HIPPARCOS PRECISE ATTITUDE DETERMINATION: A BALANCE BETWEEN ON-BOARD AND ON-GROUND CAPABILITIES

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ABSTRACT

The present paper summarises the design philosophy and task distribution between on-board and on-ground capabilities for ensuring the precise attitude determination requirements needed for a successful completion of the HIPPARCOS mission objectives. The stringent real-time on-board attitude determination accuracy of 1 arcsec (rms) for the telescope pointing directions during the normal operational mode is achievable only by continuous ground support in terms of uplinking star position information and ground monitoring of the on-board attitude estimation process. More extensive ground support is required during mission phases where the flexibility of the on-board process is insufficient for reaching or sustaining the demanded attitude determination accuracies. The paper highlights the ground-spacecraft interactions during these critical phases, e.g. initialisation of the on-board attitude estimation, as well as during occultation periods.

Keywords: HIPPARCOS, Initialisation, Pattern Recognition, Attitude Determination, On-Board Processing

1. INTRODUCTION

ESA's astrometry satellite HIPPARCOS is planned to be launched into a geostationary orbit in July 1988. Its primary objective is the collection of star position measurements over its 2.5 year mission lifetime. Elaborate on-ground processing of these data will lead to a star catalogue containing the positions, parallaxes, and proper motions of about 100.000 selected stars to an unprecedented accuracy in the order of 2 milli-arcsec and 2 milli-arcsec per year, respectively. HIPPARCOS' optical payload is equipped with two telescopes with viewing directions separated by 58 degrees. Star images from both fields of view are superimposed onto a common focal surface by means of a beam combining mirror. An overview of HIPPARCOS mission principles and objectives can be found in Reference 1. Figure 1 illustrates the HIPPARCOS satellite showing the two telescope viewing directions.

In order to be able to execute the mission objectives a real-time on-board attitude pointing knowledge to an accuracy of as little as 1.0 arcsec (rms value) in the telescope directions is required. In addition, the telescope pointing attitude rates should be known to an accuracy of better than 0.14 arcsec per second (rms).

During normal-mode operations attitude state estimates are updated by the on-board computer at 0.9375 Hz frequency on the basis of sampled gyro rate measurements providing three-axes attitude information. The star mappper signals are analysed to extract crossing times of selected stars whose position coordinates have been uplinked to the on-board computer. Offsets between predicted and realised crossing instants provide the fundamental information for updating gyro drift errors as well as the attitude estimates, cf algorithm outlined in Ref. 2. Valid star transits in the combined fields of view are expected to occur about once every 10 seconds. The on-board update algorithm uses a sub-optimal double-gain Kalman filter model where the high gain is assigned to stars with good a priori position knowledge. In total, about 60% of the

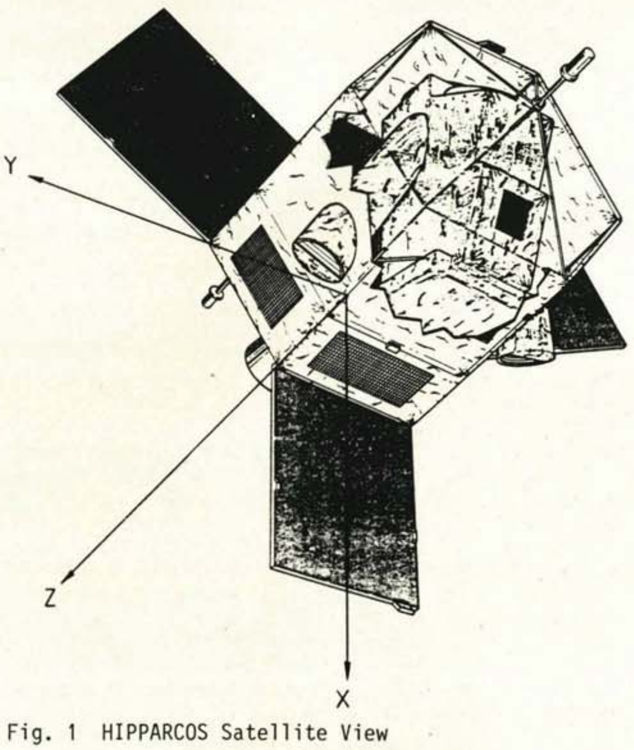

Fig. 1 HIPPARCOS Satellite View

100.000 HIPPARCOS program stars will be used for attitude determination purposes. Since such a large volume of data can not readily be managed on-board a continuous ground link is required for refreshing the limited on-board Program Star File (PSF) containing all information on the stars to be observed.

The normal-mode RTAD (Real-Time Attitude Determination) processing depicted above is naturally designed for a steady-state situation which allows only relatively minor fluctuations in gyro drift characteristics, star mapper transit frequencies, a priori star position accuracy, as well as in a priori state estimation errors at the update instants. It is precisely in situations where an ideal environment can not be guaranteed that on-ground algorithms are needed to replace or supplement on-board calculations in order that the mission can be executed with the least adverse impact on scientific results, viz:

- initialisation of on-board algorithms
- acquisition of nominal scanning motion
- emergency reacquisition
- eclipse operations
- occultation (of telescopes by Earth or Moon) operations
- unexpected RTAD contingencies

The ground support capabilities and the interactions with the two on-board computers during these critical mission phases are addressed in this paper. In this description the respective capabilities and limitations of on-ground versus on-board algorithms are highlighted with the objective of providing a global trade-off between desirable features of on-board versus on-ground algorithms derived from the HIPPARCOS design experience.

