2. OPERATING PRINCIPLE

This chapter describes those features of the Hipparcos satellite which have a major impact on the measurement principle. The key features of the payload design, the way in which the satellite scans the sky (the 'scanning law'), and the way in which the stars present in the combined field of view are observed (the 'star observing strategy') are described.

2.1. Introduction

The purpose of the Hipparcos mission is the measurement of the positions, proper motions, and trigonometric parallaxes of about 120 000 stars. To do this, a special optical telescope has been designed to function on a spacecraft placed in a geostationary orbit, above the earth's atmosphere. The telescope has two fields of view, each of size $0^\circ\!.9 \times 0^\circ\!.9$, and separated by about 58°.

The satellite is designed to spin slowly, completing a full revolution about its spin axis in just over two hours. At the same time, it can be controlled so that there is a slow change in the direction of the axis of rotation. In this way, the telescope will be able to scan the complete celestial sphere.

Measurements of the angles between pairs of stars, inferred from the relative phases of the modulated signals created by the main grid, are built up over the 2.5-year lifetime of the satellite in orbit. From many such measurements, made at many different orientations, and at many different epochs, a whole-sky astrometric catalogue will be built up, containing the positions, parallaxes, and proper motions of all of the stars on the pre-defined observing list. This list, which contains about 120 000 stars, constitutes the so-called 'Input Catalogue'.

2.2. Measurement Principle

The payload is centred around an all-reflective Schmidt telescope, the light from two sections or 'fields' of the sky is conveyed through two baffles, which are set at a fixed angle of about 58°. A 'beam combiner' allows the two fields, which are viewed simultaneously, to be projected onto the spherical primary mirror. It is then possible to determine the true angle between two stars, one in each field of view, by using the known or 'basic angle' of 58° between the two fields of view, plus the apparent separation measured on the focal surface of the telescope. This choice for the basic angle was influenced by the goal of connecting stars with very different parallax factors by measurements within the combined field of view. The precise value chosen was selected by considering the 'rigidity' of the resulting measurements made over a great-circle scanned by the satellite, as illustrated in Figure 2.1.

The focal surface on which the two fields of view are focused contains 2688 parallel slits in an area of about 2.5×2.5 cm^2, covering about $0^\circ\!.9 \times 0^\circ\!.9$ on the sky. As the telescope slowly scans the sky, the star light is modulated by the slit system, and that modulated light is sampled by an image dissector tube detector, at a frequency of 1200 Hz. At any one time, some four or five of the selected (or programme) stars will be present in the two fields of view. The detector has a small sensitive area, referred to as the instantaneous field of view, covering an area of about 38 arcsec in diameter (projected on the sky). The size of the instantaneous field of view was minimised as the result of a 'piloting budget', accounting for the *a priori* errors on the star positions, the performance of the satellite real-time attitude determination, and the fact that the instantaneous field of view is not tracked continuously to follow the moving star images.

The detector can only follow the path of one star at a time, but under rapid computer control it is able to track all the programme stars for short intervals of time during their passage across the field, which takes about 20 s.

In this way, measurements of the relative positions of the programme stars are continually being made. Due to the scanning motion of the satellite, the majority of stars in the field of view at any time appear first in the preceding field of view, and then in the following field of view about 20 minutes later. As the scans also overlap laterally when the satellite axis of rotation changes on each sweep of the sky, the stars will appear again, but this time compared with other stars. In this way, a dense net of measurements of the relative separations of the stars is slowly built up.

The satellite spin axis is kept at a constant inclination of approximately 43° to the direction of the sun, and revolves around the sun once in approximately eight weeks, resulting in a continuous and systematic scanning of the celestial sphere. Any region of the sky will be scanned many times during the mission by great circles which intersect at well-inclined angles. A typical star will be observed some 80 times in each field of view throughout the lifetime of the satellite. The number of possible connections between the observed stars is considerably enhanced due to the almost simultaneous observation of stars separated by the large basic angle. Scientists involved in the data analysis will then combine the individual measurements to form the final Hipparcos Catalogue, including the displacements due to parallax and proper motion, using techniques similar to those used in triangulation in surveying the earth's surface.

