2018.04.15

#2:The second of three reports on the early history of Hipparcos from 1964 to 1980

From TYCHO to Hipparcos 1975 to 1979

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Abstract: With this report I follow the encouragement from several colleagues to my previous historical reports, they urged me to write more about these old times. I am going as deep as possible by means of documents, my own memory and in discussions by email with colleagues. - It is worth investigating how the Hipparcos astrometric satellite mission came about: was it almost a historical necessity that had to happen because astrophysicists needed the accurate positions, parallaxes and proper motion for the study of the Galaxy and the Universe and because the technical tools were available and affordable? Was it such general circumstances or did other more special historical circumstances play a major and even decisive role? My experience from 65 years dedicated to the development of astrometry shows me that special historical circumstances were needed and decisive.

1 Introduction

The historical circumstances in Western Europe in the 1960s and 1970s played a decisive role for the creation of Hipparcos, the first space astrometry mission ever, launched by ESA in 1989. This should become clear from the following where I describe and document some of the developments of Hipparcos from its beginning with the mission definition study in October 1975 up to the mission approval in 1980. A main focus will be on the development of the Options A and B, proposed by the present author and Pierre Lacroute, respectively, in December 1975. Their similarity and differences with respect to methods of measurement and scanning will be shown. Some of the many meetings are listed where the emerging space astrometry was presented and discussed with other colleagues. My archive of papers and technical notes is described.

I am placing my reports on arXiv and they are sometimes printed, hoping that they can be of interest for colleagues and historians. I do not intend to make a book although I have been urged to do so, a book of my scientific biography, but being 85 years old a book could put me under unwanted pressure to complete. Perhaps I could write an overview in a journal for the history of astronomy.

Below follow sections #2 - #6:
#2 an overview of the years 1975 to 1979,
#3 the Mission Definition Study - October 1975 to May 1976,
#4 meetings and Phase A Study - June 1976 to 1979,
#5 a brief conclusion, and
#6 references.

The Hipparcos space astrometry mission broke through to milliarcsecond (mas) astrometry for 100 000 stars, something impossible to do from the ground, and even in an absolute celestial coordinate system thus reaching or exceeding mas accuracy, not only precision. Ground-based astrometry could have thrived without Hipparcos by means of automatic meridian circles for absolute astrometry with perhaps 50 mas accuracy. Relative astrometry on the 50 mas level was obtained with wide-field astrographs on photographic plates (like the Hamburg Zone Astrograph), but the mas accuracy could only be obtained in small fields of long-focus length, astrometric telescopes (e.g. parallaxes of a small number of targets).

That Hipparcos was affordable is astounding. At his famous talk in Prague in 1967, Pierre Lacroute mentioned a cost of 10 million French Franc for an astrometric space mission when the question of cost was asked. This was one of the reasons some listeners including myself considered the idea to be unrealistic, another reason was the primitive design. At a meeting on 18 December 1975 the AWG (Astronomy Working Group) of ESA assumed 15 MAU for space astrometry (MAU=Million Accounting Units = about a million Euro). In the end Hipparcos cost ESA about 500 MAU according to ESA (1997), i.e. almost the same as the famous Sydney Opera House. Even though such costs are not easily comparable over long intervals of time, it is clear that the original estimates were very much too low. For further information, the costs are 740 M Euro for the 5 year Gaia astrometry mission launched by ESA in 2013, and thanks to modern detector technology and larger mirrors Gaia is a factor one million times more efficient in the utilization of light from the stars than Hipparcos was.

The great vision by Lacroute about space astrometry was received with interest outside France, but it was a French project for ten years from 1964, and nobody outside France worked on it. The support in France came from several places and especially Jean Kovalevsky was leading. He was able to bring the project into ESA when it became clear that France could not do it alone, see Kovalevsky (2009). The French Space Agency had decided not to pursue any purely French scientific mission, but only support European programs. **Pierre Lacroute and Jean Kovalevsky were key persons without whom we would not have had the Hipparcos mission, nobody was there who could have replaced them, as explained in EH2011b and Høg (2017f).**

A symposium on Space Astrometry coordinated and chaired by Jean Kovalevsky, was held in Frascati, Italy, on 22-23 October 1974 and gathered 41 participants from Europe and the United States, see more in Kovalevsky (2009) and see in Sect. 3.5 my comment to my letter to C.A. Murray of 30 June 1975. This convinced ESRO (European Space Research Organization soon to be named ESA) about the scientific interest and it was decided to gather a small number of scientists for a mission definition study. I was invited and decided to join in spite of my profound scepticism. My deep scepticism about European space astrometry is explained in the letter of 30 June 1975, see Sect. 3.5.

The potential advantage of astrometric observation without the disturbing atmosphere was obvious, but the proposed instrumentation had held me from being interested. At the same time I was deeply involved in other big projects, developments of an automatic meridian circle and of a new type meridian circle, cf. Sect. 7 of Høg (2014). The paper by Requieme (1980) gives an overview of the time in that field of classsical astrometry. At this time astrometry was still being pursued at many observatories in Europe although astrophysics had long become the main research subject of astronomers. The natural consequence was that astrometry was gradually stopped and young astrophysicists were replacing astrometrists when they retired. **Thanks to this circumstance of active astrometry in Europe there was a basis on which sufficiently strong interest and enthusiasm for space astrometry could build** as soon as it began to look realistic, cf. EH2011b. This happened in Western Europe, but it could not happen in USA because astrophysics had been dominating for much longer thanks to large telescopes and good observing climate. In the USSR astrometry was strong, but political and economic conditions prevented to pursue space astrometry.

I have recently asked the opinion about the creation of Hipparcos from a number of colleague astronomers and from a historian of science, John L. Heilbron. The resulting twelve interviews are collected in Høg (2017f) to which the interested reader is referred. It was interesting and quite surprising for me to see that so different opinions existed on matters which had been clear and evident to me for years - and still are.

After the success of Hipparcos and the great interest generated by astrometric data, to this day the **astrophysical** community seems to not fully appreciate the decisive contributions toward the advent of space astronomy by e.g. Lennart Lindegren and myself. My own contributions during 65 years to the astrometric foundation of astrophysics are summarized in the poster Høg (2018a). A list of some of my papers since 2006 are given in Høg (2018b).

2 An overview of the years 1975 to 1979

This section is an adapted copy of Sect. A2 in Høg (2017f), for the reader's convenience.

Pierre Lacroute presented his ideas of space astrometry in Prague in Lacroute (1967) where I heard him, but I had never spoken with him before we met in October 1975 in Paris for the first meeting of the ESA Mission Definition Group. This meeting changed me from being very sceptical about space astrometry to become enthusiastic as explained and documented in Sect. 4 of Høg (2011b).

For the next meeting in December 1975 I proposed a new design with one-dimensional scanning, active attitude stabilization, revolving scanning mode, input catalogue etc., in all seven new features are listed in Høg (2011b), but there were in fact ten new features as now listed below in Sect. 3.1.