2. SUMMARY OF NORMAL-MODE RTAD

The HIPPARCOS normal-mode Real-Time Attitude Determination (RTAD) algorithm is performed by the on-board CLE (i.e. Control Law Electronics), a Texas 9989 microprocessor with 32 bit floating point arithmetic. This processor is responsible for executing all on-board AOCS (i.e. Attitude and Orbit Control Subsystem) algorithms. Interestingly, the RTAD processing makes use of Star Mapper transit times calculated from the Star Mapper data stream by the OBC, i.e. the central On-Board Computer, a SAAB 16 bit processor. The attitude determination results are communicated by the CLE to the OBC which uses this information for the accurate piloting of the Image Dissector Tube (IDT) instantaneous field of view to the predicted star positions on the main grid. Figure 2 provides an overview on the attitude determination task distribution between the CLE and OBC processors as well as the ground uplinks during normal-mode.

A detailed description of the on-board RTAD design and performance is beyond the objectives of this paper and the interested reader is referred to Ref. 3. A short outline of the RTAD functions with emphasis on ground-spacecraft interactions follows.

2.1 RTAD Functional Description

The HIPPARCOS attitude evolution is prescribed to follow a predetermined Nominal Scanning Law (NSL) within a maximum semi-cone angle of the scan axis of 10 arcmin and a maximum angular error about the scan axis of the same amount. The actual spacecraft attitude orientation (x,y,z frame) is described relative to the NSL X,Y,Z frame by means of the so-called Tait-Bryan angles ϕ,θ,ψ, cf. Fig. 3.

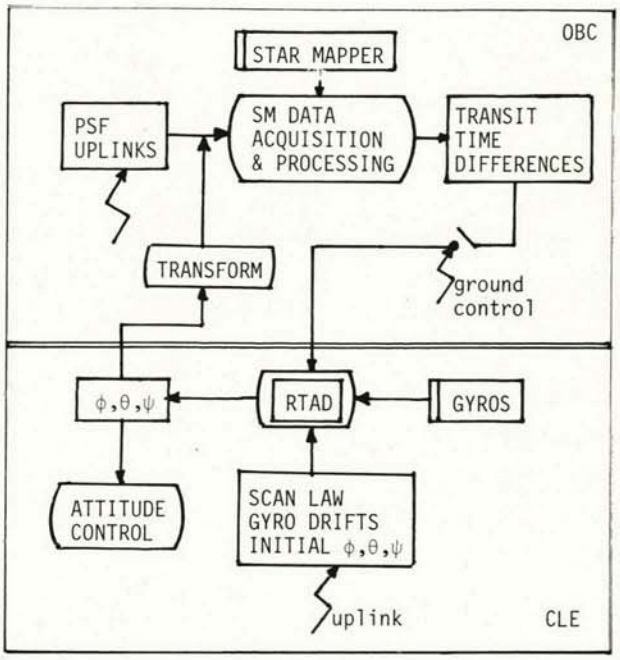

Fig. 2 Visualisation of RTAD Dialogue Between OBC and CLE

The NSL attitude evolution consists of a uniform rotation at a rate of 168.75 deg/hr about the spacecraft z axis and a slowly varying precession of the z axis at an average rate of about 0.19 deg/hr.

The nominal spacecraft rotation rates which are compatible with the NSL evolution are calculated on-board using a reference precession rate refreshed by ground uplinks at one hour intervals. Measurements of the actual rotation rates are provided at a frequency of 0.9375 Hz by the Inertial Reference Unit (IRU), consisting of five (redundant) rate-integrating gyros. A fairly intricate discrete state estimation process model can be

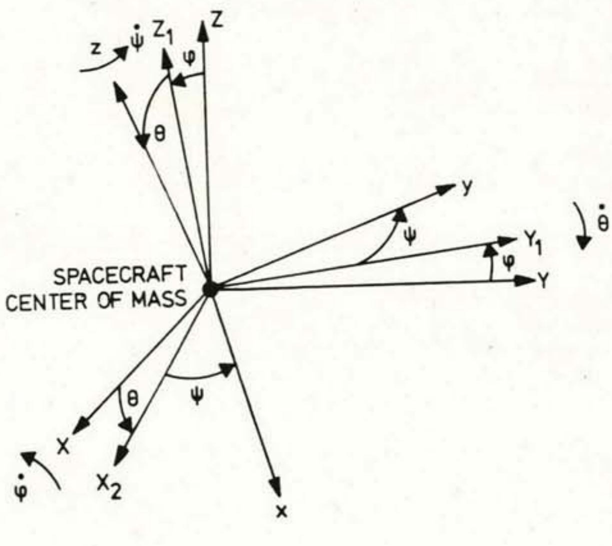

Fig. 3 Tait-Bryan Angles of Spacecraft Frame Relative to NSL Frame

constructed with the three Tait-Bryan error angles and three gyro drift rate components as state parameters. The gyro rate measurements (after pre-processing) are incorporated in the control or command vector of the state equation, cf. Refs. 2 and 3.

The measurement equation of the state estimation model uses the difference between predicted (on basis of NSL) and actually realised star crossing times over one of the three (upper inclined, lower inclined, vertical) slit systems of the Star Mapper, cf. Fig. 4. The state estimate updating is done with two different constant gain matrices depending on the quality of the a priori reference star position knowledge as communicated via the PSF uplinks from ground. The observability of the three-axes attitude angles is guaranteed by the presence of stars in each of the two fields of view. Reference star crossings which are used in the RTAD updating are expected to arrive at about 10 second intervals.

2.2 Ground Support of RTAD

During the Normal-Mode operations the correct performance of the RTAD algorithm depends critically on the uplink of correct program star information from ground. The PSF uplinks constitute the bulk of the 2 kilobits per second telecommand rate. Whereas much of the PSF information is used by the OBC for devising its star observation strategy the entries which are directly related to the RTAD calculations are the following:

i) nominal star crossing time at center of field of view (as defined by the NSL),
ii) nominal transverse coordinate of star crossing at center of field of view (also from NSL),
iii) nominal drift angle of star path relative to equatorial direction (also from NSL),
iv) field of view identification
v) reference star identifier: indicates that program star is used for attitude determination
vi) star position quality index (determined from a priori position information).

