ON-GROUND ATTITUDE RECONSTITUTION OF THE HIPPARCOS SATELLITE

E Canuto & F Donati

Dipartimento di Automatica e Informatica, Politecnico, Torino, Italy
and
Centro di Studi sui Sistemi, Torino, Italy

ABSTRACT

This paper is concerned with the on-ground attitude reconstitution (OGAR) that shall be performed off-line with a target precision better than 0.1 arcsec RMS by the Scientific Consortium FAST during the reduction of the astrometric data transmitted by the Hipparcos satellite. To achieve this target a minimum variance estimator of the satellite three-axes attitude, which processes on-board star mapper data, has been designed and implemented; trials performed under severe simulated conditions have proven that the target precision is reached with a good margin.

Keywords: Hipparcos satellite, Minimum variance estimation, Attitude reconstitution, Attitude modelling, Star mapper.

1 OUTLINE OF THE PAPER

The aim of this paper is to present the on-ground attitude reconstitution (OGAR) that has been adopted by the Scientific Consortium FAST (Fundamental Astronomy by Space Techniques) for the reduction of the science data that will be collected by the ESA satellite Hipparcos. The Hipparcos attitude shall be off-line reconstituted during its useful life by processing the data of the on-board sensors, namely rate-integrating gyros and star mappers (SM), with an average precision better than 0.1 arcsec RMS.

In the 2nd section a brief presentation of the Hipparcos satellite and its mission will be given, highlighting the on-board instrumentation for the attitude estimation and the accuracy specifications of the on-ground reconstitution. In the 3rd section the problem of estimating attitude from gyro and SM data will be formulated: since it appears as a complex Gauss-Markov estimation problem, simplified estimators trading-off between computing load and statistical efficiency are usually used. When as for Hipparcos OGAR precision is the most important target, simplifications must not impair statistical efficiency: to this end the design of a simple but sufficiently accurate model and a careful measurement selection are capital. The design of such attitude model for Hipparcos OGAR is explained in the 4th section; it has been obtained by integrating satellite state equations driven by unknown but band-limited perturbations and impulsive control torques of unknown intensity. The measurement equations and the estimation procedure for the Hipparcos OGAR are reported together with Monte Carlo results in the 5th section: a not time-recursive Gauss-Markov estimator has been implemented which processes only the SM crossings of bright stars filed in the Input Catalogue. When Catalogue errors on star positions are predominant over SM instrumental errors, star positions can be improved using the reconstituted satellite attitude as explained in the last section.

2 THE HIPPARCOS SATELLITE AND ITS MISSION

A detailed description of the Hipparcos mission principles and its implementation is contained in Ref.1; here we will limit to the aspects relevant to OGAR.

The main mission of the Hipparcos satellite is to produce a new astrometric catalogue for about 100,000 celestial objects (program stars) filed in the Input Catalogue, with an accuracy of few milliarcseconds. The principle at the base of the mission is to observe almost simultaneously celestial objects which are largely separated in the sky, by means of a compass-like telescope, having two fields-of-view (preceding and following FOV's) and a single focal plane and to measure their angular distances with precision around ten milliarcseconds. Angular measures will be obtained by on-ground processing the star photons modulated by a 2688-slits grid placed in the telescope focal plane and counted by an Image Dissector Tube (IDT), capable of piloting its spot-like sensitive area (Instantaneous Field-Of-View, IFOV) on the image of a specified star located anywhere in the grid. The measurements that will be collected by scanning the whole celestial sphere during 5 consecutive semesters, will allow to construct a tight net of angular distances between stars covering all the sphere. By solving this net, update star coordinates in a common reference frame will be obtained.

The Hipparcos satellite is essentially a spinning satellite whose spin axis is guided by the attitude

Proceedings of the Second International Symposium on Spacecraft Flight Dynamics, Darmstadt, FR Germany, 20–23 October 1986 (ESA SP-255, Dec. 1986)

control to slide on a quasi-precession cone centered on the sun-satellite line; the nominal spin rate is 11.25 rev/day and the quasi-precession rate is 6.4 rev/year. A sketch of the nominal Hipparcos orientation law is shown in Fig.1; the spin axis is orthogonal to the telescope viewing plane defined by the central directions U_1 and U_{-1} of two FOV's, separated by the basic angle $\gamma=58°$; the intersection of the plane with the unit sphere is called Viewing Great Circle (VGC).

