HIPPARCOS SATELLITE AND THE ORGANIZATION OF THE PROJECT

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ABSTRACT

The HIPPARCOS satellite is an approved project of the European Space Agency since 1980. A sketch of the past and future development of the project is given. The resulting astrometric parameters and magnitudes of 100 000 stars should be available circa 1993. Many astronomical groups are involved in the preparation of the mission together with ESA bodies and industry. Their functions and mutual interfaces are described.

The main features of the satellite are presented. While observing out of the atmosphere removes most of the effects that limit the accuracy of ground based astrometry, new causes of systematic or random errors appear in an instrument designed for a millisecond of arc level of precision. The main limitations that have been identified are discussed: basic angle unstability, mechanical jitter, grid irregularity, diffraction chromatism, shape of the image dissector sensitivity profile. The consequence is that the presently expected basic measurement precision is limited not only by the photon count errors. However, all these effects are taken into account when assessing a final accuracy of $0\rlap{.}''002$ for the astrometric parameters of a 9-th magnitude star.

I - DEVELOPMENT OF THE PROJECT

The idea of an astrometric satellite using the superposition of two distant star fields on a single focal plane by a complex mirror has been proposed by P. Lacroûte in 1965 and was first presented to the astronomical community at the following IAU General Assembly (Lacroûte, 1968). During the twelve following years, the project was studied and assessed several times by CNES and by ESA and has been greatly improved in its design and in the expected final accuracy. In 1980, the European Space Agency has taken the decision to include it in its mandatory scientific program and, beginning 1982, the system and subsystem definition phases started. This study is now over and the final approval of the project has been obtained, so that the C-D phase of detailed design and construction is star-

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ting now, January 1984. Meanwhile, four international scientific consortia were set up to take in charge the astronomical preparation of the mission and the reduction of the data. The launch is scheduled for the beginning of 1988. The observations will last $2^1/_2$ years. The final catalogues of positions, proper motions, parallaxes and magnitudes of the 100 000 stars selected for observation should be made available circa 1993, while the TYCHO Catalogue including two colour photometry and positions of over 500 000 stars will be ready by 1994 (for the discussion of TYCHO, see Høg, 1986).