These entries are prepared on-ground for each program star on the basis of the Input Catalogue provided by a scientific consortium. The uplink strategy is such that the on-board PSF buffer is kept almost full at all times in order to ensure a maximum survival time (of at least 15 minutes) in case of telecommunications link interruptions.

In addition to the uplink of PSF star data blocks as outlined above ground is responsible for communicating the demanded three-axes NSL rotation rates used in the kinematic process model of the on-board RTAD. Uplinks of these rates are performed about once per hour along with updates of the orbital oscillator (which calculates the cartesian components of the scan phase angle at 0.9375 Hz frequency).

3. INITIALISATION OF ON-BOARD RTAD

This chapter starts out with a description of the principal measurement sensor used during the initialisation phase followed by a summary of the main ground support tasks during this phase.

3.1 The HIPPARCOS Star Mapper

The HIPPARCOS Star Mapper (SM) is not a conventional sensor unit but is an integral part of the optical payload. It is intended for accurate transit time and magnitude measurement of stars as faint as B ≅ 10 magnitude at the very low satellite rotation rate of 168.75 deg/hr. Figure 4 shows one of the two (redundant) SM slit patterns. The SM is situated in the focal plane of the optical payload at the edge of the main grid about half a degree off the optical axis. Light entering either of the two telescope fields of view is deflected onto the SM by a beam-combining mirror. The SM consists of two sets of 4 parallel slits, one set parallel to the rotation axis ('vertical slit system') and one chevron-shaped ('inclined slit system'). Light passing through either of these slit systems is incident on the same dichroic beam splitter, which directs the light through two broad-band filters ('B' and 'V') onto two photomultipliers operated in photon-counting mode. Stars transit across the SM in the direction shown, covering each slit system in 0.2 seconds, with up to 7.2 seconds between the vertical and inclined transits. The photomultiplier output is sampled at 600 Hz, producing a signal similar to Fig. 5. There is no information from the SM indicating whether these four peaks were produced by a vertical or by an inclined transit, or which FOV the star was seen through.

The SM was designed with a particular data reduction procedure in mind. This procedure involves correlating the raw data as in Fig. 5 with a 4-peaked 'filter function' which is the expected analogue signal from a bright star. The 4 components of each slit system are unequally-spaced in order to reduce correlation side lobes. The position and height of the correlation peak then give the transit time and magnitude. The SM is primarily designed for operation during the main mission phase, when the on-board a priori attitude estimation accuracy at any instant is 1 arcsec rms. Under these circumstances, stars can be identified singly by their time of transit alone, and there is no ambiguity as to which slit system was involved. This is not the case during the initialisation phase, as the necessary a priori attitude knowledge is lacking.

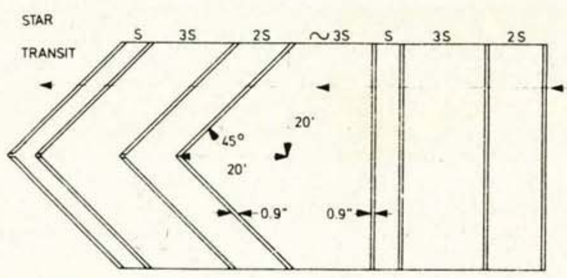

Fig. 4 Star Mapper Vertical and Inclined Slit Systems (Not to Scale)

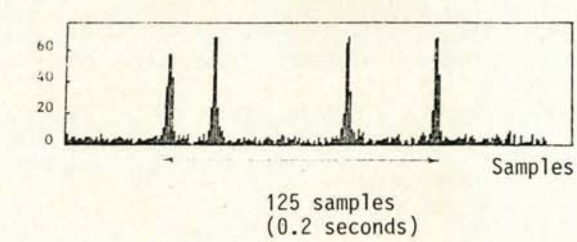

Fig. 5 Raw Star Mapper Output Signal (This signal is produced by the transit of a star of magnitude 7.2 over the vertical slit system.)

Typical random errors of measurement at B = 8.5 are about 0.2 arcsec rms in position and 0.1 in magnitude. In addition, SM measurement errors may be degraded by non-nominal velocity (causing a mismatch between the filter function and the data) and by telescope defocussing. Together these lead to a systematic magnitude error of up to 0.45, which always acts so as to increase the measured magnitude.

3.2 On-Ground Star Pattern Recognition

During this phase, the satellite remains in Sun-pointing mode under the control of a conventional Sun acquisition sensor. The z-axis is maintained within 1.6 degrees of the Sun disc centre (although this figure may be reduced by calibration - see Ref. 4). The satellite rotates slowly at a nominal rate of 168.75 deg/hour around its z-axis; however, gyro drift and deadband width may cause the rotation rate to differ by up to about 2.6 deg/hr from nominal. There is no a priori knowledge of the rotation angle. Star Mapper data and gyro readings are being continuously downlinked.

The goal of star pattern recognition is to generate from raw star mapper data, a series of {transit time, identity} pairs. Precise attitude determination is performed at the next stage of initialisation. The pattern recognition algorithm must search a catalogue covering the largest area of sky which may be observed. This area is a 360 degree strip whose centreline is a Great Circle perpendicular to the Sun direction. The strip width is governed by the maximum Sun de-pointing of the z-axis, and by the star mapper field of view; it may be up to 4 degrees wide (cf. Fig. 6).