In addition to the main instrument, the payload includes two star mappers, one of which is normally switched off and is provided for redundancy. The function of the star mapper is to provide data allowing real-time satellite attitude determination, a task performed on-board the satellite, and the *a posteriori* reconstruction of the attitude, a task carried out on the ground. The star mapper data is also used by the Tycho experiment to perform astrometric and two-colour photometric measurements of about 400 000 stars, down to about 10–11 mag. Each star mapper consists of a star mapper grid, located at the side of the primary modulating grid, and two photomultipliers measuring the light transmitted by the whole star mapper grid in two different spectral bands, roughly corresponding to the well-known Johnson B (blue) and V (visual) bands. The spectral separation is performed by means of a dichroic beam splitter, which directs the transmitted light of one colour onto one of the photomultiplier tubes, and the reflected light of another colour onto the second tube. Each star mapper consists of two sets of four slits, each set at different inclinations with respect to the scanning direction, so that the satellite attitude can be derived from the photomultiplier signals, as the star images move across the grid. The modulated light signal is converted into photon counts by the two photomultiplier tubes, which are sampled at a frequency of 600 Hz.

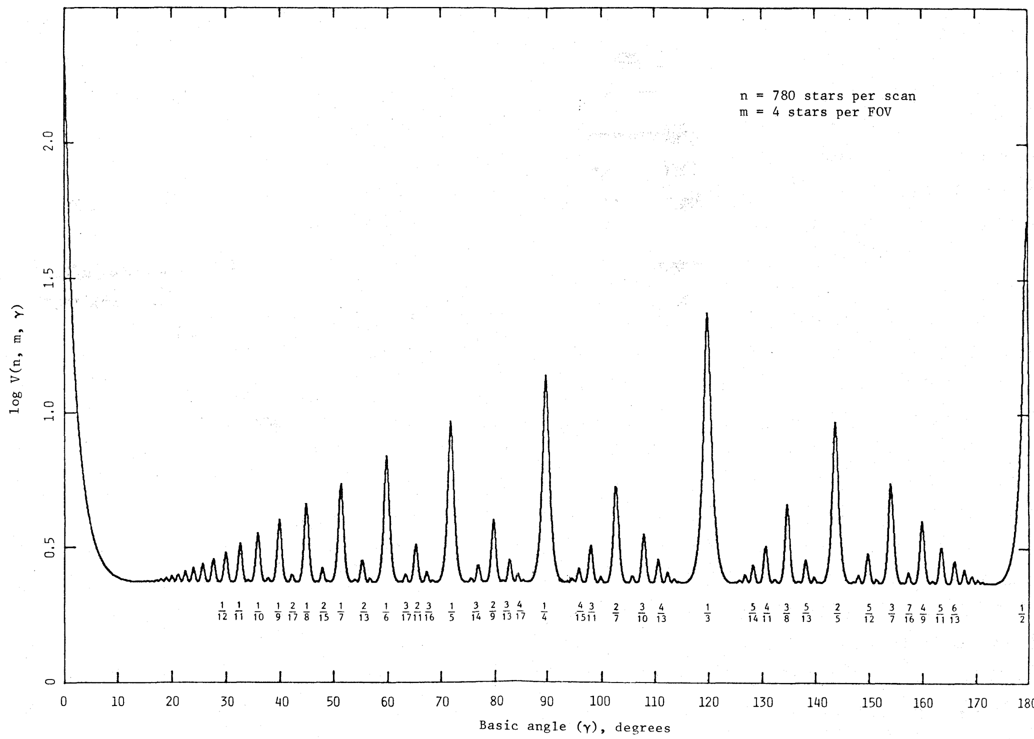

Figure 2.1. *The 'rigidity' of the solution for star abscissae on a great circle scanned by the satellite is strongly influenced by the choice of the 'basic angle' between the two fields of view. The chosen value of* 58° *was selected as providing good rigidity, at the same time allowing the simultaneous measurements of stars having very different parallax factors. Peaks in the function indicate basic angles which would be unsuitable from the point of view of the rigidity of the great circle solutions.*