In January 1976, Pierre Lacroute invited me by the letter in Figure 1 to come to Observatoire de Paris before a study group meeting for a discussion between just us two, and he tells in the letter how much he appreciates that younger persons have now entered the project. We spent several hours in fruitful and pleasant exchange of ideas. Lacroute had immediately in December 1975 agreed to aim for a scanning satellite with one telescope, not with two telescopes as in the TD Option from Frascati, see ESRO (1975). The Spacelab option, the preferred option in the conclusions from Frascati, was still mentioned as a possibility in a note (see Høg 2018) in March 1976. He adopted an image-dissector tube (IDT) to become the very efficient primary detector behind a modulating grid instead of several photomultipliers behind long slits as in his original TD Option. In notes from December 1975 to March 1976 he also introduced a star mapper with slits and photomultipliers placed before the main field, able to detect stars and measure their position as required to point the IDT spot even without using an input catalogue. But his acceptance of other features in my proposal came more gradually and the chairmen of the group were obviously keen to avoid any decisions which might be premature or perhaps against Lacroute's ideas.

2.1 The development 1976 to 1979

I remember members of the study group saying that we were diverging because Lacroute maintained two-dimensional scanning with inclined slits, passive stabilization and no input catalogue since he considered this to be simpler and more safe. I assured them that we would soon converge towards my design.

But it took much longer than expected, nearly three years before the use of a modulation grid for two-dimensional scanning, a beam combiner in three parts, and passive scanning were definitively dropped. This appears from the fact that these options are still mentioned in ESA (1978), the "report on Phase A study", and in Barbieri & Bernacca (1979), the proceedings from the colloquium in Padua. Likewise according to the study report of 26 April 1978, the use of an input catalogue had not yet been decided. The final study report ESA (1979) does mention the input catalogue in Sect. 1.7.

The use of an input catalogue had, however, been decided already in a meeting of the Science Team on 23-24 November 1977 according to Høg (1997). I could therefore in December 1977 distribute an inquiry which I had held ready for some time on projects for the satellite mission to astronomers mainly in ESA countries and I went on a round trip giving lectures at a number of institutes to generate more interest and support for the mission project. This resulted in 80 projects of scientific investigation defined by about 50 astronomers at 12 institutions in ESA countries as reported in Høg (1979). These projects were analyzed by Høg (1979) and Turon Lacarrieu (1979) for their consequences on e.g. Galactic astrophysics.

The complete acceptance of one-dimensional scanning came after January 1979, according to Høg (1997 p. xxx=30). The same page contains further notes on the slow acceptance of the principles proposed in December 1975.

Lacroute's idea of attitude stabilization by the gravity gradient would conceivably work in the low-earth orbit originally assumed, but at the meeting of the science team in November 1977 we were directed by ESA to design the mission for a geostationary orbit which had become possible with the new ESA launcher Ariane. That killed the gravity gradient as an option for stabilization and active attitude control became obligatory. That also decided in favor of an input catalogue. According to Høg (1997), the main reason to keep the option with passive stabilization was its smooth rotation, while the active control with reaction wheels produced astrometric jitter of unknown size, and this question was never precisely answered. But the problem with reaction wheels was radically solved when MATRA introduced cold gas control. That came much later, during Phase B.

> The evolution of the Hipparcos project is described in ESA (1989). An account of the early phases of the Hipparcos project up to inclusion of the Tycho experiment in 1981 was presented in Venice as Høg (1997). The above text covers the period up to 1979 with a somewhat different emphasis. The early phase in the creation of Hipparcos and the mission selection process in 1980 are broadly described in Chapter 5 of the book by Perryman (2010). In the present report Høg (2018) I am describing my archive from those years focusing on the instrument design.

3 Mission Definition Study - October 1975 to May 1976

The first meeting of the Mission Definition Group (MDG) took place in Paris, i.e. in ESA Headquarters in Neuilly, on 14 October 1975. As mentioned in Sect. 4 of Høg (2011b), hereafter called EH2011b, my "profound scepticism and lack of interest in space techniques" was here changed to the opposite. The words of the chairman Dr. V. Manno that we should forget the existing proposals by Lacroute and just think how we could best use space technology for our science, these word were the "Sesame open!" for me.

Back in Denmark, at first I looked again at a completely different method than Lacroute, mentioned in the letter of 30 June in Høg (1975d) at the use of high-precision gyros attached to a telescope that could then be pointed at any star for measurement of its position. I mentioned it to students in my lecture on astrometry, but I soon turned my attention towards a scanning satellite. I remembered the Image Dissector Tube (IDT) and our brilliant electronics engineer, Ralph Florentin Nielsen, found information for me on this device which would be able to measure many stars one-by-one in the telescope field. That was the way forward.

The IDT was a technologically mature device, invented in the 1930s for television. CCDs also existed but I do not recall that I considered this very new technology, recently however I found in my archive for these years a reprint of the review by Samuelsson (1975).

Here follow the sections:
3.1 TYCHO / Option A by Erik Høg
3.2 TD / Option B by Pierre Lacroute
3.3 Options A and B down-select process
3.4 My archive for October 1975 to May 1976
3.5 Some quotes from my archive on the mission definition
3.6 The final study report from mission definition

3.1 TYCHO / Option A by Erik Høg

My work on space astrometry during the six weeks bore fruit, at first the 9 pages dated 2 December 1975 in Høg (1975a), but I had told of the ideas and distributed notes at a second meeting in Neuilly on 18 / 19 November. These 9 pages contain my first design of an astrometry satellite, then called TYCHO. The design was sent to Pierre Lacroute with a letter of 4 December 1975, Høg (1975b). The TYCHO design differed from that presented for a scanning astrometry satellite TD by Lacroute at the Frascati symposium in 1974, ESRO (1975) by introduction of **ten** new features for a scanning satellite - **not only seven** new features as counted by me in previous papers and lectures.

These ten new design features were implemented in the final Hipparcos satellite and mission:

1) use only one small telescope instead of two large telescopes as in the TD option by Lacroute,
2) use a beam combiner of two parts as in Figure 3a, not three parts as in Figure 2b,
3) use active attitude control,
4) make the spin axis revolve around the Sun at a constant angle,
5) use an Image Dissector Tube (IDT) as main detector,
6) use one-dimensional measurement along scan,
7) use a modulating grid instead of widely spaced slits,
8) use a star mapper with one photomultiplier to detect reference stars,
9) use an input catalogue with 600,000 selected stars, see Table 1 in Høg (1975a).

#1 meant that a scanning astrometry satellite with a telescope of 16x16 cm aperture could be launched by a Scout launcher instead of two telescopes with 40x40 cm and 27x27 cm apertures which required a Delta launcher.

In January 1976 I derived from the theory by Høg (1961) of division corrections on a meridian circle that:

10) the beam combiner should have a basic angle between the two fields of view other than the 90 degrees assumed by Lacroute, especially resonances at 90 and 60 degrees must be avoided. In fact anything else between 50 and 110 degrees will do with little variation of accuracy.