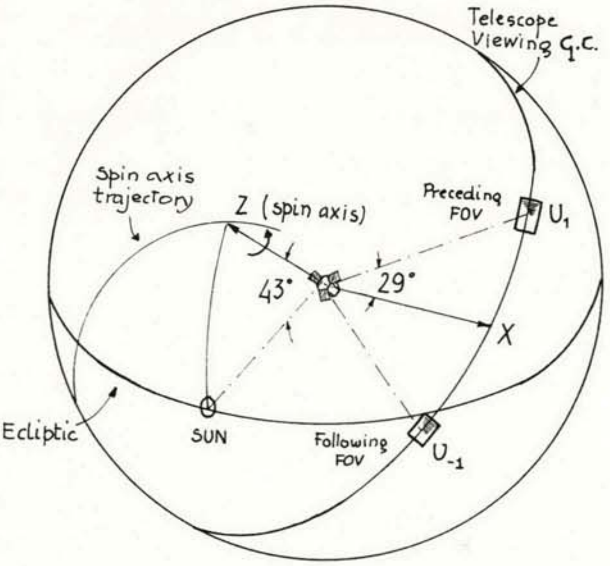

Fig.1 - Nominal Hipparcos orientation law

The spin movement allows the Hipparcos double telescope to scan a Great Circle every T_0=2.13 h; the quasi-precession movement around the sun direction allows a complete scan of the celestial sphere during half a year. The maximum permissible deviation, 10', of each satellite axis with respect to its nominal trajectory is dictated by the size of the telescope FOV's, 54'x54'.

To limit telescope attitude jitter to few milliarcsecond values, a discrete-time impulsive control (actuated by gas jet) has been preferred to a continuous-time attitude control (actuated by reaction wheels); all the three control torque components will be actuated when one of the three axes will deviate more than 10'; it results a not uniform sequence of variable control pulses whose computation has been designed to maximize the duration of the 'quiet time', i.e. the time without any actuation.

The satellite attitude is on-board estimated by real-time processing the data of three-axes rate-integrating gyros and one star mapper. Two star mappers are located at both sides of the main grid as in Fig.2, but only one of them will be used, the other being in cold redundancy; since the operating star mapper will receive star images from the two largely separated FOV's (preceding and following) of the Hipparcos telescope, it actually behaves like two separated instruments, allowing three-axes attitude observability. The star mapper is made by two groups of four aperiodic and parallel slits: the vertical slits are parallel to the main grid slits and a star nominally crosses them perpendicularly; the other four slits are 45° inclined and are folded like a chevron to reduce edge distortions of the signal. Adequate processing of the photon counts collected during the crossing of a star having magnitude $B\leq 9$, allows to locate the star on the slit reference line with a RMS error less than 0.1 arcsec (see Ref.2).

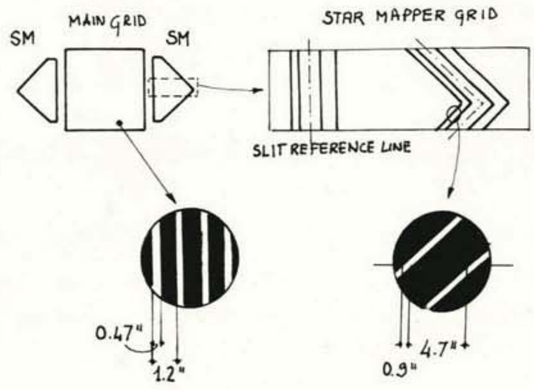

Fig.2 - The Hipparcos main grid and star mappers.

The attitude needs to be on-board estimated very precisely (1 arcsec RMS) and at high sampling rate (1 Hz) for allowing a neat piloting of the small IDT IFOV on the program star to be observed. This precision will be obtained from the observation of about 50% of the Hipparcos program stars (reference stars); the main limitation to on-board precision will be the a-priori error on reference star positions (about 1 arcsec RMS).

The attitude shall be on-ground reconstituted at the same on-board rate but with a much better precision (less than 0.1 arcsec RMS) to provide during all the Mission the telescope pointing direction with the necessary accuracy to connect star angular distances in a common inertial frame. The connection will be made by projecting the angular distances measured along instantaneous VGC's over an inertial Great Circle, called Reference Great Circle (RGC), which is intermediate to the consecutive and almost overlapping telescope scannings performed during half a day. The 0.1 arcsec OGAR precision is necessary to make projection errors caused by satellite attitude uncertainty, to be negligible with respect to instrumental errors (due to star and IDT photon noise).