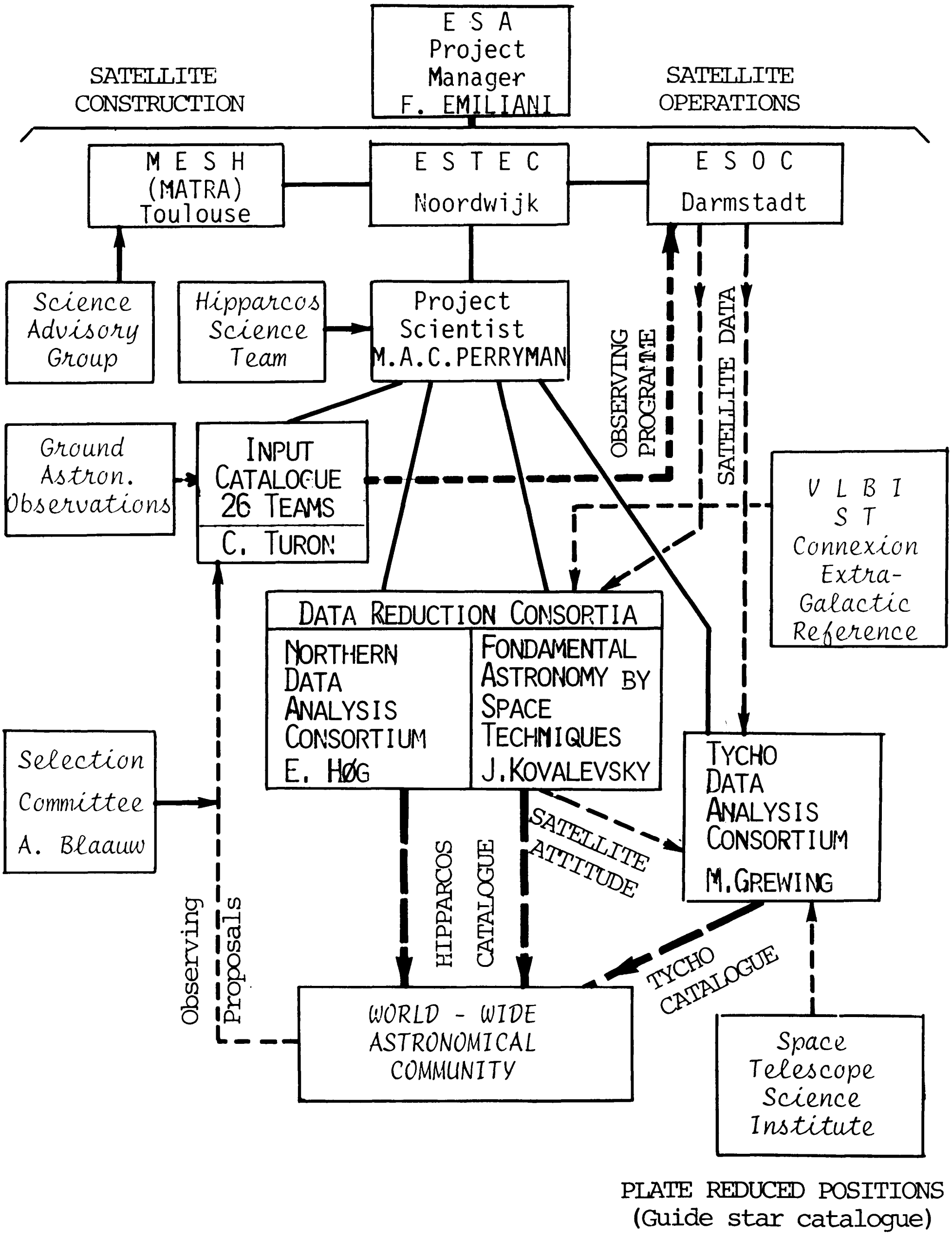
II - ORGANIZATION OF THE PROJECT

Several features of the HIPPARCOS program make it quite different from other space projects and imply a much more complex organization that for a typical astronomical satellite.

1. The first and the most important point is that all astronomical and astrophysical investigations that are expected to be conducted using the HIPPARCOS determined parallaxes and proper motions cannot be started before the final HIPPARCOS catalogue is completed, that is only when astrometrists will have finished the reduction. The data reduction is just as important as the data acquisition by the satellite and must not fail if the mission is to be a scientific success. This is why ESA has insisted upon having two strong data reduction consortia that have committed themselves to produce the final catalogue five years after the launch of the satellite. One of these consortia is the Northern Data Analysis Consortium (NDAC) headed by E. Høg; it includes six scientific teams from Denmark, Sweden and United Kingdom. The other consortium is FAST (for Fundamental Astronomy by Space Techniques). It includes 17 teams from France, Germany F.R., Italy, Netherlands and USA and is coordinated by J. Kovalevsky. Because of the great complexity of the reduction, a variety of techniques are to be applied so that consortia include not only astronomers, but also geodetists, and applied mathematicians.

2. All the data for $2^1/_2$ years mission has to be reduced globally. Every single bit of information downlinked at a rate of 20 kiloHertz has an equal weight and has to be treated with equal care since it contributes similarly to the final global solution. This means that, even if preliminary solutions shall be obtained using only part of the data (the first year for instance), the results will be unacceptable and will not be published. This is why one will have to wait five years until the catalogue will be made available.

3. For similar reasons, stars must be observed throughout the duration of the mission. This implies that the observing program, has to be decided upon in advance. ESA has set up a committee, chaired by A. Blaauw to rate the 200 or more proposals that have been submitted by astronomers from all over the world. The selection of the 100 000 stars will be done using the priorities set up by this committee, but also complying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Ground Astron. Observations
INPUT CATALOGUE 26 TEAMS
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HIPPARCOS CATALOGUE
TYCHO CATALOGUE
WORLD - WIDE ASTRONOMICAL COMMUNITY
Space Telescope Science Institute
PLATE REDUCED POSITIONS
(Guide star catalogue)

Figure 1

with the constraints imposed by the reduction procedures and the way that the sky will be scanned. One must have a very homogeneous distribution of stars on the sky, and only a small proportion of faint stars. This task was entrusted by ESA to a third international consortium "INCA" (Input Catalogue) led by C. Turon-Lacarrieu in which 26 teams of 10 countries cooperate. In addition to the selection of stars, INCA must furnish the positions and magnitudes of all stars and as much other information as possible (see Turon-Lacarrieu, 1984 or 1986). This involves a number of new Earth based observations to be done by many observatories and coordinated by INCA.