The number of stars in the input catalogue was reduced to 100,000 in March 1976. (For the actual conduct of Hipparcos observations a special Hipparcos Input Catalogue of 118,209 stars were selected in a large preparatory work before launch from some 214,000 distinct candidates contained in some 214 observations programs.)

All these ideas formed a self-consistent instrument which by mid-1976 looked as in the Figures 3a and 3b. See also the discussion in Høg (1997)**. It appears from the historical context that this self-consistent design could hardly have been proposed at that crucial time by anyone else, in accordance with my previous claim in EH2011b and Høg (2017f).**

Following an advice from the chairman, I changed the name TYCHO to Option A or Astrometric Satellite (AS) which three years later became Hipparcos. Lacroute's new TD option also equipped with an image dissector tube became Option B.

Early phases of the Hipparcos project have been further outlined in the appendix of the recent report Høg (2017f).

3.2 TD / Option B by Pierre Lacroute

In response to my proposal in December 1975, Lacroute proposed already in the same month a new version of his Option TD, TD stands for Thor-Delta launcher, from 1973 which was later called Option B. It has only one telescope instead of two and an IDT is introduced as a much more efficient detector than photomultipliers. This is documented in the archive papers in the bunch "Lacr01".

The following Figure 4 is found In a report from 12 March 1976 showing how stars are detected and measured in two coordinates by Option B, a distinct difference from Option A with one-dimensional measurement. The Option B has here a beam combiner for three directions of view shown here in Fig. 4. This is mentioned in the final MDG study report (ESA 1976) in Sect. 2.3.2 as an option with some advantages but also with some problems in the diffraction pattern. The study report finally assumes a telescope of about 25 cm diameter with two directions of view obtained by a beam combiner with two reflecting surfaces, but this does not give the required symmetry for measuring in two dimensions.

Therefore in later reports from the Phase A study a symmetric beam combiner appears with three surfaces for two directions of view. The study report version #1 ESA (1978) specifies in Sect. 2.7.2 "the complex mirror is a triple split symmetrical device". The final report ESA (1979) specifies in Sect. 3.2.1 "the complex mirror consists of two mirrors, tilted in opposite direction" and Figure 3.2 shows accordingly a mirror with only two parts.

For Lacroute, however, the Option B from March 1976 with three directions of view appears to have been important since he maintains the concept after one year when it is further discussed during the Phase A study in a report Lacroute (1977) dated 25 January 1977. It is explained on p. 1 that the most precise smoothness of attitude motion and thereby higher accuracy of measurements will be obtained by having three directions of view. The report also discusses the computations, the feasibility of the design and finally proposes to have two IDTs.

Lacroute says that an important objection against Option A is that a pointing accuracy of 1 arcsec is required in order to point the photo cathode of the IDT on a star of the input catalogue and this will be very difficult to achieve, he says. Therefore the capability of Option B to observe without an input catalogue is important.

Option B was maintained in the study in parallel with Option A. The Option B has adopted five of the above 10 features for Option A: 1, 5, 7, 8, and 10, but not the other five: it uses passive attitude control, it does not use revolving scanning, it does not use an input catalogue, it makes two-dimensional measurements, it needs a symmetric beam combiner with three parts.

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OBSERVATOIRE
11, RUE DE L'UNIVERSITÉ
TÉLÉPHONE: 35.43.00
POSTES 265 - 266

STRASBOURG, LE 6 janvier 1976

P. LACROUTE
à Monsieur Eric HØG

Mon cher Collègue,

Je vous adresse ci-joint une nouvelle étude sur le guidage proposé pour un balayage T.D. Comme je le demande à la fin, il serait bien utile, pour établir les éléments permettant de choisir un type de balayage, T.D. ou Tycho, que soit étudié assez en détail comment on pourrait réaliser pratiquement le balayage Tycho.

J'ai bien reçu la documentation dissector et l'envoi des exemplaires de votre projet méridien. Je vous en remercie.

J'apprécie vivement de ne pas être le seul à présenter des projets, car ainsi il est possible de mieux discuter ce qui est possible et ce qui ne l'est pas. En outre, étant âgé, il est probable que je ne pourrai suivre activement l'exécution des projets et la participation d'astronomes plus jeunes est très nécessaire.

Si j'ai présenté en détail certains projets, c'est pour essayer toujours de vérifier personnellement s'ils sont viables et pour soumettre mes projets à la critique de ceux qui sont plus habitués que nous aux expériences spatiales.

Je n'ai rien reçu encore de Monsieur WILSON qui devait étudier l'optique. C'est important. J'espère recevoir quelque chose de lui bientôt.

Lorsque vous aurez réfléchi aux papiers que je vous ai adressés et examiné vous-même certains problèmes, il serait probablement utile que nous puissions nous rencontrer assez tôt avant le 29 janvier pour, si possible arrêter des positions communes sur certains points avant la séance. Peut-être avec Monsieur Wilson s'il donne signe de vie. Il est probable que cela serait une bonne avance dans le travail du groupe.

= tidsnok

Bien cordialement.

P. LACROUTE.

Figure 1 Letter of 6 Jan. 1976, one of many kind letters from Lacroute. He mentions that we should meet in person before 29 January and so we did.