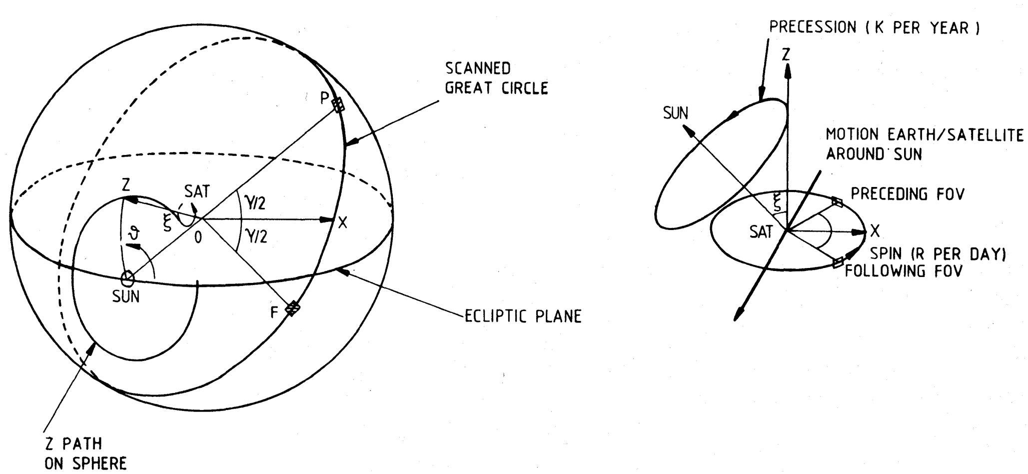

Figure 2.2. *Definition of the telescope reference frame.*

2.3. The Scanning Law

The Hipparcos satellite will scan the sky in a manner that ensures complete coverage of the celestial sphere several times during the mission. The satellite attitude motion is most easily described in terms of the movement of the telescope with respect to the ecliptic reference system.

The telescope reference frame (Figure 2.2) is the rectangular right-handed frame (OXYZ), where the origin, O, is the intersection of the two lines of sight, OP and OF, of the telescope; the plane (X,Y) is coincident with the plane (P,F); and the X-axis is the bisector of the basic angle POF (see also Volume III, Chapter 1).

The satellite scanning motion is then defined as follows: the Z-axis of the telescope reference frame rotates at a constant angle $\xi = 43°$ around the sun direction, following the sun in its apparent motion along the ecliptic and performing $K = 6.4$ revolutions per year. At the same time, the satellite rotates around the Z-axis in the (X,Y)-plane performing $R = 11.25$ revolutions per day. The motions of the axes OP and OF of the preceding and following fields of view, which scan the celestial sphere, result directly from this scanning motion.

Quantitative Description of the Scanning Law

In precise terms, the nominal sun line is defined by the following orientation:

$$\mathbf{s}(d) = \mathbf{l}\cos\lambda_s + \mathbf{j}\sin\lambda_s \qquad [2.1]$$

$[\mathbf{l}\,\mathbf{j}\,\mathbf{k}]$ being the ecliptic coordinate triad for the mean ecliptic and equinox of J 2000.0, and:

$$\lambda_s = L + 2e\sin g + \frac{5}{4}e^2\sin 2g \qquad [2.2]$$

$$L = -1.38691 + 0.0172021240d \qquad [2.3]$$

$$g = -0.04114 + 0.0172019696d \qquad [2.4]$$

$$e = +0.016714 \qquad [2.5]$$

where d is the time in mean solar days from the reference epoch adopted for the nominal scanning law, defined as 1988 Jan 1, $12^{\mathrm{h}}00^{\mathrm{m}}00^{\mathrm{s}}$ UTC (in practice, d is defined in terms of the satellite on-board clock).

The composition of the precession of the spin axis Z and the rotation of the earth (and satellite) around the sun results in a motion of the Z-axis on the celestial sphere, with a speed designated V_z. The orientation of the telescope reference frame with respect to the heliotropic reference frame is described by the attitude angles ν, ξ, Ω (see Volume III, Chapter 1). The speed V_z is kept approximately constant by modulating the precession angle ν.