The complete organization of the mission is sketched in figure 1. In addition to the three consortia already presented, a fourth consortium was created: the "TYCHO Data Analysis Consortium" (TDAC) under the direction of M. Grewing in order to prepare the reduction of the TYCHO data. In this chart, various scientific consulting bodies are shown and the main iteractions are indicated.

III - DESCRIPTION OF THE SATELLITE

The principle of HIPPARCOS has been described already in several places (see, for instance, Høg, 1980 or Kovalevsky, 1982). A more detailed presentation of the instrumentation is in press (Kovalevsky, 1984). The reduction methods are also described in the last reference as well as in Lindegren, 1986. So, in this paper, we shall only describe the few features that are the most critical in the accuracy assessment of the mission.

Figure 2 shows schematically the principle of the instrument: a zerodur beam combiner consisting of two semi-circular mirrors is used to superpose two stellar fields separated by an angle $\gamma=58°$. This basic angle is the angular standard of the mission. The telescope is an all reflective Schmidt telescope (focal length: 140 cm, aperture, 29 cm). The combined rays coming from both stellar fields F_1 and F_2 are reflected by a flat folding mirror. Then a spherical mirror focalises the images on a grid. The useful field is $0\overset{\circ}{.}9\times0\overset{\circ}{.}9$, in which a perfect definition of the sky to focal surface transformation must exist. This is achieved by applying a Schmidt type correction on both components of the beam combiner, so that the actual instrument is an all-reflective Schmidt.

While the satellite is slowly rotating about an axis perpendicular to the plane of the two fields, the images move on a grid composed of 2700 parallel equidistant slits (period: $1\overset{''}{.}2$).

The light of a star crossing the field of view is modulated by the grid and is then transmitted by relay optics to an image dissector tube (IDT) which detects only the photons produced in a very small instantaneous field of view (IFOV).

While several stars are present the field, the IFOV is switched from one star to another. The photoelectrons produced by the IDT are counted

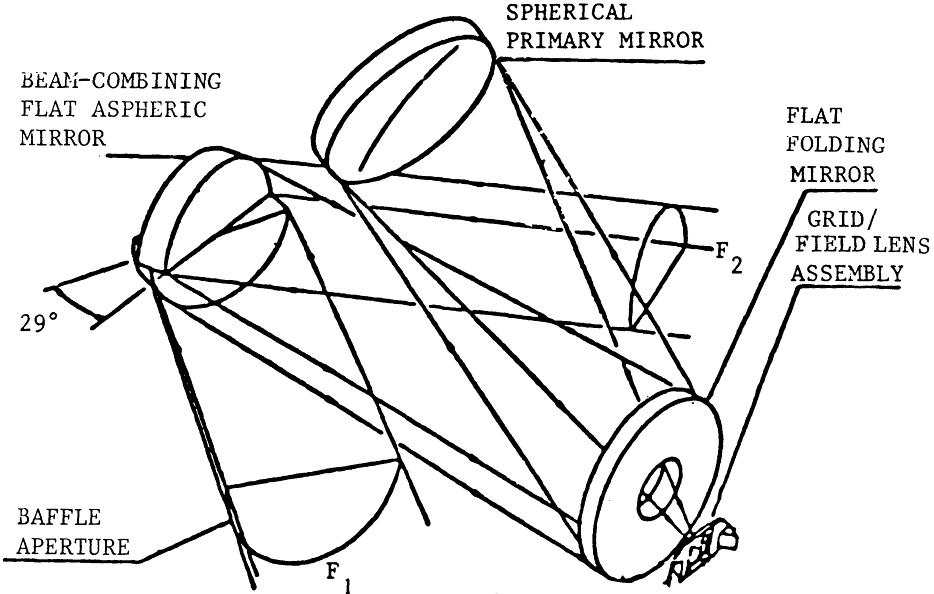

FIGURE 2

with a frequency of 1 200 Hertz. Successive stretches of photon counts are used to determine the phase of the modulation curve. The angle between two stars, in projection on the plane of the two fields is equal to the basic angle, plus an integer number of grid steps, plus the phase difference between the modulation curves transformed into arc seconds on the grid. So, the measurement of the phase differences is actually a vernier-type of measurement of the projection on a great circle of the angle between the two stars.