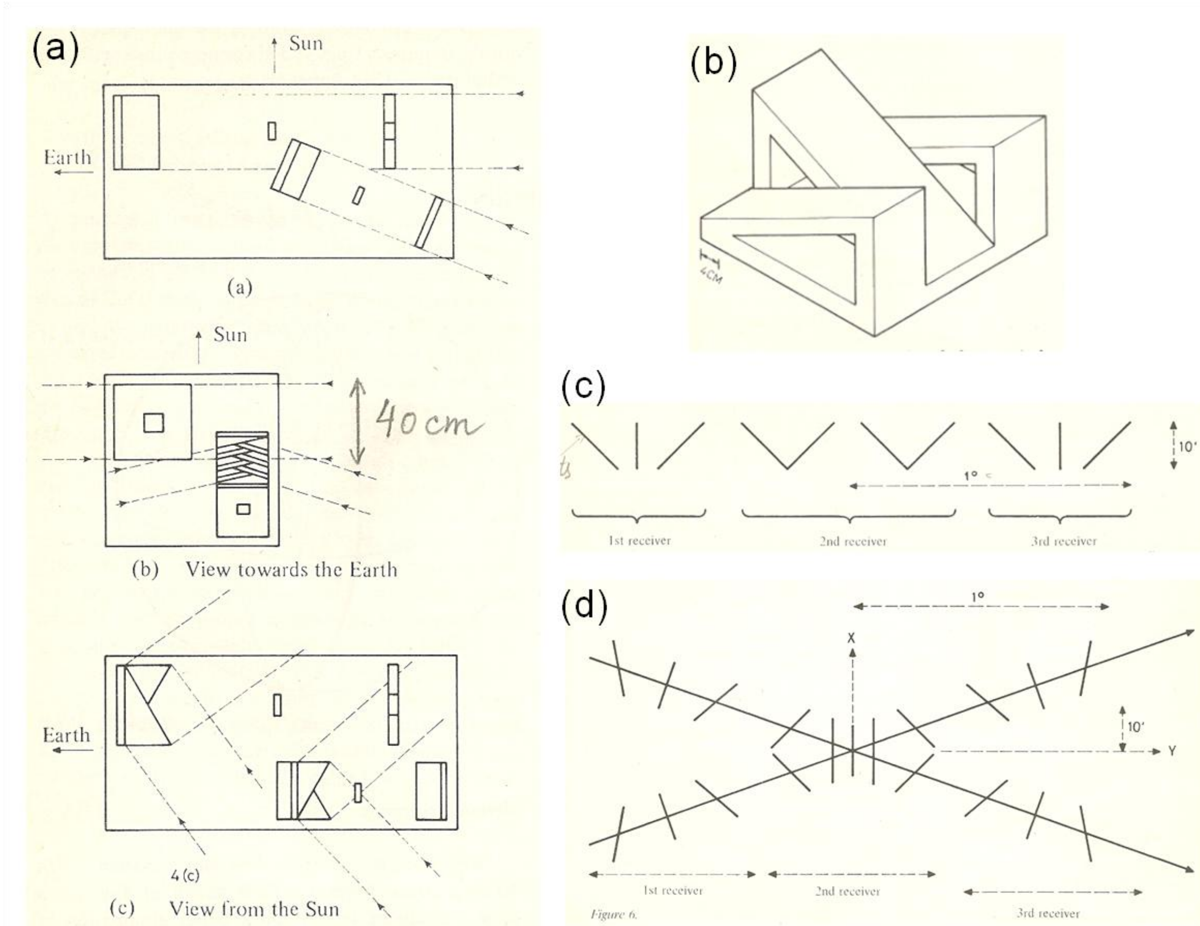


Figure 2 (a): Two telescopes as proposed by Lacroute in 1974. By rotation about a spin axis pointing in the direction to the Sun the telescopes will continuously scan the sky with slits as in (c) and (d). **(b)**: A beam combiner placed in front of the telescope aperture will combine the beams from two fields on the sky separated by an angle of 90 degrees. The angle will be very stable as defined by the rigid material. **(c)** and **(d)**: The stars will cross the slits and be measured by six photomultipliers. The upper system is used in the larger telescope of (a), the lower one in the smaller telescope. Since the latter telescope is scanning a small circle on the sky the stars from the two fields move in different directions on the focal plane. Source: Lacroute (1974) and copied from EH2011b.

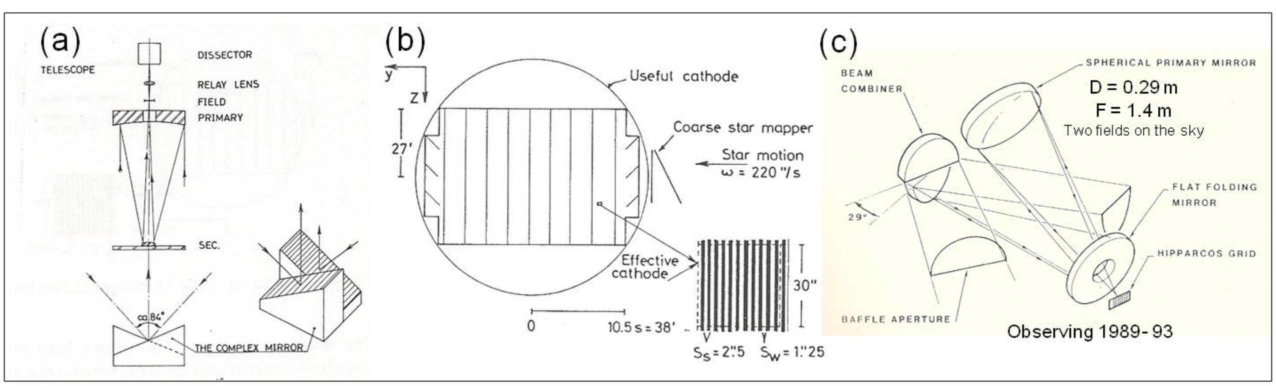


Figure 3 (a) and **(b**): Hipparcos design according to Option A by mid 1976 (EH1977). **(c)**: When launched in 1989, the Hipparcos telescope was very different, a folded Schmidt system. The slit system and detectors were quite similar to (b), but the Tycho star mapper slits were implemented for the Tycho experiment proposed in 1981. Source: Copied from EH2011b.

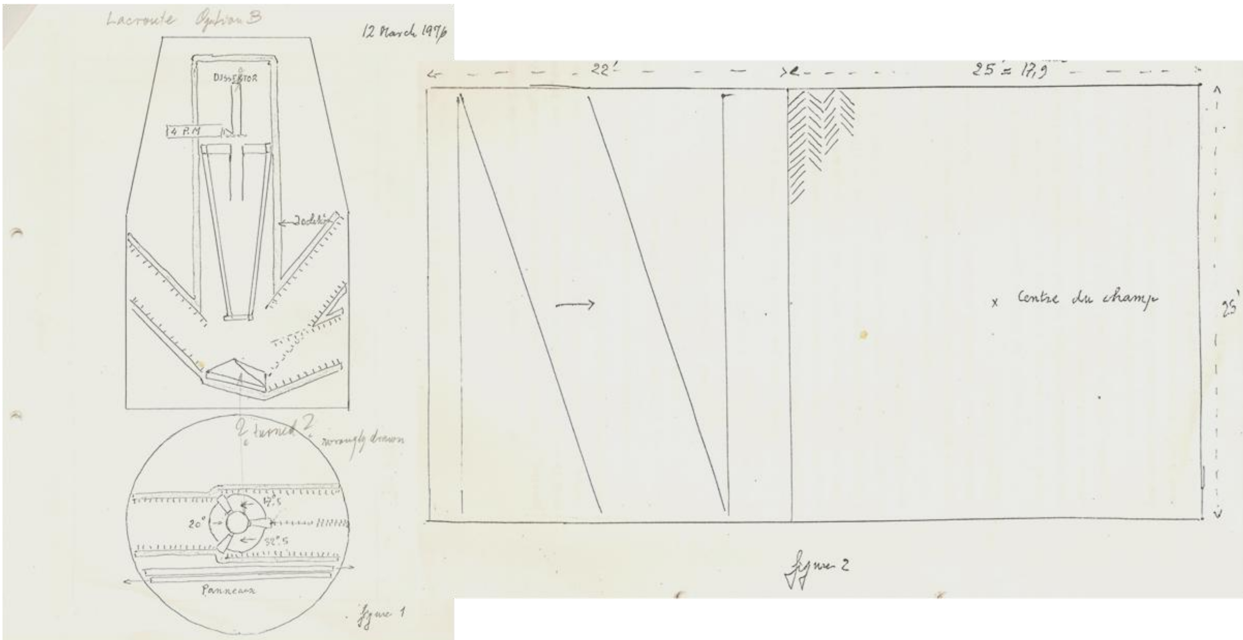


Figure 4 Option B on 12 March 1976. **Left**: Beam combiner and baffles for three directions of view. **Right**: Focal grid common for the three fields of view. The star mapper with four slits allows observation without an input catalogue since the position of a star can be derived if it is detected with sufficient SNR at all four slit. Two-dimensional measurement can then follow in the IDT field at right. Source: Lacroute 1976.