$$\nu = \overline{\nu} + a_1\cos(\overline{\nu}) + a_2\sin(2\overline{\nu}) + a_3\cos(3\overline{\nu}) + a_4\sin(4\overline{\nu}) \qquad [2.6]$$

where $\overline{\nu} = \overline{\nu}_0 + 6.4\lambda_s$, and the coefficients a_i are the following:

$$a_1 = -0.163\ 784\ 59 \qquad [2.7a]$$

$$a_2 = -0.013\ 077\ 77 \qquad [2.7b]$$

$$a_3 = +0.001\ 232\ 43 \qquad [2.7c]$$

$$a_4 = +0.000\ 123\ 41 \qquad [2.7d]$$

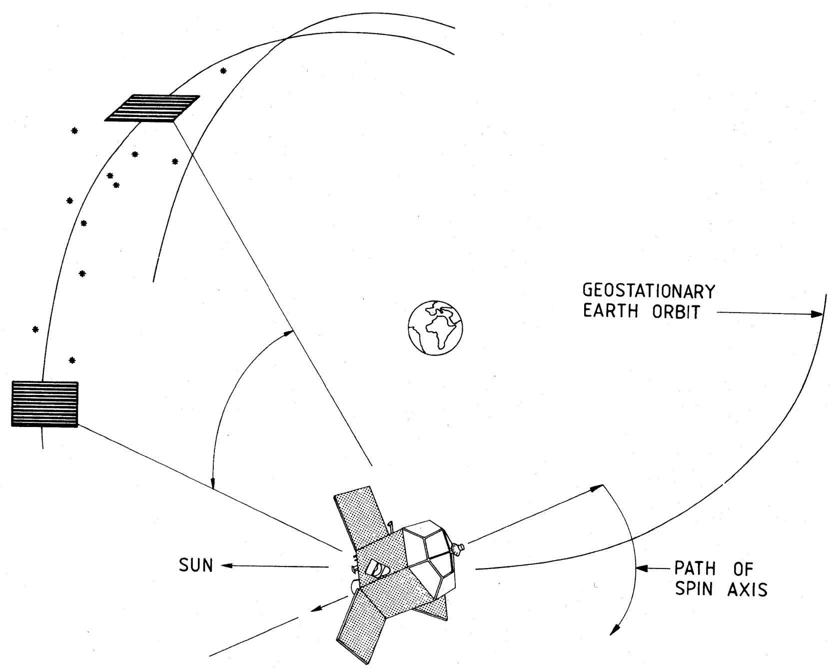

Figure 2.3. *The measurement principle of the Hipparcos mission. The two fields of view scan the sky continuously, and relative positions of the stars along the scanning direction are determined from the modulated signals resulting from the satellite motion.*

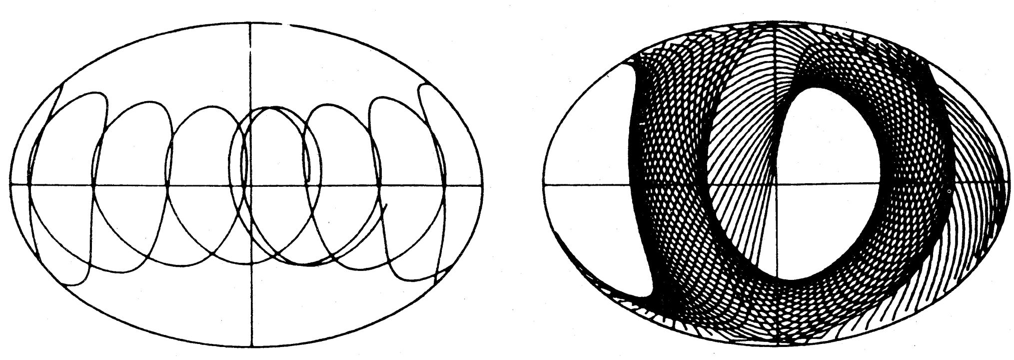

Figure 2.4. *The scanning motion of the Hipparcos satellite on the celestial sphere. On the left, the path of the spin axis is shown for a time interval of slightly more than one year. The sky is shown as a projection in ecliptic coordinates, and in this framework the sun appears to move along the horizontal line. In the right figure, the corresponding path of one of the fields of view over 50 days is shown. In this illustration, only one great circle scan per day is shown, the actual scanning being 11.25 times faster.*

The instantaneous spin rate, ω_z, is kept approximately constant by modulating the heliotropic attitude angle, Ω, as follows:

$$\Omega(d) = \Omega_0 + 2\pi R(d - d_0) - \nu \cos\xi + (b_1\bar{\nu} + b_2 \cos\bar{\nu} + b_3 \sin(2\bar{\nu}))\frac{\sin\xi}{K} \qquad [2.8]$$

where:

$$b_1 = +0.082\ 152\ 69 \qquad [2.9a]$$

$$b_2 = +0.990\ 061\ 17 \qquad [2.9b]$$

$$b_3 = +0.040\ 452\ 13 \qquad [2.9c]$$

The parameters used in the nominal scanning law are the spin rate, $R = 11.25$ revolutions per day (168.75 arcsec s^{-1}), the revolving scanning angle, $\xi = 43° \pm 0\overset{\circ}{.}5$, and the average precession rate, $K = 6.400 \pm 0.002$ revolutions per year. The principle of the scanning measurements is illustrated in Figure 2.3, and the resulting scanning of the celestial sphere is shown in Figure 2.4.