OGAR will process all the SM crossings of bright program stars ($B\leq 10$); to eliminate the prevailing uncertainty of the Input Catalogue star coordinates (worse than 1 arcsec RMS), OGAR shall be iterated using intermediate Hipparcos Catalogues until Catalogue errors on star positions will appear negligible with respect to SM errors.

3 THE ATTITUDE ESTIMATION PROBLEM.

The Hipparcos attitude vector x(t) at time t during an RGC period is defined as a triple of Euler angles (ψ,ϑ,φ) which align the satellite body frame (X,Y,Z) to the satellitocentric inertial RGC frame (O,Q,P). The body frame is defined by the pole Z of the telescope viewing plane and by the bisector X of the central optical directions U_1 and U_{-1}; Y is consequently defined. The inertial frame is defined by the RGC pole P and by a direction O lying on the RGC plane and defining the origin of the RGC longitude; Q is consequently defined. The nutation angles $-\varphi$ and $-\vartheta$ take respectively Y and X on the RGC plane and $-\psi$ aligns X to O; during an RGC period the nutation angles ϑ and φ will remain less than 100'. An RGC and its origin O define a pair of coordinates: α, the longitude, and β, the latitude, which identify any star direction.

The Hipparcos body frame must follow the nominal rotating frame, specified by the orientation law; the attitude error vector is a triple of Euler angles which align body to nominal frame. They are estimated in real-time by the on-board Attitude Control System, using gyro and SM measures, for computing the actuating signal u which command the three-axes control actuators.

If we assume a rigid spacecraft, the attitude $x(i)$ at discrete times iT, T being the sampling period, is modelled by the dynamics and kynematics nonlinear state equations:

(1) $\omega(i+1)=F[\omega(i),c(i),d(i),i]$

(2) $x(i+1)=G[x(i),\omega(i),i]$

where c is the control torque vector produced by the actuators, d is the vector of external and internal disturbance torques, ω and Ω are respectively the vectors of the actual and nominal spacecraft inertial rates.

When, as usually, disturbance torques d are not directly measured, Eqs. 1 and 2 must be completed with the disturbance model:

(3) $d(i)=D[x(i),w_d(i),i]$

where $w_d(i)$ is an unknown and unconstrained signal (e.g. a white noise realization); the most simple disturbance model is of course obtained by assuming $d(i)=w_d(i)$.

To account for discrepancies between actuating signals u and control torques c, also actuators must be modelled; if their dynamics can be neglected a general model is:

(4) $c(k)=D[u(k),w_a(k),k]$

where k is the sampling index of the actuation times, which may not have a uniform rate, and w_a has the same properties as w_d; in this case the most simple model is $c(k)=u(k)+w_a(k)$.

The gyro measurements, indicated by $y_g(j)$, are the increments of the gyro output rates, computed during the j-th sampling period of length T_g (usually $T=T_g$); they measure the mean inertial rates $\omega(j)$ in the j-th sampling period up to a discrete-time white noise n_g and a random walk d_g (called drift-rate bias), driven by a white noise w_g, according to the well known state equations (Ref.3):

(5) $d_g(j+1)=d_g(j)+w_g(j)$

(6) $y_g(j)=T_g\,\omega(j)+T_g d_g(j)+n_g(j)$

The SM output y_s is the estimate of the crossing time t_s of a program star through a SM slit; the corresponding measurement equation is a scalar implicit equation which expresses, up to a random and uncorrelated error n_s, the alignement of the apparent star direction (given by star Catalogue coordinates) with the plane passing through the slit reference line (depending on satellite attitude). The equation depends on the type of crossed slit, which is parameterized by the following indices:

1. FOV index f: 1 for preceding and -1 for following FOV
2. slit inclination index l: 0 for vertical, 1 for upper chevron and -1 for lower chevron slits

and holds:

(7) $0=\alpha-l\beta-q'(l,f)x(t_s)-\eta_s(t_s,\vartheta,\varphi,\beta,l,f)-n_s$

$q'(l,f)=[1,-l\cos(\gamma/2),lf\sin(\gamma/2)]$

where $\eta(.)$ is the RGC projection of the VGC longitude ($\approx\gamma/2$) of the slit reference line and is a nonlinear function of nutation attitude angles and star latitude. SM equations must be completed with the Catalogue equations:

(8) $\alpha=\hat{\alpha}+\delta\alpha,\quad \beta=\hat{\beta}+\delta\beta$

where $\hat{\alpha}$ and $\hat{\beta}$ are the mean apparent star RGC coordinates computed from the Catalogue and $\delta\alpha$ and $\delta\beta$ the Catalogue errors.

