
154. Hipparcos: from concept to launch

IN ESSAY 4, I gave a historical perspective on the early days of the Hipparcos mission and the ‘push to space’. Here, I resume this historical account describing the journey from the early concepts of Hipparcos to its launch in 1989.

The start of my own involvement

I HAD JOINED ESA IN JANUARY 1980. I had a degree in theoretical physics, and arrived with a PhD from the Cavendish Laboratory in Cambridge. My research had been in Nobel Laureate Sir Martin Ryle’s radio astronomy group, where I had been investigating the nature of distant radio-emitting galaxies.

Hipparcos was unknown to me, and I had followed neither its concept studies of the late 1970s, nor the political struggles surrounding its eventual adoption which were being played out around me during my first months in The Netherlands.

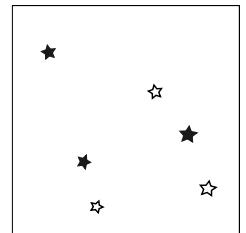
I knew little enough about stars, and could barely have imagined spending the next thirty years of my life in the field. But ESA was looking for someone to take on the role of coordinating scientist for Hipparcos, a field new to the organisation also. Dr Brian Fitton, head of the astronomy division at the time, suggested that I take a look at the project, to see if it held any interest.

Although measuring star positions had sounded uninteresting to me, I had not appreciated how ingenious the new technique was. Neither had I been aware of the advances in science which could be expected as a consequence of its successful execution.

Reading the description drawn up as part of the feasibility study, and on which the various advisory groups had based their own judgments months before, I was immediately captivated. The satellite concept was elegant in its observing principles, and it was a masterpiece of instrumental creativity. I will try to describe these features in outline. Equally remarkable were the mathematical manipulations necessary to construct the resulting star catalogues on ground, which I shall not.

THE WAY THAT THE MEASUREMENTS were made can best be explained in three conceptual steps. To start, imagine looking up at the night sky in a Universe in which everything is at rest. You are on an Earth which is neither rotating nor moving in orbit around the Sun, the Sun is not moving through space, and the distant stars are fixed points of light. In this simplified picture, the location of each star is described by just two coordinates, corresponding to angles of latitude and longitude on a map of the Earth or sky.

The figure shows three stars from one area of sky a few degrees in size (filled), superimposed on three stars from another field some way distant across the sky (open) because of the split-view mirror. Now picture a swathe of a degree or so in width which covers a full circle around the celestial sphere, crossing some of these stars. And imagine measuring the angles connecting successive pairs of stars as we step around the sky along this swathe. Back to the starting point, these pairs of angles would add up to 360 degrees. Our measurements would give an estimate of the star positions stepped around this circle, one with respect to another.



*Conceptual step 1,
with stars fixed in space*

A second circle laid out across the sky in a different orientation gives another set of angular measures between all the stars in that new circle. With lots of these circles, at all sorts of different directions crossing the sky, the result would be a dense network of many different pairs of angles between any chosen star on the sky, and the many others all around it.

The satellite from its vantage point high above the Earth would turn slowly across the heavens, completing one measurement circle in just over two hours.

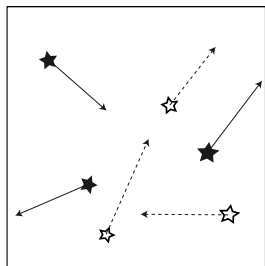
In its three years of observations it would trace out ten thousand of these circles. By continually twisting its spin axis as it scanned, the circles criss-crossed the sky in all sorts of directions. In the process, each of the hundred thousand stars was observed more than a hundred times, each being connected to countless others.

With the thousands upon thousands of measurement arcs, and with the linking up all of these triangles, what would drop out of the computer reconstruction on the ground is a map of the stars with the position of each one relative to every other. The resulting map is very rigid; every star is snapped tightly into its place by the dense network of other measurements. Three years later—only a few weeks or months of observations are not enough—and a full map of positions across the sky would result. No time is wasted in the survey: the satellite just spins round and round very slowly, building up its network of measurements for analysis on the ground.

The rigidity of the map is greatly strengthened by the two widely-separated viewing directions. Imagine a 4-armed windmill at night with its arms turning slowly, a telescope attached to just two adjacent arms, somehow able to see the whole sky as if through an invisible Earth. Labeling positions around a circle as if laid out on a clock face, then stars at 12 o'clock are 'connected' to those at 3 o'clock. A little later on, as the arms turn, the stars at 3 o'clock are connected to those at 6 o'clock. Similarly those at 6 are connected to those at 9, and later those at 9 to those at 12 again.

Sadly, those at 1 o'clock are only ever tied to those at 4 o'clock, those at 4 to those at 7, and so on. So we would have a kind of rigidity, but the pieces of the circle aren't themselves very well connected together. The situation improves almost magically if the angle between our two telescopes doesn't divide exactly into a full circle—Hipparcos chose fifty eight degrees. Then, as the structure turns, and after just a few rotations, all parts of the sky have been connected up, and the star positions are pinned down very tightly indeed.

THE DESCRIPTION OF THE METHOD started by imagining that the stars are fixed in the sky. Proceeding one step further towards reality, now assume that each star is no longer stationary, but instead is moving on a straight path through space.



Conceptual step 2, with stars moving through space

It's important to recall here that their distances are so vast that they move only through very tiny angles, even over a year or more. They can be moving towards us, away from us, or in any other direction, and with any velocity. Our angular measurements always allow us to pick out the star's proper motion, that part of the star's angular movement projected onto the celestial sphere. This means that although all the stars are moving, in a seemingly random way on the sky, we only need two extra numbers to describe their motion.