The satellite is revolving at a speed of one rotation in a little more than two hours. While the mission proceeds, the axis of rotation of the satellite drifts slowly on a circle around the Sun. Thus, the two fields of view slowly scan the whole sky. The scanning law has been optimized in order to maximize the accuracy of the parallax determination, and it is necessary that the actual motion of the satellite does not diverge by more than 10'. This implies that, on-board, there is an active attitude control. Intermittent actuations of gas jets are used to ensure this control with the accuracy required. The instantaneous knowledge of the attitude is obtained through gyroscope readings and the observation of the transit of stars of known positions through a star-mapper. In addition to the scanning control, the on-board accurate attitude determination - expected to be correct to 1" - is necessary to set the IFOV on the star to be observed.

IV - LIMITATIONS OF THE ACCURACY

The advantages of space astrometry with respect to ground based observations are self-evident: no refraction, no atmospheric turbulence, no gravitational flexures of the instrument. In addition, in the case of HIPPARCOS, the possibility of observing the entire sky from the same instrument and the independence from the Earth rotation and precession, are very positive factors for a global astrometric program.

However, at the millisecond of arc level of accuracy, other limitations occur that are now being identified. Definitely, the size of the diffraction pattern and the photon statistics are not the only factors that limit the accuracy of HIPPARCOS and, consequently, of any instrument in space. We shall describe the most important of those that are present in HIPPARCOS. Some of them are specific to this mission, but others will be present in most space experiments, so that some of the preliminary results already assessed for HIPPARCOS should serve as indications in planning new missions.

1. Basic angle statibily

The basic angle of the complex mirror is the angular standard of the measurement. Its actual value will be determined systematically throughout the mission, but it is essential that it is constant during a given rotation of the satellite so as to permit closure equations over a scanned great circle. This stability requirement is very severe: 0".001 at three sigma during $2^{1}/_{2}$ hours. This implies a very refined thermal control of the optics, to better than 0°.2. Because of the very high accuracy requested for the modelling of the position of a star image on the grid, a great thermo-mechanical stability is required for the whole instrument. It does not seem that, with the present state of the art, errors of the order of 1 millisecond of arc can be avoided.

2. Jitter

Moving pieces induce periodic motions of the satellite. When the periods are so short that they cannot be taken into account by the attitude reconstitution, the images have an erratic motion that cannot be corrected. In the case of HIPPARCOS, the maximum amplitude allowed has been set to 0".003. This very low limit has excluded the use of inertial wheels as means of controlling the attitude. For the sake of comparison, the jitter amplitude caused by wheels in Space Telescope is estimated to be at least the order of 7 milliseconds of arc. The adoption of gas jets for attitude control has permitted to meet the specifications. The jitter is reactivated every 5 to 15 minutes. The main frequencies, around 3 Hertz, are due to solar panels and the damping is very slow, but many other frequencies are present.

It does not seem feasable to reduce jitter to less than one or two milliseconds of arc in any spacecraft with pointing capability.

3. Chromaticity

The phenomenon now known as chromaticity - or diffraction chromatism -

has been ignored until now in astronomical optics, because much larger disturbing phenomena occur in ground-based astrometry. This is more the case in space, where the optical effects have to be analysed to a millisecond of arc. The theory of this particular effect can be found in Le Gall, 1983.

HIPPARCOS telescope, being a Schmidt telescope, has a residual coma. The effect of the coma is to distort the diffraction pattern which becomes elongated and asymetric. Since the size and shape of the diffraction pattern is wavelength dependent, the same applies to the coma pattern. And there is no reason that the photocenters of colocated monochromatic distorted diffraction patterns coincide. The displacement of the photocenters in function of the wavelength is called "chromaticity".

In the case of the nominal - perfect - HIPPARCOS telescope, the theoretical chromaticity is of the order of 0"001. But misalignments greatly increase the coma and - consequently - the chromaticity. Launch conditions and the subsequent vibrations of the instrument are unavoidable causes of such misalignments. It is foreseen that the actual chromaticity may be as large as 5 milliseconds of arc, larger than the photon noise error for stars up to magnitude 9. This is a large effect that will have to be calibrated and corrected using the colour indices of the stars (they will have to be known to 0.2 magnitude).