The initial precession angle, $\bar{\nu}_0$, is provisionally set to 221°. Although this angle will be fixed throughout the mission, its precise value may be modified, depending on the actual launch date (it has a weak influence, for example, on the impact of earth and moon occultations). The value of Ω_0 is decided by ESOC during operations—it may be modified after any re-acquisition of the scanning law.

The above description defines the 'nominal scanning law', i.e. the nominal paths of the fields of view on the sky throughout the mission. Deviations of up to ± 10 arcmin about the three satellite axes are tolerated in practice, attitude motion within these limits being controlled autonomously on-board by means of the attitude and orbit control system (see Chapter 18).

2.4. Star Observations

At focal-plane level the result is a continuous flow of stars from both viewing directions. Each star crosses the field of view of the telescope in 19.2 s, and some 4–5 programme stars, on average, are in the combined field of view at any time.

A grid covering a square field of $0\overset{\circ}{.}9 \times 0\overset{\circ}{.}9$ is situated at the focal surface of the telescope. It consists of 2688 parallel slits perpendicular to the scanning direction, with a period of 1.208 arcsec. The grid modulates the light of each crossing star, which is then collected by an image dissector tube and converted into photoelectron counts.

The sequence of photoelectron counts obtained during the transit of a star can be used to derive its phase. From the phase difference of two stars observed almost simultaneously in the field of view, their angular separation can be derived.

The instantaneous field of view of the image dissector tube is circular with a diameter of 38 arcsec. The instantaneous field of view position can be directed at any point of the field of view by varying the currents applied to the deflection coils. Only one star can be followed at a time; hence strictly simultaneous observation of two stars is not possible. Quasi-simultaneous observations in practice are achieved by switching very frequently the instantaneous field of view from one star to another following a predefined scheme. The scheduling policy used to reposition the instantaneous field of view this way and allocate the observation time to the various stars is called the 'star observing strategy'.

Optimising the Star Observations

The star observing strategy algorithm, implemented in the on-board computer, makes a selection, at regular time intervals, from the programme stars which cross the field of view (information about the stars expected to cross the fields of view, on the basis of the nominal scanning law, is uplinked from the ground station to the satellite at regular intervals.). The star observing strategy determines those stars that have to be observed, and allocates to them appropriate observation times.

The choice of the algorithm depends on optimisation criteria related to the performance of the mission, and on system constraints due to the hardware environment in which the star observing strategy has to operate. The main optimisation criteria are the following:

(1) minimisation of jitter effect: since observations of stars in the combined field of view are not strictly simultaneous, the attitude jitter of the satellite could introduce considerable noise in the measurements. The star observing strategy must be able to minimise this effect by proper interlacing of star observations;

(2) distribution of observations between the two viewing directions: implicit in the Hipparcos concept is the capability of measuring relative angular distances between stars located far apart on the celestial sphere. It is one of the objectives of the star observing strategy to make sure that, when several stars are present in the combined field of view, angular distances are measured, whenever possible, between stars coming from the different fields of view;

(3) compatibility with the overall observing programme: in order to achieve the target precision at the end of the mission, stars of the various classes of magnitudes should receive, on average, a certain, predefined, global observation time. One of the functions of the star observing strategy is to ensure that stars receive, during their crossing of the fields of view, a time allocation compatible with their global observation time;

(4) special emphasis on the observation of bright stars: observations of bright stars ($B < 9$ mag) are particularly valuable. Their positions can be measured with high precision, and subsequently used in the determination of the attitude of the satellite during the relatively long time periods (400 s on average) between attitude control jet firings. This 'smoothing' of the attitude determination provides, in turn, connections between pairs of bright stars not simultaneously present in the combined field of view. These additional connections can considerably improve the final astrometric results. The star observing strategy is implemented such that bright stars are observed as long as possible, that is as soon as they enter the field of view and until just before they leave it;

(5) minimisation of errors due to grid imperfections: imperfections in the manufacture of the grid could induce errors in the phase measurements of a star. These errors are considerably reduced by a proper choice of the observation scheme.

