ESOC in Support of Satellite Operations

First-Look Monitoring Feedback

This interface (described above) proved to be very successful in identifying any trends in basic angle evolution and other payload phenomena. Already during the routine phase, as on-board heaters started to fail, Utrecht were able to provide important information when it was necessary for ESOC to perform special thermal control operations (see Chapter 12). Given that thermal instabilities could cause payload deformation, it was critical for ESOC to know within days rather than weeks if operations were degrading the scientific data. This would allow corrective actions to be attempted. Additional important assistance was given in analysing the star mapper data during the two-gyro operational phase, as attempts were made to revive the spacecraft after hibernation (see Chapter 15).

Basic Angle and Grid Rotation

During the commissioning phase, it was necessary for ESOC to perform an initial coarse calibration of the basic angle (the angle between two fields of view) and grid rotation (the misalignment of the image dissector tube and star mapper grids with respect to the scanning plane), to refine the operations of the ground real-time attitude determination software. Thereafter, Utrecht were able to process the scientific data to yield more accurate values, which were fed back into the ground real-time attitude determination input data, giving rise to improved convergence of the attitude determination software. In addition, on 23 January 1990, the first calibrated grid rotation was used on-board resulting in a significant improvement in on-board real-time attitude determination performance. The real-time attitude determination ‘innovations’, which give a measure of the attitude corrections necessary between star mapper transits, were reduced from about ±5 arcsec to about ±2 arcsec. Subsequent monitoring of the basic angle by the consortia is described in Section 10.2.

9.4. Data from NDAC to ESOC in Support of Satellite Operations

Gyro Misalignment

The on-board real-time attitude determination system relied on integrated gyro outputs for determining the attitude between star mapper transits. The conversion of the satellite body rates around the operational gyro input axes was performed on-board and on-ground using a suitable projection matrix, and assuming the pre-launch calibration of the alignments. The NDAC Consortium, unlike the FAST Consortium, used the gyro output for the scientific data reduction. A by-product of the initial NDAC processing, conducted at the Royal Greenwich Observatory (RGO), was a calibration of the gyro misalignments with respect to the nominal positions. On 4 July 1991, the RGO was able to supply a newly calibrated projection matrix for uplink to the spacecraft. Subsequently, as the gyro configuration changed, due to gyro failures, particularly at the start of two-gyro operations, further projection matrices were supplied by the RGO for operational use.

External Disturbance Torque and Thruster Calibration

A further product of the NDAC processing, performed by the RGO, was a detailed study of the external disturbance torques acting on the spacecraft as well as the evolution of the thruster performance with time (see Volume 3, Chapter 8 for further details). The thruster performance results were used by ESOC to perform tuning of the thruster on-time coefficients as part of the on-board attitude control. One significant result was to show a difference in performance between the plus and minus thruster around each axis. This however could not be compensated for in the original real-time attitude determination design since separate on-time coefficients were only available for each thruster axis and assumed identical performance for both thrusters around that axis.

This was valuable information in defining the real-time attitude determination algorithm for zero-gyro operations (see Chapter 16). The revised real-time attitude determination relied on an on-board disturbance torque model, which had to be updated on a regular basis from ground predictions. In addition, independent on-time thruster coefficients were applied for each thruster. The RGO participated with ESA and Matra Marconi Space in defining the new algorithm, using the experience already gained in determining the variability of the various torques around the orbit.

Although the disturbance torques around each of the spacecraft axes were broadly repeatable, with combined periods equal to the spacecraft rotation and orbital periods, the effect of the Earth's magnetic field, and a number of small partially-explained torques (such as gravity gradient and magnetic torques), could change fairly rapidly. For zero-gyro operations, this required a fast response time to re-calibrate and uplink the revised torques. To this end, the RGO supplied their on-ground attitude reconstitution software to ESOC for use in operations, to perform disturbance torque and thruster calibrations during every perigee passage for the next orbital period.

Preliminary Catalogue Results

NDAC were able to feed back their preliminary star positions and brightnesses to ESOC, via the INCA Consortium, to be used for the on-board programme star file. This was done in two stages as more results became available.

In February 1991, Input Catalogue Version 8 was received and implemented at ESOC, containing approximately half the programme stars updated from Hipparcos data. By November 1992, Input Catalogue Version 10 was received, with nearly all of the input catalogue stars now containing early Hipparcos results. The improvements in accuracy of the positions were, by that time (as expected), largely masked by the intrinsic performance accuracy of the real-time attitude determination. This and the greater reliability in the magnitude estimates allowed ESOC to tune the selection criteria for real-time attitude determination guide stars and to tune the on-board star mapper processing parameters to optimise the correct identification of guide stars in the star mapper data stream and virtually eliminate any possibility of mis-identifying stars, which could lead to an unexpectedly large innovation error in the on-board control.

All of the above support from the FAST and NDAC Consortia, when combined with additional work performed by ESOC and Matra Marconi Space, contributed strongly to the overall improvement in real-time attitude determination performance which was achieved by 1992, before significant problems with noisy gyros were experienced (see Chapters 14–15). By that time, real-time attitude determination innovations were consistently around ±1 arcsec, compared to the start of the mission figure of ±5 arcsec. Moreover the regularity with which real-time attitude determination was staying converged after perigee was also increased.