4. Grid irregularities

In the present state of the art, it is not possible to make perfect grids. The fact that HIPPARCOS grid has to be drawn on a curved surface does not simplify the manufacturing. One micrometer on the grid represents 0"15 on the sky, that is a 45° phase difference in the light modulation. The goal is to be able to determine the phase to about 1°5. This means only 30 nanometers on the grid!

The electron beam techniques to manufacture the grid are capable of such an accuracy only in very small areas. The presently proposed method to manufacture the HIPPARCOS grid is to build a patchwork of quasi identical squares of 32 grid periods. The grid would consist of more than 7 000 such elementary grids with some uncertainty of the order of 0"01 left in their relative positioning. This is too large for the required precision and this stitching errors will have to be calibrated to 0"003 or better and phase corrections should be applied for observations in every elementary square. Some observations of stars whose images moves at the border of two elementary grids may have to be rejected in order to reduce the resulting positioning error to less than 2 milliseconds of arc.

This limitation being of a mechanical origin, no major improvement of this cause of error seems possible in the nearest future. CCD cameras may have a better resolution capacity, but they have been rejected for HIPPARCOS because their fiability in a very large field of view was not yet guaranteed with a sufficient certainty.

5. IDT profile

Several difficulties have been identified in the use of the image dissector tube to isolate the star light from other sources in the fields of view. All of them originate from the fact that the IDT sensitivity σ in function of the distance to the center of the IFOV is not rectangular, but is a smooth curve as shown in figure 3. The IDT profile has, of course, a sharp drop around r=30", the theoretical radius of the IFOV, but there remains a non negligible transparency even at large distances from the IFOV. In addition, the sensitivity starts to decrease from the very center of the IFOV and can be represented, in a small region of the field, by a linear function of r. Let us describe three consequences of these properties of the IFOV.

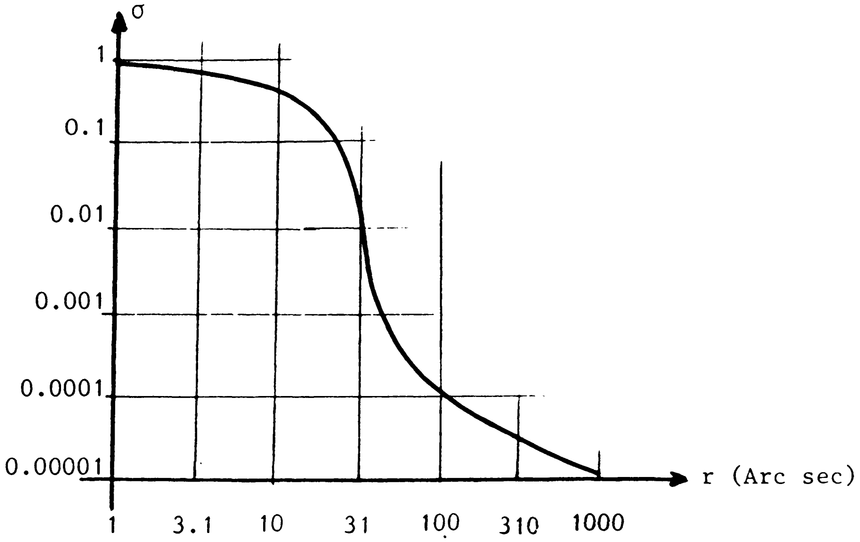

Figure 3

a) The veiling glare. The remaining sensitivity of the IDT at large distances of the observed star has normally a minor consequence: the parasitic light increases the background noise. But in the case of HIPPARCOS, this light is also modulated by the grid. Generally, the phase of the parasitic modulation does not coincide with the phase of the central image and the combination of the two modulations produces an error in the phase of the observed star. This veiling glare error may be large when a bright star is present in the field. Table 1 shows what are the distance and the magnitude difference ΔM between the disturbing and the observed star that cause an error of 3 milliseconds of arc in the determination of the position of the central star.

If the magnitude difference is smaller for a given distance, the error increases very rapidly: 1.5 magnitude more will multiply the errors by 4. So when bright stars will be present in the field, corrections will have to be applied. To do this, the exact relative positions of both the observed and the perturbing stars will have to be known to a very great accuracy. In practice this will be possible, only if the disturbing star is part of the HIPPARCOS program. Since, on the other hand, the density of HIPPARCOS stars should not exceed 3 stars per square degree, great difficulties will be encountered in trying to obtain the desired accuracy in highly populated regions such as open clusters.