The main system constraints related to the hardware environment in which the star observing strategy has to operate are the memory and CPU time limitations of the on-board computer; the synchronisation with the telemetry format, the attitude and orbit control system, and the cold gas thruster firing; and constraints due to the downlink telemetry resources.

2.5. The Star Observing Strategy

The star observing strategy algorithm is built around a rigid time hierarchy and its operation is driven by three star-dependent parameters uplinked from ground. The time hierarchy is based on the following definitions:

(1) the sampling period, $T_1 = \frac{1}{1200}$ s, is the sampling time during which photoelectron counts are accumulated by the image dissector tube;

(2) the instantaneous field of view repositioning period, $T_2 = 8T_1 = \frac{1}{150}$ s, is the shortest time interval (or 'slot') during which the instantaneous field of view remains pointed on a given star. Each star is always observed for an integer number of slots, and the instantaneous field of view remains pointed at the same location on the grid throughout a slot. If a star is observed for more than one slot, the position of the instantaneous field of view is updated between the slots;

(3) the interlacing period, $T_3 = 20T_2 = \frac{2}{15}$ s, is the period of time during which a group of up to 10 stars are observed;

(4) the observation frame period, $T_4 = 16T_3 = 2.13\dot{3}$ s, is the period of time during which essentially the same group of stars are observed in the same order and with a given observation time allocation (exceptions are discussed below);

(5) the transit time, $T_5 = 9T_4 = 19.2$ s, is roughly the time interval taken for any given star to cross the field of view of the telescope.

Star-Dependent Parameters

The star-dependent parameters uplinked from ground, and on which the star observing algorithm operates, are:

(1) the selection index, b, is the parameter used to calculate the priority with which a programme star must be observed with respect to the other programme stars simultaneously present in the field of view;

(2) the minimum observation time, x, is the minimum number of slots of T_2 which, at frame level, must be allocated to a star in order to achieve a sufficient precision in phase extraction. x is a function of the magnitude of the star;

(3) the target observation time, y, is the observation time which, at frame level, must be allocated to a given star in order to achieve, at the end of the mission, the global observation time associated with that star. y is also a function of the magnitude of the star.

The values of the star-dependent parameters may vary during the mission, to take into account the past and projected observational history of the star, but they are fixed during each crossing of the field of view by the star. The values of x and y for a star of given magnitude have been determined on the basis of simulations carried out by the Input Catalogue and Data Reduction Consortia, and are uplinked during the mission from the Operations Control Centre to the satellite, where the star observing strategy is implemented.

Other parameters included in the star observing strategy algorithm are: the predicted time of entrance of the star in the field of view; its magnitude; a flag indicating whether the star is observed in the preceding or following viewing direction; and a flag indicating whether the star should be observed by the star mapper for attitude-measurement purposes (a subset of some 40 000 programme stars, in particular bright stars with good *a priori* positional accuracies, fall into this category).

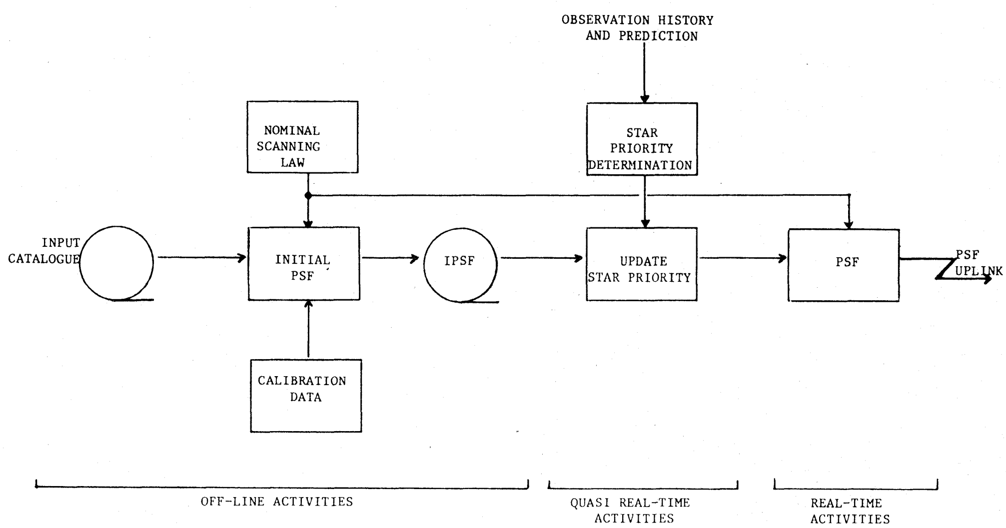

Figure 2.5. *Data processing involved in the generation of the programme star file.*