3.2.1 Statement of problem. The design of the initial star pattern recognition algorithms is 'steered' by the following factors:

i) SM design coupled with no a priori star position knowledge:
   - the whole of the raw photomultiplier data must be searched for star transits
   - transits across the vertical slit system must be distinguished from those across the inclined slit system using the available transit time and magnitude data (B,V)
   - there is no easy way to determine whether a star has crossed on the upper or lower half of the chevron slit system.

ii) Two Fields Of View (FOVs) coupled with uncertainty in z-axis direction:
   - it is not known in advance how to combine two regions of the catalogue corresponding to the two FOVs. Because the number of possible combinations would be very large, stars observed through different FOVs must be separated before searching the catalogue
   - HIPPARCOS is not spin-stabilised. Variations in the z-axis direction create problems for the FOV separation algorithm by reducing the 'overlap' between the two FOVs
   - uncertainty in z-axis direction governs the size of the catalogue which must be searched. After all losses are considered, about 8-15 observed stars must be located in a catalogue of 1000-1500 stars.

iii) Magnitudes (SM measurement bias and catalogue errors):
   - the bias may be up to 0.45 and the errors are unlikely to be smaller than about 0.2 rms on average. Thus, magnitudes will not greatly aid catalogue searching.

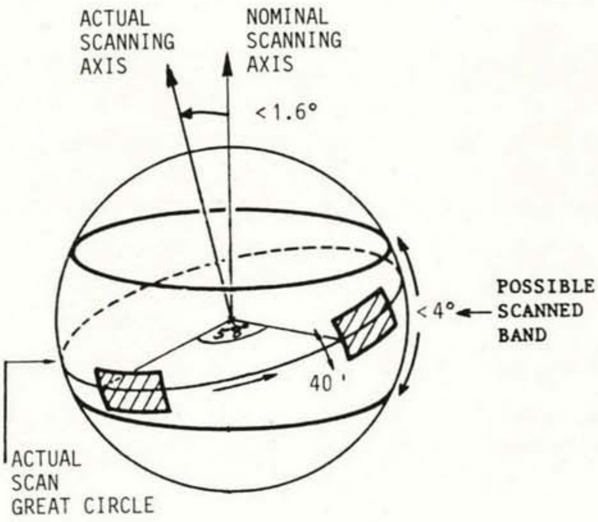

Fig. 6 Visualisation of Scanning Plane (The hatched areas represent the areas of sky scanned by the two FOVs.)

On-ground star pattern recognition has been divided into four stages, each of which passes its output data to the input of the next stage:

1) Peak detection
2) Slit distinction
3) Field of view separation
4) Matching with catalogue.

These stages are described in the following four subsections. The description of stages 2, 3 and 4 is based on the results of two simulation studies (Refs. 5, 6), during which the algorithms were developed.

3.2.2 Peak determination and filtering. Every raw SM datum is tested against a pre-set threshold (corresponding to approximately B=9). Data exceeding the threshold may be a peak from the first of the four slits (of either of the slit systems). The expected locations of the other 3 slits are tested against the thresholds. Only if 4 peaks are found, is the CPU-intensive filtering carried out (see section 3.1). This stage yields three numbers per transit: t, B, V.

3.2.3 Slit distinction. Successive transits of the same star image across the vertical and inclined slit systems are separated by between 0.3 and 7.2 seconds, depending on the transverse coordinate of the star image. In the absence of random magnitude errors, both transits would naturally register the same B and V magnitudes. (Magnitude bias will apply equally to both slit systems.) It is therefore possible to 'pair' transits separated by no more than 7.2 seconds by comparison of their magnitudes. This is done in two stages as illustrated by Fig. 7. Two transits occurring within 7.2 seconds of each other are denoted a 'valid pair' if their B and V magnitudes are equal within ΔB_1 and ΔV_1. Each member of the pair is then tested separately to ensure that it could not form half of another pair. If there is no other transit (apart from the other member) within $\pm$ 7.2 seconds whose magnitudes lie within ΔB_2, ΔV_2, there is said to be 'no other partner'. Only if both

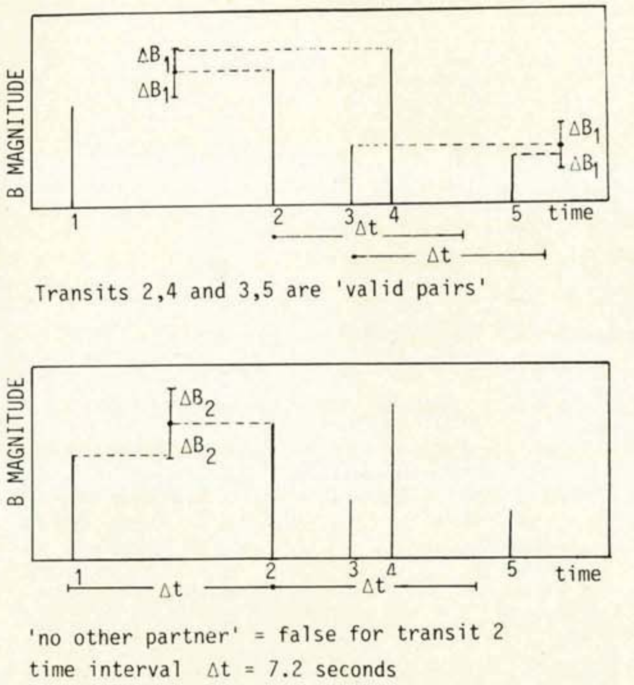

Fig. 7 Visualisation of Slit Distinction (Transits 2 and 4 must be discarded because they cannot be paired unambiguously.)

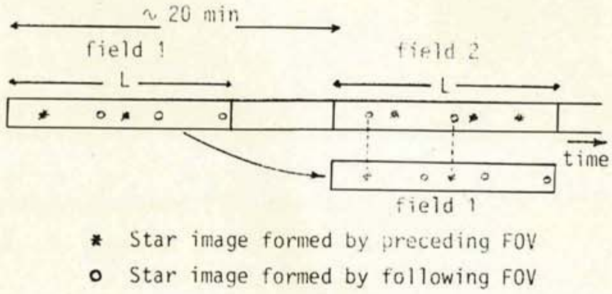

Fig. 8 Visualisation of FOV Separation (Field 1 has been redrawn below field 2 so that the superposition of common star images can be seen.)

members of the pair pass the second test, is the pair accepted; otherwise it is discarded. The magnitude thresholds are set according to the expected random magnitude measurement error. This procedure leads to between 35% and 60% of star images being discarded by the algorithm.