3.3 Options A and B down-select process

These options were maintained in the study as having comparable astrometric performance and as subject to further studies which may result in the selection of one of the options or a combination of both, as the final study report from the mission definition says. In the end all ten features of Option A were implemented in Hipparcos.

A recent search in my archive has shown that the use of active attitude control and of an input catalogue were adopted at a meeting on 23-24 November 1977. Adoption of one-dimensional measurement and of a beam combiner with only two parts took longer, it had not yet happened in the first version of the Phase A study report ESA (1978) of 26 April 1978, but in the final report ESA (1979) of December 1979 it was there, just in time for the ESA committee meetings in 1980 where the fate of Hipparcos and other satellite projects would be decided. It would be an all-or-nothing decision - for Hipparcos it was ALL as told in Høg (2017d).

In the meantime many other issues were studied as shall be illustrated below, one of them was the immense task of data reduction which was developed assuming the Option A with revolving and one-dimensional scanning, especially after Lennart Lindegren joined us in September 1976.

3.4 My Archive for October 1975 to May 1976

My archive of reports and correspondence about the first period of ESA studies is placed in five boxes of 7 cm thickness. They are labeled by pencil: "Frascati 1974 Rumastrom. 1975-76", "ESA Historisk 1975-

1976" and for the later period "ESA 77-81-82", "Phase A3", and "1979 AS. 8". My scientific archive will in due time be placed in the Royal Library in Copenhagen according to an agreement of 2010.

Høg: Høg01:

About 2 cm = 150 pp from Oct. 1975 to April 1976. E.g. the following:

The 9 pages dated 2.12.1975 in Høg (1975a) were "Input to MDG (Mission Definition Group) on Space Astronomy", received by ESA on 5 Dec. as the stamp on my copy shows. A copy was given to Catherine Turon in 2007 for the Paris archive.

A letter to the chairman of the MDG is contained in Høg (1975c). It is a 2-page report of my (first) visit to ESTEC on 10/11 Dec. mainly to discuss and learn about sensing, stability and control of the attitude of a spacecraft.

Many pages contain further work on Option A: The angle between axes i.e. the basic angle, optical systems, low-dispersion spectroscopy proposed, attitude control, attitude requirements cf. Sect. 3.4.5 in ESA (1976), data reduction, scientific objectives cf. Sect. 2.1 in ESA (1976), optical astrometry projects compared with FK4 = Table 3 in ESA (1976) on p. 18. Here are found my originals to the Figures 1, 2, 3, and 4 in ESA (1976).

Lacroute: Lacr01:

About 120 pages =15 mm received from Lacroute, stacked with the oldest at bottom. They are all typewritten including about 3 pages with drawings of focal plane and telescopes. Some are from 5 and 10 December 1975 in French. They are replaced on 1.01 1976, and 5.01 and 16.01, and Feb 1976. They are on the options Tycho, TD and SpaceLab. Then follow on 12 March translations to English ~20 pages.

Jan. - April 1976:

R.N. Wilson: 13 pp on optics

W.N. Brouw: 3 pp on rotational velocity analysis

K.H. Davis: 4+2 pp on baffling and on detectors

P. Bacchus: 7 pp on optics, in French

M. Schuyer: 10 pp on launch vehicle, system requirements, S/C configuration, S/C subsystems

From the other members of the MDG, **M.G. Fracastoro**, E. **Roth** and **Soo**, I have no papers in my files but I am sure they contributed to the study report.

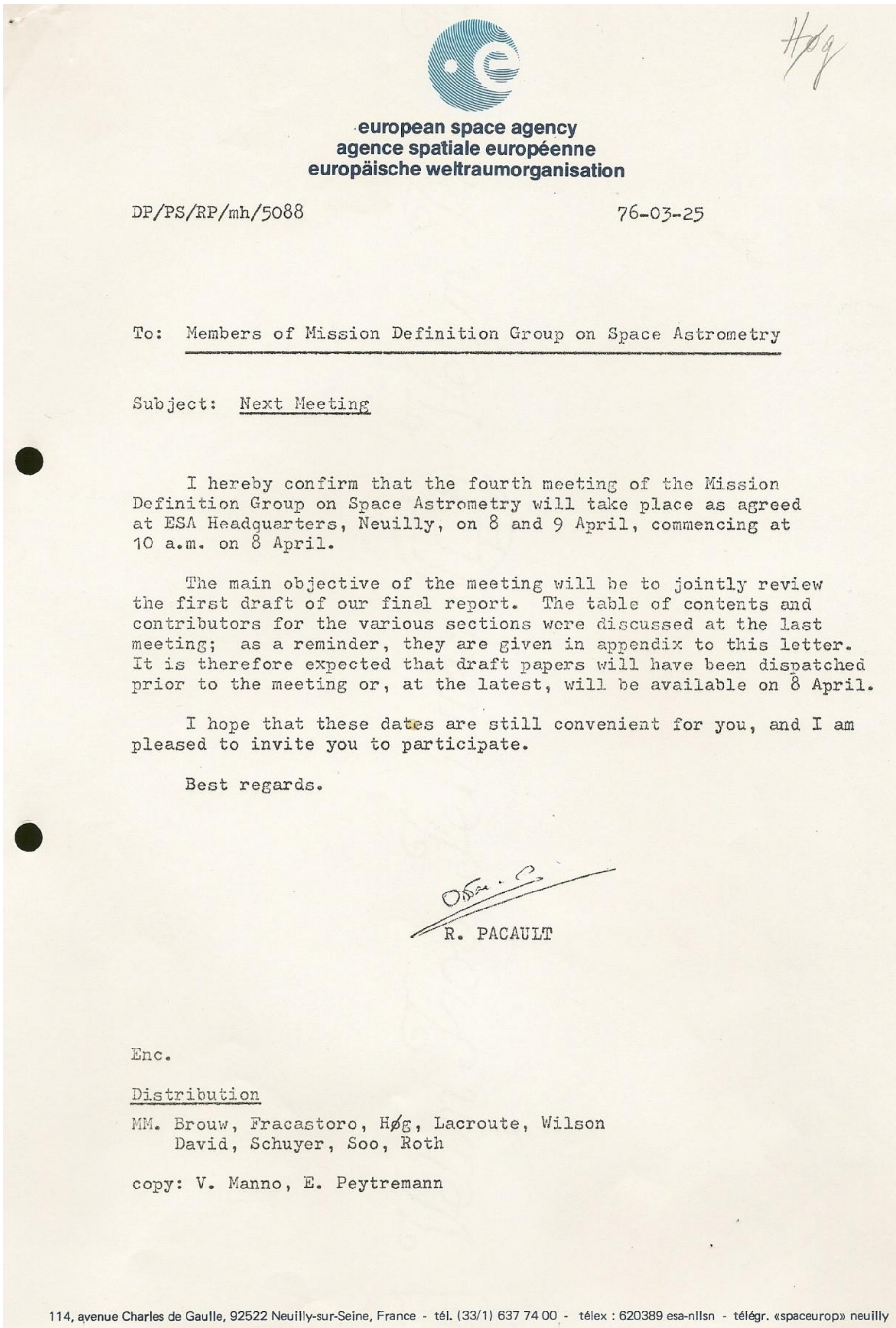
R. Pacault: 3 pp on invitation to the fourth meeting on 8/9 April 1976 on drafting the final report of MDG, with list of members of MDG and table of contents and contributors: http://www.astro.ku.dk/~erik/xx/pacault2.pdf and p. 1 shown here as Figure 5 (pacault1.pdf)

1975: H. Samuelsson: 7 pp on Space application of CCD sensors. A review by Samuelsson (1975).