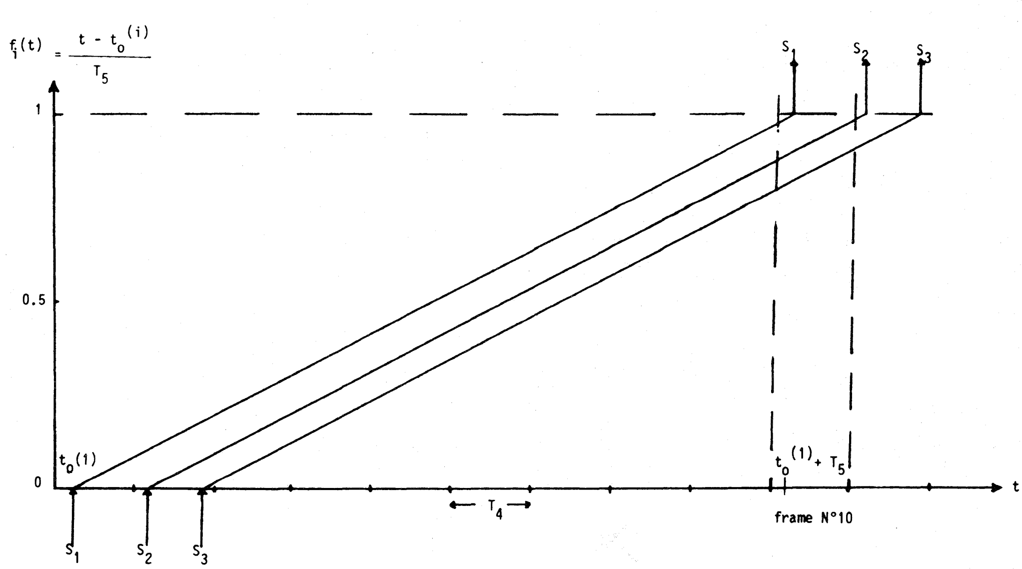

Figure 2.6. *The flow of programme stars in and out the combined field of view, illustrated by means of a time diagram.*

During the satellite operations, the Operations Control Centre processes the star data derived from the Input Catalogue and the observational history of the programme stars to produce a so-called 'programme star file', containing the information to be uplinked to the satellite. The programme star file contains star identifications, magnitudes, field of view entering times, viewing direction flags, and the current values of the three star-dependent parameters discussed above. A scheme for the data processing involved in the generation of the programme star file is shown in Figure 2.5.

Fully and Partially Observable Stars

When a frame of $T_4 = 2.13\dot{3}$ s is considered, stars that remain in the combined field of view during the entire frame are called fully observable stars; those that remain in the combined field of view only for a part of the frame, but not less than three interlacing periods ($3T_3$), are called partially observable stars—these can be stars that either leave or enter the combined field of view during the frame period.

One way to visualise the flow of programme stars in and out of the combined field of view is by means of a time diagram, such as that shown in Figure 2.6. A star S_i enters the field of view at time t_0^i and leaves it at time $t_0^i + T_5$. The 'transit line':

$$f_i(t) = \frac{t - t_0^i}{T_5} \qquad [2.10]$$

represents the fraction of transit time spent by the star in the field of view:

$$0 \leq f_i(t) \leq 1 \qquad [2.11]$$

One can easily identify the stars that are present in the field of view at a given time t' by drawing the line $t = t'$: they are those whose transit lines are intercepted by $t = t'$.

By marking on the t-axis the time intervals corresponding to subsequent frames of $T_4 = 2.13\dot{3}$ s, one can also identify the stars present in a given frame. For example, in frame number 10 of Figure 2.6, there are three stars present in the combined field of view, of which two are fully observable stars and one is a partially observable star, leaving the field of view before the end of the frame period.