Now the general attitude estimation problem can be formulated. Given:

1. the following data measured during the time horizon $[t_o,t_f]$: SM crossing times t_s and the corresponding star coordinates, gyro rate increments y_g and actuating signals u,
2. a second order statistics for the uncorrelated measurement errors: n_g and w_g (gyros), n_s (SM), $\delta\alpha$ and $\delta\beta$ (Catalogue), and the driving noises w_a and w_d,
3. the measurements Eqs. 4, 6, 7 and 8 and the constraint Eqs. 1, 2, 3 and 5,

solve the set of Eqs. 1-8 into the following unkowns: the states $x(i)$, $\omega(i)$, $d_g(j)$, the disturbance torques $d(i)$ and the control torques $c(k)$ at the corresponding sequences of samples.

Since the number of equations is greater than the number of unknowns and the second order statistics of the noises is assumed known, the problem must be solved as a Gauss-Markov estimation, i.e. using the Weighted-Least-Squares criterion.

The solution of this problem is very complex due to the high number of equations and unknowns; thus in practice simplified estimators have been designed by dropping constraint equations and unknowns and/or measurements; the simplification level is always the result of a trade-off between computing load and the estimator efficiency as measured by the expected attitude variance.

Computing load is particularly constraining in Real Time Attitude Estimation (RTAE) problems, i.e. when attitude must be estimated at a current time from past measurements; a first consistent reduction of computing load is obtained by adopting a time-recursive Gauss-Markov estimator in the form of a Kalman filter. Computing load appears instead not very limiting when attitude must be off-line reconstituted using past and future mesurements (AR); one can still solve this problem by running the corresponding RTAE Kalman filter backwards and forwards in the time interval of the measurements and then by optimally weighing backward and forward estimates, but a not time-recursive Gauss-Markov estimator can be employed as well.

Coming back to the simplification problem, different classes of simplified, but not efficient, attitude estimators are used:

1. Kynematics estimators (Ref.3): the most simple way of reducing the number of equations and unknowns is to assume that the inertial rates $\omega(i)$ are unknown and unconstrained signals; by this way all the dynamics constraints are neglected and the estimator solves only Eq. 2 and Eqs. 5-8. In practice it is posed $T=T_g$ and inertial rates $\omega(i)$ are substituted, sample by sample, in Eq. 2 with the gyro measurements $y_g(i)/T_g$ obtained from Eq. 6, and the only unknowns are attitude, gyro drift-rate bias and star coordinates. When only attitude estimation is needed, the latters are eliminated in SM Eq. 7 by substituting longitude and latitude unknowns with the Catalogue values obtained from Eq. 8.
2. Dynamics estimators: to obtain with the same instrumentation a more efficient attitude estimator, one must take into account in some way that inertial rates are actually band-limited signals with a frequency bandwidth well below gyro half sampling rate. The most usual way is to assume that the rate errors $\Delta\omega=\Omega-\omega$ satisfy the state equations:

   (9) $\Delta\omega(i+1)=F[\Delta\omega(i),d(i)-c(i),i]$

   driven the uncompensated disturbances $d(i)-c(i)$ which are assumed white noise realizations. This estimator solves the same equations as the kynematics one plus Eq. 9 and inertial rate errors add to attitude and gyro bias as problem unknowns.
3. SM estimators: an alternative way for reducing computation load is to drop measurements instead of constraint equations; in practice only gyro measures can be dropped, but in this case the spacecraft dynamic constraints on inertial rates (Eq. 1) must be taken into account to not fall into a problem with more unknowns than equations.

When precision instead of computing efficiency is rewarding, one must look for efficient (i.e. minimum variance) estimates through a solution of the complete estimation problem; at this point simplifications are still possible: e.g. discarding too noisy redundant measurements or reducing degrees of freedoms (d.o.f.) in constraint equations; but they must not impair statistical efficiency. This route has been followed by the authors pushed by the concern of guaranteeing the high OGAR precision during all the Hipparcos mission. The main features of the Hipparcos attitude estimator are:

1. a simple model of the three-axes attitude has been so designed that modelling error might be guaranteed to be well below OGAR target precision (see Sect.4);
2. of the on-board measurements only SM data are used, since it has been proved (see Ref.4) that minimum variance estimates might be well obtained without processing gyro readings;
3. a not time-recursive Gauss-Markov estimator has been adopted, since reconstitution will run off-line (see Sect.5);
4. the reconstituted attitude is used to improve star coordinates when Catalogue errors are prevailing (see Sect.6).