1975: **A. Boksenberg**: 2 pp on Television Detector Techniques. A reprint.

11 June 1976 Copenhagen, Colloquium on Space Astrometry. See Sect. 4.1.

10 July 1976 Director of Planning and Futures Programmes of ESA: 3+6 pp. Open Letter to Space Scientists: Solicitation for Membership of Scientific Consultant Groups for: GRIST, SEOCS, Space Astrometry, and EXUV.



Høg

european space agency
agence spatiale européenne
europäische weltraumorganisation

DP/PS/RP/mh/5088 76-03-25

To: Members of Mission Definition Group on Space Astrometry

Subject: Next Meeting

I hereby confirm that the fourth meeting of the Mission Definition Group on Space Astrometry will take place as agreed at ESA Headquarters, Neuilly, on 8 and 9 April, commencing at 10 a.m. on 8 April.

The main objective of the meeting will be to jointly review the first draft of our final report. The table of contents and contributors for the various sections were discussed at the last meeting; as a reminder, they are given in appendix to this letter. It is therefore expected that draft papers will have been dispatched prior to the meeting or, at the latest, will be available on 8 April.

I hope that these dates are still convenient for you, and I am pleased to invite you to participate.

Best regards.

R. PACAULT

Enc.

Distribution

MM. Brouw, Fracastoro, Høg, Lacroute, Wilson
David, Schuyer, Soo, Roth

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Figure 5 Invitation to the fourth meeting on 8/9 April 1976 on drafting the final report of the mission definition, distributed to the members of MDG as listed and including a table of contents and contributors.

The members of the Science Team were:

C. Barbieri	Istituto di Astronomia, Padova (I)
F. Beeckmans	Visiting Scientist, Space Science Dept (ESA)
E. Høg	University Observatory, Copenhagen (DK)
J. Kovalevsky	CERGA, Grasse (F)
P. Lacroute	Dijon (F)
R.S. Le Poole	Sterrewacht, Leiden (NL)
L. Lindegren	Observatory, Lund (S)
C.A. Murray	Royal Greenwich Observatory, Herstmonceux (UK)
K. Poder	Geodetic Institute, Charlottenlund (DK)
F. Scandone	Florence (I)
S. Vaghi	Visiting Scientist, ESOC

ESA staff members on the study were:

H. Olthof	AWG Secretary
R. Pacault	Future Projects Study Office
E. Roth	Mathematical Analysis Division
M. Schuyer	System Engineering Department

Requests for further information or additional copies of this report should be addressed to:

Dr. H. Olthof
Scientific Programme Directorate
European Space Agency
8-10, rue Mario-Nikis
F 75738 Paris Cedex 15.

Figure 6 Team members of the Phase A study according to the ESA study reports of 1978 and 1979.

3.5 Some quotes from my archive on the mission definition

25 October 1974: Høg (1974) 1p. Letter from Høg to R. Pacault giving credit for the arrangement of the Frascati Symposium and urging ESRO to study the feasibility of the proposed space astrometry projects. Copies of the letter were sent to Lacroute, Kovalevsky, Requieme, Strand, Fricke. - My concerns are stated in a letter of 30 June 1975, see below.

27 May 1975: ASTRO(75) 6, 26 pp on blue paper: Report on 14th Meeting of the Astrophysics Working Group held on 20-21 February 1975 at ESTEC, Noordwijk. p.15: Space Astrometry MS(74)36, 21 lines including a strong recommendation to perform a mission definition study as also recommended by the Solar System group. - In Frascati box.

30 June 1975: Høg (1975d) 2pp. Letter from Høg to Murray where I disagree with the conclusion in the report from Frascati. I explain my concern about "the technical feasibility of the proposed European Space Astrometry", the results as proposed by Lacroute in Frascati are not much better than can be obtained from the ground, "the effort on ground-based observations might decrease due to the great hopes attributed to space astrometry", "time is not ripe for space astrometry in Europe yet", and I mention my design of an Astrometric Space Telescope. My scepticism about space astrometry does not apply to the American astrometry project on the LST (Large Space Telescope). - But a few months later,

with hindsight, I became grateful that the Frascati meeting had the **great leader Jean Kovalevsky** who was strong enough to write the conclusion and bring European space astrometry ideas into ESA.

1 October 1975: Letter from R. Pacault on the ESA Astrometry Mission Definition Study with a letter of appointment as a consultant to the group for the period 12 October 1975 to 31 Match 1976. Prior to this letter I received a phone call from ESA in Paris in which I was asked if I would join a study group. I agreed to join in spite of my scepticism because I considered it my duty to tell my opinion even if pessimistic or negative.

18 October 1975: My proposal for an Astrometric Space Telescope, 5 pp + 2 figures in Frascati box.

20.10 - 7.11.1975: My input to MDG Space Astrometry, 14 pages, incl. 6 figures, is placed in the Frascati box and was distributed at the second meeting on Friday **21 November**. Scientific arguments about reference stars; choice of payload where the scanning is compared with the spacelab version proposed by Lacroute and with a third alternative: a free-flyer with many maneuvres; complex mirror replaced with half-reflecting mirrors in two figures; on 3.11 a slit micrometer with image dissector is discussed and the revolving scanning is proposed, 4 figures are included, one of them showing a grid for two-dimensional scanning; on 7.11 UV/Visible Photometry with TYCHO is discussed.

12.11. 1975: FSP(75)16 from Neuilly, 4pp, Notes on the First meeting of MDG. Attendance: W. Brouw, E. Høg, P. Lacroute, R. Wilson, V. Manno and R. Pacault for ESA Headquarters, B. Morgenstern and M. Schuyer from ESTEC.

3 Dec. 1975 my proposal to ESA for a Shuttle-independent mission for astrometry with the TYCHO satellite described in Høg (1975a).

18 Dec. 1975 from AWG/Manno: mission profiles for the 1980-1990 period: SpaceLab experiment on Astrometry 15 MAU, if 500 MAU is assumed for all missions and nothing is allocated if 250 MAU is assumed. (MAU= Million Accounting Units).