Distance from the IFOV r	ΔM causing an error of 0.″003
100"	3.7
300"	5.5
1000"	7.5
3000"	9.8

b) Double stars. When both stars are in the IFOV, what will be observed is a certain combination of the phases produced by each component. This phase difference is a function of the position angle of the companion with respect to the slits. A specific reduction algorithm will have to be used to take care of this pecularity. If one expects to be able to deduce some knowledge about the distance between the components, this will inevitally be done at the expense of a loss of accuracy in the determination of the astrometric parameters.

If, in addition, the separation between the two components is of the order of the radius of the IFOV (20 to 40 arc seconds), then errors in centering of the IDT will produce large random differences in the amplitude of the light modulation of the secondary and consequently of the resulting combined phase. This supplementary cause of error is so important, that no significant result on double stars of such separation and with comparable magnitudes of components may be expected. Such stars should be excluded from the observing program.

c) IDT guiding errors. It is not possible to modify continuously the position of the IFOV by applying slowly varying deflection currents in the tube. It has been decided that the IFOV will remain fixed during 1/150th of a second, corresponding to 8 sampling periods. During this time, the star image moves by approximately one grid period. During this time, the distance of the star to the center of the IFOV changes, and therefore the amplitude of the modulation registered by the photomultiplier varies. The reduction procedure will attempt to describe the modulation received by a constant amplitude periodic curve. P. Granès and myself have shown that this produces, finally, a spurious error in the phase determination of the order of several milliseconds of arc if the IDT sensitivity profile is analogous to the one presented in figure 3. This is a random non gaussian error that adds to the photon noise independently of the magnitude of the star. Its main influence is to limit the accuracy of bright star observations for which the photon noise is no more the dominant source of error.

CONCLUSIONS

A large number of simulations and accuracy analyses have been performed by ESA, by industrial and by scientific consortia. They all agree that with the present design of the satellite, the nominal final accuracy of 0".002 for parallaxes and 0".002 per year for proper motions is achieved for 9-th magnitude stars, provided that they are observed at every possible scan and that the cumulated observing time is 600 seconds. For fainter stars, the main limitation is due to photon noise, and the above mentionned precisions raise to 0".005 even if the observing time is doubled. For brighter stars, however, the errors described in the preceding section - and some others - become predominant so that the final accuracy achieved will not be very much better than the 0".002 figure given above.

So, in conclusion, although several new sources of error have been identified and evaluated, the accuracy goal announced five years ago still holds.

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Discussion:

GUINOT: From which platform will the satellite be launched?

KOVALEVSKY: HIPPARCOS will be placed in a geostationary orbit by an ARIANE launcher from the Guyana launching pad.

CURRIE: A word of warning on jitter from Space Telescope: The damping of materials (graphite-epoxy and metals) and of mechanical joints may be much less than normally encountered in computer programs for the analysis of spacecraft vibrations.

KOVALEVSKY: We are quite aware that there are forecasts of rather hazardous jitter amplitudes. The numbers I quoted here are taken from a very wide range of amplitudes provided by the Industrial Consortium. They are on the pessimistic side of the range.

THORNBURG: When do you hope to fly "HIPPARCOS 2" for proper motions?

KOVALEVSKY: A second HIPPARCOS is in the minds of the scientists, but has not been approved. It is to be remarked that the standard errors of the proper motions which will be produced by the HIPPARCOS main mission will be of the order of $0\farcs002$/yr. The consistent set of some 80000 proper motions is already a large gain over the existing situation. A second HIPPARCOS, improving proper motion by a factor of 10 should be launched 10-15 years after the first.

TOWNES: Are the error estimates averages or the most pessimistic predictions? Do the photon counts refer to a single passage?

KOVALEVSKY: The nominal photon statistics error is deduced from a nominal observing time amounting to 5 seconds for 9^m stars. All the other causes of error can be treated as random in the general reduction procedure. Because of the great variety of positions of great circles on which a star is observed, all these errors can be considered as random. This is why errors in the order of $0\farcs001$ or $0\farcs002$ have a small effect when they are combined with the photon statistics error.

de VEGT: Could the jet gas affect the quality of the observations?

KOVALEVSKY: Most likely not. Many of these things we will know after launch.