4 MODEL OF HIPPARCOS ATTITUDE

The Hipparcos attitude motion is the composition of the nominal spin and quasi-precession motions and of residual perturbations due to interaction of disturbance and control torques.

The most severe disturbances are torques due to solar radiation pressure on spacecraft surfaces, gyro moments, spacecraft gravity gradient and spacecraft electric dipole in the earth magnetic field; less severe disturbances, but still contributing to perturb attitude above OGAR precision, are torques due to earth albedo, earth infrared emission and solar wind. An estimate of their peak values is reported in Tab.1.

Tab.1 - Expected peak values of perturbations

Perturbing cause	Peak value [microNm]
Solar radiation	11.
Gyro moments	10.6
Gravity gradient	1.5
Earth magn.field	0.65
Earth infrared em.	0.06
Earth albedo	0.03
Solar wind	0.01

The solar radiation and wind torques, due to spin motion and a quasi-constant sun aspect angle, are expected to be periodic with the spin motion; the gyro torque is expected to be constant. The other torques are periodic over 12 or 24 hours due to geostationary orbit and are modulated by spin motion.

The sum of the disturbance torques has been modelled as unknown deterministic, periodic and band-limited signals with period T_0 and frequency bandwidth known; thus each disturbance component can be modelled as a finite Fourier series with unknown coefficients.

The active control torques are actuated by firing cold gas jets at discrete times (in average one actuation every 600 s). The characteristics of the actuating pulses (duration and torque level) are known, but to account for actuator dynamics and misalignements control torque components has been modeled as ideal impulses of unknown intensity centered on the known actuation times.

The model of each attitude angle has been obtained by integrating linearized dynamics and kynematics state equations of a rigid body, driven by the Fourier series of the disturbance torques, the impulse train of the control torques and the unknown initial states (inertial rates and Euler angles). The resulting attitude model during any spin period T_0 is the linear superposition with unknown coefficients of two classes of linearly indipendent functions:

1. a train of impulse responses of the spacecraft dynamics, which models the large bandwidth component of the attitude due to impulsive

control torques;

2. a series of trigonometric functions with fundamental period T_o, which models the low frequency components mainly produced by solar radiation torque.

This model looks robust, since it is based on very simple assumptions like spacecraft and telescope rigidity (jitter due to solar panel vibrations has been verified by Industrial Consortium to be less than 3 milliarcsec), stability of spin period and sun aspect angle, type of control actuations. In addition the trigonometric series included in the model can be conveniently expanded to make the approximation error compatible with the OGAR target precision.

If the values at time t of the attitude functions are collected in a 3-rowed matrix A(t) and the related unknown coefficients in the vector p, the attitude vector x(t) can be written as:

(10) $x(t)=A(t)p+e(t)$

where e(t) is the model approximation error. Eq. 10 substitutes the set of Eqs. 1-4 of the complete estimation problem.

The dimension m of the vector p yields the degrees of freedom of the attitude model. As already said, they can be easily accomodated by extending or limiting the bandwidth of the Fourier series; an optimal choice of the d.o.f. would minimize for a given set of measurements and noise statistics, the norm of the estimated residuals; but this optimum is only reliable for simulated data. Thus a more realistic choice is to a-priori fix d.o.f. to make model approximation error negligible with respect to target precision in a simulated environmment and to equip the estimator with statistical tests to verify model adequacy from real data.

Using a detailed simulator it has been found that the RMS modelling error might be lowered to about 0.01 arcsec if a 15th order Fourier series (bandwith≈0.002 Hz) is used; moreover appropriate statistical tests (F-tests) have been designed to verify this model from real data, possibly during the Commissioning Phase preceding Mission Phase.