At this stage, the transit times may (optionally) be corrected for the effects of scan rate variations using gyro data. This permits smaller tolerances to be used in the next stages of pattern recognition.

3.2.4 Field of view separation. Use is made of the fact that the two HIPPARCOS FOVs scan (approximately) the same strip of sky but with a phase difference of 58 degrees (the 'basic angle' between the two telescopes). Data from the SM are recorded from t=0 for a length of time 'L'. At some later time (approximately 20 minutes) the satellite will have rotated 58° from t=0. Data are recorded again for the same length of time 'L'. The stars which were seen through the Preceding FOV (PFOV) during the first period may now be seen through the Following FOV (FFOV). This is shown in Fig. 8. The two sets of data are referred to as 'field 1' and 'field 2'.

In practice the FFOV will not scan exactly the same strip of sky during field 2 as the PFOV scanned during field 1. Reduced overlap between fields 1 and 2 leads to a proportional reduction in common stars. Assuming that overlap is sufficient, these common stars may be identified by pattern recognition. (This is achieved by the same algorithm used for matching, see Sec. 3.2.5). In order for pattern recognition to be successful for up to 1.6 degrees Sun de-pointing, the overlap must be at least 15 arcmin wide (out of a total SM width of 40 arcmin).

An important side-product of FOV separation is an estimate of the mean rotation rate or, equivalently, the mean drift of the z-axis gyro. This is derived from the time difference between two observations (PFOV and FFOV) of the same common stars.

3.2.5 Matching against a catalogue. This is the final and most critical stage of pattern recognition. The input to this stage consists of the transit times (and, optionally, magnitudes) of 8-15 observed stars, together with the same data for each of 1000-1500 stars in a catalogue strip. The output from this stage consists of the identity of some or all of the input stars. A correlation-type algorithm is used to search through the catalogue for a pattern which resembles the observed pattern.

Before matching commences, the transit times output by FOV separation are converted to angles around the scanning Great Circle using the estimate of the mean rotation rate. This step is essential for the success of the matching stage.

At a closely - spaced series of points around the catalogue strip, the observational star data are correlated with the catalogue data. This correlation consists simply of counting the number of stars which align with a star in the catalogue (within a specified tolerance). This value is known as the 'alignment count'. If magnitudes are used, each aligning observed star is only counted if its magnitude is the same as that in the catalogue (again within a specified tolerance).

At each point along the 360 degree strip, one or more observed stars may align by chance with a star in the catalogue (in addition to the one star made to align exactly). These chance alignments form a 'background noise' against which the peak alignment count (corresponding to correct identification) must be distinguished. The peak count will be equal to the number of observed stars, provided that the catalogue is complete and the tolerance includes all observational errors.

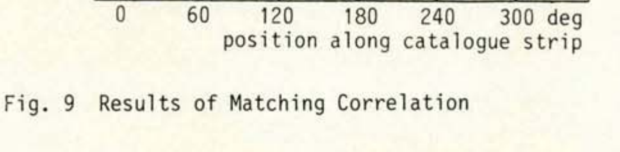

Fig. 9 Results of Matching Correlation

If the catalogue is very dense, the peak alignment count may in fact be a noise peak. A 'goodness-of-fit' measure is used to identify spurious peaks. All peaks at or above a threshold level are tested. Figure 9 shows the alignment count versus position in the catalogue. The 18 out of 8245 offsets were tested by comparing their 'goodness-of-fit' measures. The peaks denoted F (there are in fact 8, too closely-spaced to be resolvable) give the correct identification of the stars.

3.3 On-Ground Fine Attitude Estimation

A detailed description of the Fine Attitude Estimation concept is given in Refs. 7 to 9. Here, an overview of the most salient features is given.

3.3.1 Statement of the problem. The pattern recognition algorithm described above produces transit times of recognised stars over the Star Mapper slit systems. These observations along with gyro rate outputs will form the fundamental entries into the estimation model. It is expected that validated star transits will become available about once every 30 seconds in average. The order in which the recognised transits appear uniquely defines whether the particular transit refers to a vertical slit system crossing or an inclined slit system crossing. Due to the inclined slit ambiguity, however, it is not a priori known whether the crossing takes place over the upper or lower inclined slit system, cf. Fig. 4. This difficulty is not encountered in the normal-mode on-board RTAD because of the arcsec-level a priori attitude knowledge.

Another difficulty is introduced by the fact that payload alignment biases are not known accurately during this initial phase of the mission. The pre-launch calibration values have become invalid due to launch effects and because of the microgravity environment. It is expected that the predicted values of basic angle and grid rotation angle may be off by up to 5 arcsec and 3 arcmin, respectively. The latter effect results in a linearly varying star transit bias of up to ± 1 arcsec at the extremes of the slit systems.

Finally, it should be appreciated that also the actual characteristics of the gyro noise and drift behaviour may deviate from predicted values. This aspect is aggravated by the fact that thermoelastic distorsions between the SM and gyro package result in artificial gyro drift rates. Although estimates for these effects are available from pre-launch thermal models the actual in-orbit behaviour may not be compatible with the predictions.

The objective of the on-ground Fine Attitude Estimation (FAE) is to obtain arcsec-level accuracy for the instantaneous Tait-Bryan attitude orientation angles relative to a Sun-pointing reference frame, cf. Fig. 3. At the same time, also the rotation rates and gyro drift rates will be determined to an accuracy level below 5 milliarcsec per second (averaged over the SM update intervals). The on-ground estimates of the attitude orientation angles will eventually be used in generating inputs for the on-board RTAD process (cf. Section 3.4).