17 Feb. 1976 my letter to Gibson, the Director General of ESA: My thanks for the invitation to become member of AWG. - My concern about long-term planning of both space astrometry and ground-based astrometry. I urge that not only the Galactic distance scale be mentioned in the ESA report (ASTRO (75) 16), stellar kinematics must be included, and I urge that space astrometry be called pioneering, not only exploitation. I was a member of AWG for three years and was succeeded by Andrew Murray.

23 January 1976: letter from R. Pacault on the third meeting of the study group, postponed from 29 February to take place on 19 and 20 February. The final report of the group is to be issued by the middle of April 1976.

5 April 1976: My arrival to Turin for lecture and discussion during three days at the observatory on invitation by prof. M.G. Fracastoro, member of the study group.

8 -9 April 1976: Fourth meeting of the study group in Neuilly.

3.6 The final study report from Mission Definition

It is available here as ESA (1976) and dated 25 January 1977. A preliminary version was issued in May 1976, available for the meetings in Copenhagen in June 1976. Some notes:

Telescopes: The telescopes for the two options are different in the final report because the required fields have different size, but the final Hipparcos telescope shown in Figure 3c was proposed much later by the industrial contractor MATRA during Phase B.

Beam combiner: For Option A the beam combiner is shown in Figure 1 consisting of two mirrors as in the final Hipparcos. I proposed in November 1975 an alternative beam combiner for Option A with full apertures for both fields obtained by a semi-transparent mirror in a pentagon arrangement, but this was dropped later on. R. N. Wilson comments in "third report on Optics" of 9 April 1976 on symmetry of the pupil. For Option B Figure 5 shows only two mirrors, thus without symmetry across scan as needed for the two-dimensional measurement. We will return to this problem in the Phase A study.

Satellite and Orbit: For the baseline options A or B a small spacecraft of 125 kg is launched by a Scout vehicle into a low sun-synchronous orbit at an altitude of 550 km according to the final report.

Terminology evolved in those years: Complex Mirror became Beam Combiner; Axes of Vision > Fields of View; Angle beteen Axes > Basic Angle; Guide Field > Star Mapper; Preselected Stars > Input Catalogue; TYCHO > Option A > Astrometric Satellite (AS) > Hipparcos.

On the names TYCHO/Hipparcos: I had in 1975 and also later proposed the name TYCHO for the mission but in vain. In 1981 however, a year after the Hipparcos mission had been approved in 1980, I proposed to take down all the photon counts from the star mapper slits in order to obtain astrometry from at least 400,000 stars. This was approved by the science team and by ESA and called the "Tycho experiment". It led us (Høg et al. 2000) to publish the Tycho-2 Catalogue with astrometry and two-colour photometry of the 2.5 million brightest stars of the sky. This meant that twenty times as many stars were catalogued as by the originally approved Hipparcos mission from 1980.

4 Phase A Study - June 1976 to 1979

Here follow in Sect. 4.1 a list of meetings before the beginning of Phase A, in Sect. 4.2 notes from the Phase A study itself, and in Sect 4.3 notes on special studies and International Meetings.

The Phase A study was carried out in the years 1977 and 1978 and the results were presented in two versions: Version 1 of 26 April 1978 in ESA (1978) and the final version of 26 December 1979 in ESA (1979).

4.1 Meetings June 1976 to Dec. 1976

10 June 1976 meeting of AWG in Copenhagen/Brorfelde: The proposal from AWG for astrometry is now 55 MAU. Astrometry is now placed under Conventional Satellite.

11 June 1976: Colloquium on Space Astrometry at Copenhagen University.
Rationale and program on 3 pp at ESA (1976a). List of 49 participants scanned to Colloquium (1976).

28-30 June 1976 in Paris: Symposium with presentation of Study Results for Future Scientific Missions
1 July Meeting of AWG to issue recommendations
2 July Meeting of SAC to make recommendations

30 August 1976 in Grenoble at the General Assembly (GA) of IAU: Joint meeting of Comm. 8 and 24 on astrometry. I presented: EH1977, Future astrometry from space and from the ground.

22 Sep. 1976 I had a meeting in Copenhagen with Lennart Lindegren, a Danish student, and a colleague where I explained the project and especially the challenging task of data analysis. This meeting is described in Høg (2008): **the great result of the meeting was that Lennart Lindegren became dedicated to space astrometry for the rest of his career. Without Lennart Lindegren there would have been no Hipparcos mission approval in 1980, in accordance with my previous claim in EH2011b and Høg (2017f).**

8/9 Dec. 1976 in Paris: Meeting of AWG. Teams for the feasibility studies (i.e. Phase A) were selected, the 12 members for astrometry were 7 astronomers and 5 from ESA, see the list of names in Figure 6 and a detailed list in: http://www.astro.ku.dk/~erik/xx/77AstromTeam.pdf.
More about the selection process on p. 3 in: Høg (2008).

4.2 Phase A study February 1977 to March 1978

According to ESA (1976) p.93, the Phase A study was recommended by the advisory committees in mid-1976 and decided by SPC in October 1976. A team set up in December, supported by ESA staff, was entrusted with the precise definition of the scientific specifications for the study. These studies were carried out from May 1977 to March 1978 by Airitalia and AML. During the latter part of 1978 and in 1979 the study was updated and refined by ESA staff and Matra.

Input before the first meeting to be held on 15 Feb 1977 from members of the study team as requested by the chairman. This input description is based on ESA (1976)=DP/PS(76) 11, Rev.1 and papers in my archive.

19 Oct. 1976 from L. Lindegren, 7 pp: A three step procedure for deriving positions, proper motions, and parallaxes of stars observed by scanning great circles (Option A). Link given at LL2017.

2 Nov. 1976 from L. Lindegren, 8 pp: Relative mean errors of the five astrometric parameters. Link given at LL2017.

20 Nov. 1976 from L. Lindegren, 11 pp: The detailed equation of condition in Step 1. Link given at LL2017.

3 Dec. 1976 - 4 Jan. 1977 from E. Høg, 4+3+3+7+2+1=20 pp:

Notes to Phase A of Space Astrometry

1. Realization of an inertial frame
2. Table 5. Mission models &
   Table 6. Comparison of scans
3. Attitude control, Option A &
   Table 7 Attitude requirements
4. Natural samples of nearby stars
   with Tables 8 and 9, Fig. 20
   Table 10. Sources of absolute proper motions
5. Natural samples and selection effects
6. Fig. 21. The roles of astrometric obs.

25 Jan. 1977 from P. Lacroute, 7 pp: Evolution of Option B, 3 field opt. system, improvement of the proposal from February 1976. Given at Lacroute (1977) with the file. See more above in the section on Option B.

8. Feb. 1977 from C.A. Murray, 10 pp: He sees the greatest impact of a mission from the measurement of 6000 parallaxes for bright stars.