5 THE HIPPARCOS ATTITUDE RECONSTITUTION

Since gyro readings are disregarded, the OGAR measurement equations are obtained from the SM Eq. 7, by replacing the unknown star coordinates with their Catalogue values and the attitude x with its model (Eq. 10). Let us rearrange Eq. 7 by separating terms which are linear in the attitude from the nonlinear term

(11) $y(t_s,\vartheta,\varphi)=\hat{\alpha}-l\hat{\beta}-\eta(t_s,\vartheta,\varphi,l,f)$

which plays the rôle of a SM measure; by neglecting in Eq. 10 the model approximation error e(t) one obtains:

(12) $y(t_s,\vartheta,\varphi)=q'(l,f)A(t_s)p+n_s-\delta\alpha+l\delta\beta$

The set of the SM Eqs. 12 for all the crossing times t_s in the estimation horizon $[t_o,t_f]$ can be rewritten in matrix form using the following notations: $y(\vartheta,\varphi)$ is the vector of SM measures; Q is the model matrix having the generic row $q'(l,f)A(t_s)$, ε_s is the SM error vector, ε_α and ε_β are the Catalogue error vectors of the SM crossing stars; since a star may be observed more than once, ε_α and ε_β are related to y by a pair of matrices L and M having at any crossing time t_s a row which is null except for a positive or negative unit entry in the column of the observed star; it results:

(13) $y(\vartheta,\varphi)=Qp+\varepsilon_s+L\varepsilon_\alpha+M\varepsilon_\beta$

Since the three error vectors are assumed to be uncorrelated random vectors with covariance matrices Σ_s, Σ_α and Σ_β respectively, the covariance matrix Σ of the total error $\varepsilon=\varepsilon_s+L\varepsilon_\alpha+M\varepsilon_\beta$ holds $\Sigma=\Sigma_s+L'\Sigma_\alpha L+M'\Sigma_\beta M$. At the 'first reconstitution' based on Input Catalogue, Σ is not diagonal and shall be inverted using an ad hoc algorithm; instead at 'intermediate' and 'final reconstitutions' the approximation $\Sigma\approx\Sigma_s$ holds, since intermediate Hipparcos Catalogue errors are expected to be negliglible (less than 10 milliarcsec RMS) with respect to SM errors.

The matrix Eq. 13 can be solved into the unknown vector p as a nonlinear Gauss-Markov estimation problem, i.e. iteratively in the parameters of the nutation angles ϑ and φ appearing in the measure vector y. The solution algorithm has been implemented using Householder orthogonal transformations, which are well suited due to the rather limited number of unknowns.

A typical reconstitution is made over a time horizon comprised between two actuation times and lasting less than the spin period T_o; during this interval about 13 control actuations happen and less than 600 program stars cross SM slits, but less than 450 can be unambiguously located by SM processing (see Ref.2) giving a total of 1800 equations, against a total of about 250 unknowns in case of a 15-th order Fourier series. Thus one expects that attitude reconstitution smooths consistently star coordinates errors and achieves a good reduction of the measurement error variance.

The OGAR algorithm has been tested using a detailed numerical simulator of the satellite attitude and Star Mapper measurements. The results reported hereafter refer to a quite conservative case of the final OGAR:

1. 300 stars observed during each of 6 scanning circles at uniform rate;
2. Catalogue errors of star RGC coordinates negligible with respect to SM errors;
3. uniform standard deviation of SM measurements equal to 0.1 arcsec;
4. attitude model with a 15th order Fourier series;
5. impulsive control at a nonuniform rate ranging between 0.0013 and 0.0025 Hz.

Six independent Gauss-Markov estimations have been performed, each processing the SM measurements collected during one scanning; OGAR performance is evaluated by the rms difference between estimated attitude and simulated values (Monte Carlo error) and by the root mean estimated variance (estimated error). The results reported in Tab.2 confirm the expected reduction of measurement variance, which guarantees a good margin versus target precision.

Tab.2 - RMS errors of a 'final OGAR' (6 scannings)

Values [arcsec]	Monte Carlo psi	Monte Carlo theta	Monte Carlo phi	Estimated psi	Estimated theta	Estimated phi
Maximum	0.031	0.041	0.066	0.027	0.034	0.063
Average	0.029	0.037	0.063	0.026	0.034	0.062

The diagram of the Monte Carlo error for the angle φ during the first of the 6 scannings as well as of the estimated standard deviation are shown in Fig.3. The peaks of the estimated standard deviation correspond to control actuation times and to the initial and final instants of the reconstitution horizon.