3.3.2 Modelling of the measurements. The measurements available for FAE are the downlinked rotation rates provided by the three active gyros as well as the transit times of recognised stars over the SM slit systems. Gyro rate measurements are available every 1.067 seconds but will be incorporated in the FAE algorithm only at instants when SM transits are available. In this manner, the effective noise in the rate measurement is reduced to about 3 milliarcsec per second (for a typical 30 second update interval). The expected variation in gyro drift rate over this interval is about $2 * 10^{-4}$ deg/hr.

The SM transit times available for FAE are ordered in pairs (for inclined and vertical slit crossings of the same star) where each pair may come from either field of view. Vertical slit crossing times provide information on the scan rotation angle of the spacecraft, as well as on the z-axis gyro drift rate. The inclined slit crossing times are combined with those of the vertical slit crossing of the same star resulting in a measurement of the star's transverse offset relative to the spacecraft equator (Fig. 4). These measurements provide information on the scan axis orientation relative to the star's inertial position. In addition, information on the drift rates of the equatorial gyros is obtained. For a meaningful attitude determination it is essential that stars from either field of view are considered as this effectively results in two independent inertial reference directions for the scan axis orientation. Under these circumstances also the two gyro drift rates become completely observable.

The effect of the basic angle bias can be eliminated by considering only vertical slit transits from one field of view direction for the scan phase estimation. The combination of both inclined and vertical transits as used in the estimation of the scan axis orientation can still be used for both fields of view as the basic angle bias has no effect on this. Eventually, it is possible to calibrate the basic angle bias down to below 1 arcsec by using transit times from both fields of view for one star along with accurate scan rate information.

The effect of grid rotation on the vertical slit crossings can properly be modelled as a random noise since its expected value over the slit is zero. Its effect on the measured transverse offset of the star crossings can be shown (Ref. 9, Section 2.5) to have a maximum value of 2.8 arcsec.

Finally, it is mentioned that because of the slit distinction ambiguity a preparatory rough scan plane estimation phase is necessary. This phase is concerned with the establishment of a rough scan plane determination to an accuracy of perhaps 5 arcmin by an ad hoc procedure.

3.3.3 State estimation model and results. The state estimation model is based on a 9-dimensional state vector consisting of the three Tait-Bryan attitude angles (relative to a Sun pointing inertial reference), three angular rates and three gyro drift rate components. A discretised linear state model describing the transition of the state vector (as well as its covariances) in-between SM measurement updates can be derived from the kinematic and dynamical (Euler equations) relationships for the attitude angles and rates, respectively, whereas the gyro drift rate model is of the usual random walk type with the drift noise entering in the model's system noise. The principal torque influence during the Sun-pointing phase is generated by gyro reactions to the imposed scanning motion. In comparison, solar radiation, gravity-gradient and magnetic torques are hardly significant and may be modelled as torque noise which constitutes the system noise of the attitude model. Another important aspect is the fact that there is a dynamic imbalance of up to 3 degrees between the spacecraft reference axes and the principal axes. This introduces additional 'inertial' torques which should be incorporated in the state transition model.

Updates of the state estimates are carried out by means of the Kalman filter procedure. In order to avoid cumbersome matrix inversions the incoming measurements (i.e. three gyro rates, scan angle and star crossing elevation) are treated one by one where each refers to the same instant. The optimal Kalman gains are calculated on the basis of the expected measurement noise and a priori state covariances. Thruster actuations are incorporated in the model by a sudden rate change accompanied by a corresponding relaxation in the rate covariance.

Figure 10 shows the results of a simulation run under relatively adverse conditions (i.e. maximum grid rotation bias and unknown torque and Euler cross-coupling biases of 10%). The star distribution in terms of the slit crossing position and field of view are drawn from a random number generator. In the region between 15 and 22 minutes 12 out of 14 trials drew the same field of view resulting in an observability problem for the θ angle. It is seen that three-axes attitude determination accuracies of the order of 1 to 2 arcsec (rms) can be achieved after about 10 minutes.

3.4 Closing the On-Board RTAD Loop

This phase forms the transition between FAE, which runs in real-time on-ground, and RTAD, which runs continuously on-board. Closing of the RTAD loop is therefore the phase during which the emphasis of software activity shifts from the ground segment to the satellite. During this transition, close cooperation is required in real-time between on-ground and on-board software.

3.4.1 Comparison of RTAD and FAE. During RTAD, the scanning law (for initialisation) follows a Great Circle approximately perpendicular to the Sun direction. On-board control algorithms maintain the three-axes attitude within ± 10 arcminutes of nominal. The RTAD algorithms estimate the Tait-Bryan angles within about 1 arcsec rms of their actual values. Continuous PSF uplinks allow the RTAD to track changing gyro drifts.

Contrast this with the situation during FAE. The satellite is scanning a path which is nominally a Sun-pointing Great Circle, but the satellite attitude is maintained only within 1.6° semi-cone angle of nominal. This path will not in general be the required scanning law. The on-board Tait-Bryan angles are set to zero before RTAD is switched on. This does not represent the correct satellite attitude relative to the required scanning law. On-ground, FAE estimates the inertial attitude from downlinked SM and gyro data to arcsec level accuracy.

3.4.2 Proposed operational sequence. The approach which will be adopted is to define the scanning law in such a way that a slew is not necessary. The ground software must perform the following tasks:
- definition of a scanning law and preparation of the PSF
- initialisation of the on-board programs so that they generate good estimates of the true attitude deviation, and so that scanning continues according to the PSF.

The on-board attitude estimates are initially improved (if necessary) by uplink of the results of on-ground processing of the SM data stream.