10 Feb. 1977 from C. Barbieri, 5+6 pp: Comments to Document ESA (1976)=DP/PS(76) 11, Rev.1. On p. 1: Opt. A seems to offer definite advantages because obs. limit as faint as 13 mag, but the seemingly much higher complexity of Opt. A over Opt. B gives worry. Repeating the mission after 10-15 years is mentioned here and in other reports as important for the accuracy of proper motions.

12 Feb. 1977 from L. Lindegren, 11 pp: The determination of the celestial sphere (Option A). Link given at LL2017. - A possible scheme for the reductions in Option A is sketched, the three-step method, with the purpose of getting a firmer basis for preliminary estimates of accuracies and for estimates of the required computing times.

14 Feb. 1977 from R. le Poole, 3 pp by hand: Comments to Document ESA (1976)=DP/PS(76) 11, Rev.1. On p. 1: Opt. A by far most attractive, particularly if revolving scanning can be implemented. Therefore detailed study of Opt. A. recommended keeping Opt. B as backup.

15 Feb. 1977 from J. Kovalevsky, 5 pp: Rotation of the satellite.

Input after the first meeting held on 15 Feb 1977 from members of the study team

28 Feb. 1977 from L. Lindegren, 7 pp: On the possibility to measure parallactic displacements normal to the scan in Option A. Link given at LL2017. It is concluded that it will not be advantageous to introduce inclined slits. - This conclusion did not lead Lacroute to reconsider the inclined slits in Option B.

18 March 1977 from P. Lacroute, 2 pp by hand: Notes on the choice of grids. Grids for Option B with 3 fields discussed.

22 March 1977 from P. Lacroute, 4 pp by hand: Study on programmes for space astrometry.

21-22 March 1977 was the time of the meeting between C. Barbieri and R. le Poole, an undated report with 6+2 pp came shortly after: Comments on the proposed designs. Discussion of rectangular apertures versus half-mirror assembly assembly for the basic angle, concluding that the half-mirror is more attractive because of the symmetry. The Option B with three mirrors is omitted from discussion because it does not have rectangular apertures.

25 March 1977, from Simon J. Larcher, ACM, 30 pp: Proposal for theoretical study of the accuracy of an astrometric satellite.

31 March 1977 from ESA DP/PS(77)7, 17 pp: Technical specifications for Phase-A study of an astrometric satellite.

14+21 April 1977 from P. Lacroute, 5 pp: Comparison between option A and B.

27+28 April 1977: Second team meeting in Paris.

23-24 November 1977: Meeting of the team. Since the Ariane launcher had become available we were directed by ESA to adopt this as basis for our design, according to Høg (1997). The initial concept of a small satellite of 125 kg (yes, only 125 kg!) with a telescope of 20 cm aperture to be launched by a Scout vehicle into a low-earth orbit was therefore changed. Hipparcos became a larger spacecraft of 836 kg (see the mass analysis on p.58 in ESA 1979) with a telescope of 25 cm aperture to be launched into a near-geostationary orbit in a dual-launch with Ariane. This decision meant that only active attitude control could be used as proposed for Option A, no passive gravity gradient control as wanted for Option B would be feasible in this orbit far from the Earth.

At this same team meeting in November 1977 it was agreed to use an input catalogue, and the meeting agreed that I could launch an inquiry to astronomers about scientific projects. This inquiry by letters mostly to European astronomers is described in Høg (1979) and is mentioned in Sect. 1.7 of the final study report ESA (1979). The letters were followed up by visits to astronomical institutes in order to gain interest for space astrometry by discussion and colloquia. My travels in those years included Bochum, Munich, Heidelberg (ARI), Königstuhl (MPIA), Bonn, Hoher List, Herstmonceux (RGO), Hamburg, Aarhus and Washington.

There were other meetings of the science team but I have no details. !!!???

4.3 Studies and International Meetings 1978 and 1979

Padua, Italy, June 5-7, 1978: Colloquium on European satellite astrometry.

The proceedings by Barbieri & Bernacca (1979) list 47 participants and 32 contributions on 303 pages. NASA ADS gives a list of content with authors and titles of the contributions but no abstracts.

Study of Option A/Hipparcos: In late 1978 a study was started in Copenhagen to determine whether accurate positions and parallaxes could be derived from one-dimensional observations with a scanning satellite like Hipparcos. The study made use of numerical simulations and the data reduction method proposed by Lindegren. The least-squares problem involving thousands of unknowns (astrometric data and attitude angles) was handled with a general geodetic adjustment program at the Danish Geodetic Institute. The good condition of the problem was confirmed and the results were cited in ESA (1979, p.75) and published by Høyer, Poder, Lindegren & Høg (1981).

When asked about the time of this study Lindegren answered recently that it probably took place between December 1978 and October 1979 and he mentions two of his Technical Notes (TN) in Lindegren (2017). He wrote: The TN 1978-12-04 "Reconstruction of the celestial sphere. Suggestions for a numerical study of error propagation" could be the starting point, and the TN 1979-10-16 "Formulae for comparison of Copenhagen simulation results with theoretical predictions" could be near the end.

Lennart Lindegren was at ESTEC as a visiting scientist for eight months, starting in March 1979. He worked there on the final version of the Phase A study report ESA (1979) which is dated December 1979, just in time for the important meetings in January 1980 about the mission approval, reported in Høg (2017d).

Montreal, Canada, August 14-23, 1979: General Assembly of the IAU. There were presentations, but I have no details. In the Hipparcos Catalogue, I read: "The dialogue with the international scientific community was continued at special meetings: at the General Assemblies of the International Astronomical Union in Grenoble in 1976 and in Montreal in 1979, and at the Colloquium on 'European Satellite Astrometry' in Padua in 1978." No further details.

Meetings at ESTEC, January 23/14 January, 1980: The final decision by the AWG took place where Hipparcos was recommended and the EXUV project lost. This crucial meeting is described and discussed in Høg (2017d) where **Edward van den Heuvel is shown to be a person without whom there would have been no Hipparcos mission,** see especially my discussion with van den Heuvel on p. 8 in Høg (2017f). Ed as an X-ray astronomer was expected to support the EXUV mission, but he saw the much greater scientific value of Hipparcos and he was able to convince some other astrophysicists to vote for Hipparcos, enough to gain a majority in the AWG.

Hipparcos Science Team: Documents from the time after 1980 are listed in ESA (2018).

5 Conclusion

My notes from meetings are short, in pencil and hard to read. A much better source to the meetings exists in the extensive and nicely written notes in the hard cover protocols by Lennart Lindegren - if and when they become available.

I will stop my report here and leave the interested reader to consult the references and the official reports from the studies ESA (1976, 1978, 1979) and the overviews in ESA (1989) and the above Sect. 1.

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6 References

A warning about dropbox. Links in my reports have often been like : https://dl.dropbox.com/u/49240691/GaiaRef.pdf . But in early 2017 the dropbox-company suddenly without warning or explanation made such links invalid. I have then moved all the files in dropbox to my institute where they are available as e.g. : http://www.astro.ku.dk/~erik/xx/GaiaRef.pdf. I am sorry for this inconvenience.

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