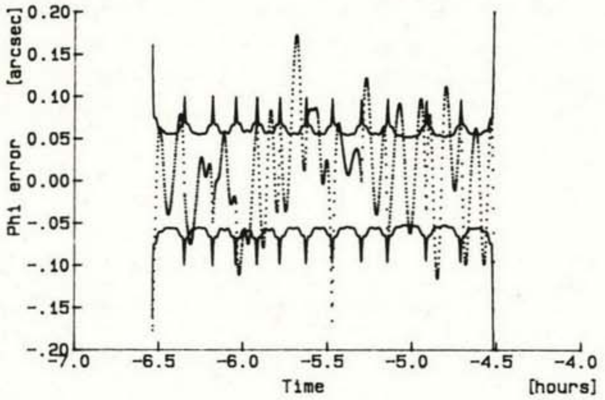

Fig.3 - Attitude Monte Carlo error and 1-sigma strip computed from the estimated variance

6 IMPROVEMENT OF STAR COORDINATES PRECISION

The smoothing properties of the attitude reconstitution can be conveniently used for improving the Catalogue precision of the observed stars, when the Catalogue variance is larger than the SM one. For the Hipparcos data reduction this improvement, if adequate, may help to unambiguously locate program stars within main grid slits, 1.2 arcsec large, at the very beginning of data reduction.

The theory underlying this improvement, called 'dynamical smoothing', has been presented in Ref.5 for the unidimensional case (improvement of star RGC longitude using the spin angle ψ reconstituted from the star grid coordinates estimated from IDT photon counts); since then the theory has been extended by the authors to Star Mapper data, which allowing to reconstitute the three attitude angles, make possible the improvement of both star RGC coordinates ('three axes dynamical smoothing').

The equations of this problem are the SM Eq. 7, the Catalogue Eq. 8 and the attitude model Eq. 10. At first sight the estimation problem is much larger than a pure attitude estimation since now also star coordinates are unknown (e.g. 900 unknowns in addition to attitude unknowns for one scanning); but a deeper analysis shows that the problem can be decomposed into two consecutive steps:

1. first the attitude reconstitution is obtained using the Catalogue values of the star coordinates as explained in Sect. 5;
2. since the reconstituted attitude is a minimum variance estimate, the coordinates of each star can be improved just by knowing the spacecraft attitude at the time of a SM crossing; for improving longitude vertical crossings are sufficient, instead for improving latitude both vertical and inclined crossings are needed.

Trials up to now made have given very encouraging results. The results reported in Tab.3 refer to the following case:

1. six satellite scannings for a total of 12h21', with 72 actuation times;
2. about 1000 different stars usable by attitude reconstitution corresponding to about 350 stars for scanning;
3. Catalogue errors on both star RGC coordinates simulated as a zero-mean white gaussian noise with s.d. of 1 arcsec for all the stars;
4. uniform standard deviation of SM measurements equal to 0.1 arcsec;

These results confirm that the Input Catalogue improvement also in the case of a single SM crossing (through vertical and inclined slits) is sufficient for solving main grid ambiguity (longitude RMS error <0.2 arcsec).

Tab.3 - Monte Carlo errors of attitude angles and improved star positions

Values [arcsec]	psi	theta	phi
Maximum	0.10	0.47	0.79
Minimum	0.06	0.26	0.48

Values [arcsec]	longitude	latitude
Maximum (1 crossing)	0.14	0.42
Average (all the stars)	0.09	0.33

ACKNOWLEDGMENTS

The results reported in this paper were obtained by dr. Belforte of Centro di Studi sui Sistemi under a contract with Consiglio Nazionale delle Ricerche (CNR), Piano Spaziale Nazionale.

REFERENCES

1. Perryman MAC 1985, Ad Astra: HIPPARCOS. The European Space Agency's Astrometry Mission, ESA BR-24.

2. Canuto E & al 1983, The star mapper data processing, Proc. F.A.S.T. Thinkshop, Processing of scientific data from the ESA astrometry satellite Hipparcos, Padova (Italy), 156-162.

3. Lefferts EJ & al 1982, Kalman filtering for spacecraft attitude estimation, J Guidance & Control 5(5), 417-429.

4. Donati F & al 1986, High accuracy on-ground attitude reconstitution for the ESA astrometry HIPPARCOS mission, Manuscripta Geodaetica 11, 115-123.

5. Donati F 1983, On dynamical smoothing, Proc. F.A.S.T. Thinkshop, Processing of scientific data from the ESA astrometry satellite Hipparcos, Padova (Italy), 251-254.