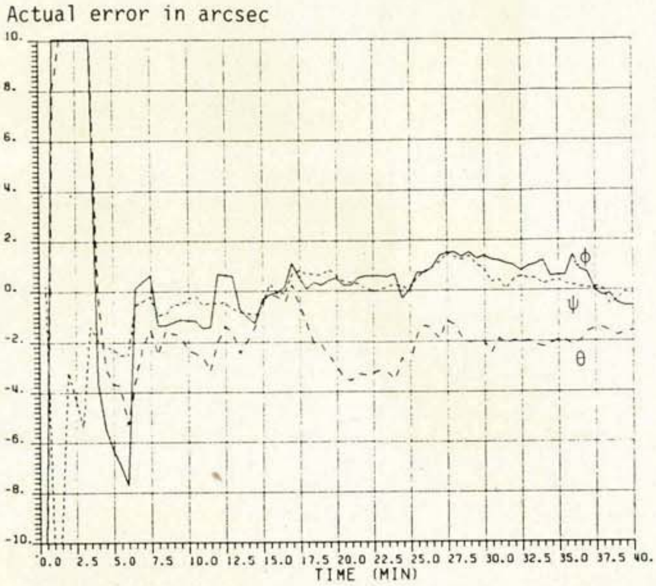

Fig. 10 Results of On-Ground Attitude Determination

The exact sequence is as follows:

1) The on-board RTAD and attitude control programs are started without the on-board SM measurement program. The Tait-Bryan angles, initially zero, will evolve under the influence of torques within the attitude control deadbands. FAE continues to estimate the precise inertial attitude on-ground.
2) At some later time on-ground PSF preparation begins. The scanning law initial attitude is defined by zero values of the on-board estimates of the Tait-Bryan angles.
3) From this time on gyro drifts are monitored (from FAE estimates). If they change more than a prescribed amount, they are uplinked in order to prevent on-board values of $\phi,\theta,\psi = 0$ drifting too far away from what ground PSF preparation is based upon.
4) After some more time the PSF is uplinked and on-board SM measurement processing is started if the on-board attitude estimation error is below 20 arcsec. This is due to the maximum width of the SM acquisition window.
5) If the error is more than 20 arcsec, SM data processing must be carried out on-ground. Uplinks of the SM measurement (see next Section) are used to reduce the error.

3.4.3 On-ground SM data processing. The on-board algorithms for the processing of raw SM data read star positions from the PSF and attempt to locate the transits in the stream of SM counts. The data are reduced to the 'SM measurement' α_m, which is transmitted to RTAD (see Fig. 2 in Section 2.1).

The reverse approach will be used for on-ground SM data processing. On-ground star pattern recognition already provides the transit times and identities of stars crossing the SM. These are cross-referenced against the on-ground PSF and then combined with the output of the FAE software to calculate α_m.

It is necessary that the uplink of α_m should reach the on-board software within 40 seconds after the original star transit. (This is in order to prevent the attitude information from becoming out-of-date.)

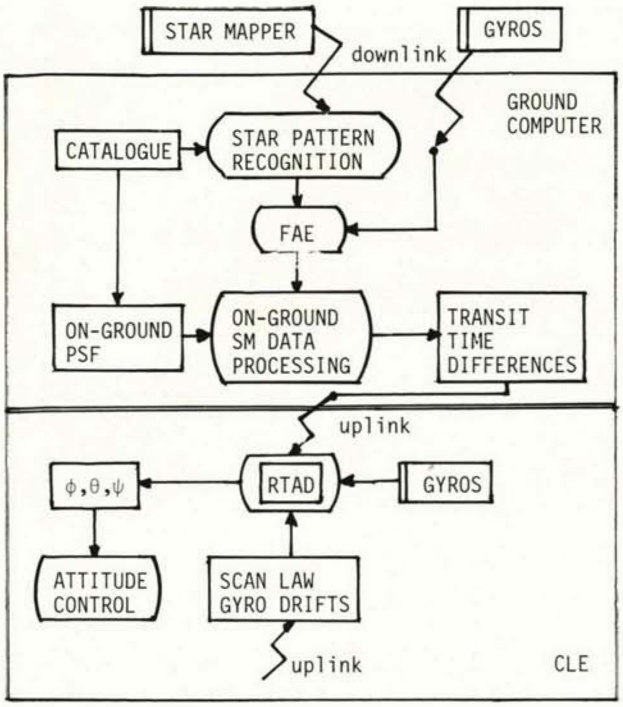

Fig. 11 Ground-Spacecraft Dialogue During Closing of RTAD Loop

This puts a stringent requirement on the complete ground segment performance. An overview of the on-ground / on-board loop is shown in Fig. 11. Comparison with Fig. 2 shows how ground fulfils the functions which the OBC software performs in normal mode RTAD.

After the on-board attitude determination error falls below 20 arcsec, the on-board RTAD loop is closed by ground command.

4. GROUND SUPPORT OF RTAD

After the on-board autonomous RTAD processing has been initialised the nature of ground support changes drastically. The main objectives of the involvement of the ground during normal-mode operations are the assurance of proper RTAD functioning, the diagnosis of anomalies and, finally, the assistance during particular periods of the mission when the proper RTAD functioning is in danger (e.g. during eclipses and occultations).

4.1 Normal-Mode Monitoring

4.1.1 RTAD functional checks. A regular monitoring of the RTAD performance is performed on-ground throughout the mission in order to quickly identify serious software or hardware malfunctions affecting the mission performance. It is of interest to identify trends in performances in order to implement an adequate and timely correction in the case of slow performance degradation. The on-ground monitoring will concentrate on straightforward checks providing significant information on the performance of the on-board RTAD algorithm, viz:

- duration between successive updates of the state estimates by means of Star Mapper measurements
- trends in expected minus actual Star Mapper transit times
- trends in gyro drift rate estimates and their changes during updates
- trends in Tait-Bryan angle estimates and updates.

It is foreseen that the frequency of checking is about once per 100 sec. All monitoring information will be logged for the long-term trend evaluation.