Star Selection

The star observing strategy algorithm involves both star selection and observation-time allocation. Star selection proceeds according to the following rules:

(1) from the data contained in the programme star file and the real-time attitude calculated on-board, identify the stars present in the combined field of view for the next frame; retain the first 15 of them for further selection;

(2) among the stars retained, identify the partially observable stars and classify them into 'leaving' and 'entering' stars;

(3) identify the fully observable stars;

(4) if there is at least one fully observable star, select up to two partially observable stars (one leaving and one entering) provided that they are brighter than magnitude $B = 9$ mag, choosing the brightest in each class;

(5) if there is no fully observable star, select up to two partially observable stars (one leaving and one entering) choosing the brightest in each class;

(6) once the partially observable stars, if any, are selected, proceed to the selection of the fully observable stars as follows: (a) select alternatively one star from the preceding and one star from the following viewing direction, until one of the two groups is exhausted;

then add the remaining stars; (b) within each of the two groups, select stars according to their priority index, defined by:

$$P_i = (-1)^k \frac{t_k - t_0^i}{T_5} b_i \qquad [2.12]$$

where i is the star identification number of star S_i, k is the frame identification number, t_0^i is the time of entrance of star S_i in the field of view, t_k is the mid-time of frame k, b_i is the selection index, and T_5 is the transit time. Priority is then given to stars with the higher values of P_i. (Due to the factor $(-1)^k$, priority indices change sign from one frame to the next, in such a way that priorities are alternating: the star with the highest priority in frame k is, as a rule, the star with the lowest priority in frame $k+1$);

(7) the complete list of stars selected consists of the partially observable stars, if any, plus a number of fully observable stars, if any, such that the total number of stars selected for observation during the relevant frame period does not exceed ten. (The alternating priority parameter ensures that, in those (rare) cases where more than 10 stars are simultaneously visible in the combined field of view, those stars not observed during one frame period are observed during the subsequent frame).

Observation Time Allocation

Observing time is allocated over an interlacing period of $T_3 = \frac{2}{15}$ s. The resulting time allocation is repeated for the 16 interlacing periods contained in a frame, except for the change described at point (5) below. The observing time is allocated as follows:

(1) if there is no fully observable star in the field of view, allocate 10 slots of $T_2 = \frac{1}{150}$ s to each partially observable star when two partially observable stars are selected, or all 20 slots of T_2 to the one partially observable star, if only one partially observable star is selected;

(2) if there is at least one fully observable star in the field of view, allocate two slots to each partially observable star selected. Once the observation time allocation to partially observable stars is completed, allocate the remaining slots available to the selected fully observable stars as follows:

(3) allocate, in sequence, to each fully observable star its minimum observation time x_i, until either the list of stars is exhausted or the number of slots available (20) in the interlacing period is exceeded. In the latter case, drop the remaining fully observable stars from the observation list and no longer consider them. In the absence of any partially observable stars, at least two fully observable stars, if present, shall always be observed, by allocating, if necessary, an observation time shorter than the minimum observation time (for the faintest stars the nominal x_i is larger than 10 slots);

(4) allocate the remaining slots, if any, one by one to the fully observable stars actually observed, on the basis of their so-called 'performance index' z_i, defined as:

$$z_i = \frac{n_i}{y_i} \qquad [2.13]$$

where n_i is the actual number of slots already allocated to the star in the interlacing period, and y_i is the target time. Allocate the first available slot to the star with the lowest performance index, and so on;

(5) if a partially observable star is actually observed, allocate the 2 slots which are free when the star is *not* present in the field of view to the fully observable star with the lowest performance index—referred to below as its 'associated' fully observable star.

Execution of the Observing Sequence

Once these two functions are completed, the actual observation sequence is executed in the following order:

(1) in each interlacing period the fully observable stars are observed in order of entrance in the field of view;

(2) all slots devoted to the same star are contiguous;

(3) during the interlacing periods in which partially observable stars are present, the observation slots of each partially observable star are contiguous with the ones of its associated fully observable star;

(4) the entering partially observable star is observed after its associated fully observable star;

(5) the leaving partially observable star is observed before its associated fully observable star;

(6) if there is no fully observable star, the leaving partially observable star is observed before the entering partially observable star.