4.1.2 Gyro performance monitoring. Good gyro performance is essential for the proper estimation of attitude variations in-between Star Mapper updates. The evolution of the gyro output should be quite regular and is well predictable on the basis of expected or observed torque influences and gyro drift characteristics. A sampling of gyro rate outputs and calculated drift estimates at regular intervals should provide sufficient information on the gyro performance evolution.

4.1.3 Thruster performance monitoring. Thruster actuation pulses disturb the smooth free-drift attitude motion of the satellite and are undesirable from a scientific data processing point of view. The control law design is such that actuation-free intervals are maximised under the given constraints (see Ref. 3). The controller therefore makes use of expected thruster control torques when calculating the on-times of the thruster firings. It is important that the actual thruster performance is consistent with predicted characteristics used by the on-board CLE control software. Occasional checks of the observed rate variation (through the gyros) will be carried out and updates of the on-board thrust values may be performed on this basis.

4.1.4 Disturbance torque monitoring. During normal-mode the main disturbing torque influences are solar radiation pressure and gyro reactions torques. In order to maximise free-drift intervals the on-board controller makes use of a time-varying disturbance torque model when calculating the actuation on-times. It is obvious that such calculations are meaningful only if the predicted torque model is adequate. Therefore, ground estimates of the observed disturbance torques will be compared with the on-board model and updates will be uplinked when discrepancies become significant.

4.2 Occultation Support

Occultations of the payload field of view directions by the Earth or Moon occur typically a few times each day and may last up to 15 minutes. During this interval no Star Mapper updates can be performed since the optics must be protected by payload shutters. This means that gyro drift rates are not at all updated during this period. Because of the thermo-elastic distorsion rates of the gyros relative to the payload the effective gyro drift errors just after the occultation period are far too large to ensure proper RTAD performance, Ref. 3.

By dedicated ground support the attitude errors must be reduced to an acceptable level which would allow the OBC to acquire the Star Mapper data for the filtering process. This is accomplised by means of a ground-based model for the 'thermal' part of the gyro drift evolution over a scan revolution. On the basis of such a model the expected average drift over the occultation period can be calculated and uplinked to the satellite at the start of occultation. In this manner the attitude estimation error at the end of the occultation would be minimised. A second drift uplink is required at the end of the occultation in order that RTAD operates with the best possible gyro drift estimate during the period just following the occultation. It is expected that considerable in-orbit tuning of the thermal drift model will be required before reliable RTAD operation can be guaranteed after each occultation. Similar ground support may be required also during eclipse transitions.

5. ON-BOARD / ON-GROUND TASK DISTRIBUTION

The distribution of mission support tasks between on-board and on-ground software constitutes an important aspect of the satellite system design. The actual solution adopted in the case of the HIPPARCOS precise attitude determination implementation has been outlined in the preceding chapters. The design philosophy which is selected in actual fact reflects a natural balance between available on-board and on-ground capabilities and constraints since it is the final outcome of numerous trade-offs. It is therefore of interest to identify the main considerations relevant to the on-board / on-ground distribution of support tasks. This analysis would be useful in evaluating design options for future spacecraft. It can not be excluded however that advances in relevant technologies (e. g. on-board autonomy) may eventually remove some of the present constraints.

In the following sections a short account of the on-board / on-ground trade-offs is provided for the main software support functions introduced above.

5.1 RTAD Algorithm

The RTAD results are required on-board for piloting the IDT instantaneous field of view onto the main grid. A ground loop (implying RTAD calculations by ground software) would mean that attitude results will be available only about 30 seconds after the event. This fact alone would significantly affect the achievable attitude determination accuracy. The on-board loop, on the other hand, has a delay of just a few seconds. Naturally, other considerations such as on-board data handling capabilities and ground segment constraints play an important role in the on-board versus on-ground RTAD trade-off as well. It is of interest to point out, however, that RTAD as implemented in the HIPPARCOS case demands an almost continuous ground link for providing PSF and NSL information because of on-board storage limitations. Furthermore, all of the performance monitoring, fault assessment and correction is performed on-ground. The reason for this must be found in the larger flexibility and CPU power available for on-ground software. Finally, it should be noted that the complex initialisation procedure can only be done by ground software.

5.2 Star Pattern Recognition

This algorithm as used for HIPPARCOS is relatively CPU-intensive and requires considerable data storage as well. When also the reliability considerations (e. g. the algorithm must be robust to a great number of error sources) are taken into consideration it becomes obvious that at present such an algorithm can only be performed by ground software.

5.3 Fine Attitude Estimation

The FAE algorithm could in principle run on-board since its complexity is not essentially different from that of the RTAD algorithm. However, its inputs are the results of the on-ground pattern recognition software. Furthermore, FAE is only used for initialisation of RTAD processing. An on-board implementation would therefore make little sense.

5.4 Conclusions from HIPPARCOS Design

The conclusions from the cursory assessment made above are summarised in a global manner in Table 1.

Table 1. Aspects of On-Board & On-ground Algorithms

ON-BOARD ALGORITHMS	ON-GROUND ALGORITHMS
fast on-board turnaround	fairly long delay
repetitive nature	once or few times
routine application	initialisation
simple to mild complexity	high complexity
low CPU demands	high CPU demands
low storage demands	high storage demands
little monitoring	performance checking
little fault correction	fault correction
little adaptability	high adaptability

6. CONCLUDING REMARKS

The main spacecraft-ground interfaces for supporting the HIPPARCOS precise attitude determination functions have been summarised. The objective of the paper was the demonstration of the intricate balance between the on-board and on-ground capabilities which is essential for achieving the particularly demanding 1 arcsec (rms) real-time on-board three-axes attitude knowledge. Finally, a global assessment of the respective aspects of on-board versus on-ground algorithms has been presented on the basis of the HIPPARCOS design experience.

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