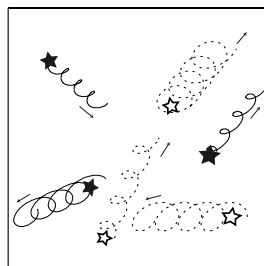
So we now have four numbers describing each star: one pair tell us its coordinates at a chosen moment in time, and a second pair tell us how it moves across the sky over one year.

Even though the relative positions of all the stars appear to be changing in a very complicated way with time, the mathematical description of this motion is actually very simple. Just these four numbers are all that's needed to describe each star's resulting position, even over a period of several years. Again, the fact that we have made a hundred or more observations of each star over a time interval of several years, means that these four numbers are extremely well nailed down.

At this point, I stress again that we have not measured the true space velocity of each star—just its angular motion on the sky. As for the aircraft analogy earlier on, we would need to know the distance to convert the apparent angular measure into a true space velocity.

FOR THE THIRD STEP IN THIS EXPLANATION, we now need to include the fact that each star has its own, unknown distance from the Sun—some are far away, some are relatively nearby.

As we have seen, each star's distance can be described by just one number, its parallax. This just provides a direct measurement of the star's distance through a knowledge of the Earth's orbital dimensions. The key point for the measurements is simply that each star's back-and-forth motion during one year is described by just one single additional number, the size of this parallax angle.



Conceptual step 3, with parallax included

The final picture is in fact very simple: although the stars will be moving one with respect to another in a very complex way depending on their space motions and their distances, the motion of each star on the night sky is fully described by just five numbers: the two position coordinates, the two proper motion coordinates, and the parallax angle.

Together, these five numbers describe where the star is at any particular moment in time, how it moves through space, and how far away it is. Astronomers currently use the start of the year 2000 for the reference time, and the star positions in the published catalogues are adjusted to this specific moment.

If we need to know where a certain star is on, say, 21 September 2014, because we want to point our telescope there on that date, we take the catalogue position at the start of 2000, and add just over fourteen years of the star's proper motion through space.

From this celestial jigsaw of measurements, from this interminable sequence of angular separations, stepping around the sky over three years, we can reconstruct their motions and their distances; their stereoscopic, three-dimensional distribution, and their motion through space. There's nothing particularly special about the three years of measurements either. Longer would have given results a little better, but there is always a balance between the quality of the results, the cost of operating the satellite, and the time taken to do the computations on ground. There are, of course, endless scientific and technical complications which in reality accompany this simplified picture. However, none affect the basic principles.

If the preceding description is a little confusing, the essence is simple: all stars are moving through space, and all appear to move through the effects of parallax as the Earth goes round the Sun. Measure their relative separations carefully and repeatedly, and we can reconstruct all of these movements.

At the time of its acceptance by ESA in 1980, the project was little more than a concept on paper. There was a description of the science goals and measurement principles, a detailed explanation of how the observations could be carried out, and an outline of the number-crunching needed on ground. After the battle for selection, a new challenge began: to come up with a detailed instrument design, and to build the satellite itself.

The ESA project team

AFTER HIPPARCOS HAD BEEN accepted by ESA, the first high-level task inside the organisation was to select a project manager, and a project team with him, who would take responsibility for the project, and report up through the management line of the scientific directorate. Ernst Trendelenburg, ESA's director of science at the time, duly nominated Italian engineer Franco Emiliani to fill the role.

Emiliani had come from an early career in the Italian navy working on surface-to-air missiles. In ELDO from 1967 overseeing construction of the launch facilities in French Guiana, and thereafter in the Space-lab team in ESA, he trod a balanced line between forceful leadership and a courteous and engaging style. He duly put together a team of twenty or so engineers who would

assist him running the project from the ESA side. Their task would be to prepare and manage the industrial contracts, work with Arianespace to prepare for its launch, liaise with the team at ESOC who would operate the satellite in orbit, and keep track of costs and schedule.

The project team was divided into four sections: one responsible for the experimental payload, one for the supporting spacecraft systems, one in charge of the assembly and verification, and one for the overall performance. Over the next eight years, the team directed the progress and monitored the costs of the large industrial teams delegated to carry out the detailed design and subsequent construction.

In addition to his technical and management skills, Emiliani had a significant curiosity in the science underlying the mission, a keen interest in understanding the details of how it worked, and considerable respect for the scientists who were driving the project from outside ESA. They are not universal characteristics of managers of large projects, for whom the actual goals may be of only passing interest. But an enthusiasm for the underlying purpose is an enormous asset, and in this case contributed to the motivation of the entire team, facilitated the technical negotiations with industry, and contributed to the makings of a collaboration between the space agency and the scientific community which worked particularly well.

Another most important straightjacket was imposed on the team. When the project had been accepted by the Science Programme Committee in 1980, it was on the basis of the accuracy that the earlier study had indicated would be possible—two thousandths of one second of arc for the positions and parallaxes of every star. Emiliani accepted the challenge, and passed it on to his team as their overarching objective, their Holy Grail that would be ESA's, industry's, and the science community's demanding quest and enduring mantra for the long decade ahead.

In such a project, ESA is the customer. Through the project manager, the customer sets the specifications, the budget, and the schedule. Once contracts are awarded to the industrial teams capable of designing and building the satellite, the project team agrees (or otherwise) to the solutions proposed, tracks the performances, costs, and schedule, and arbitrates on any disputes. For those tempted to think that the task might be a light one, how many have engaged a contractor for house repairs, and duly overrun their starting budget?

The main industrial contracts were awarded, after keen bidding, to two major industrial teams. To secure the contracts—which would guarantee business, jobs, and prestige for years—their bids had to be extensive and meticulous, describing their company's experience and the individuals that would be assigned, their preliminary designs, technical issues, and detailed planning of schedule and cost. Each bid from the two leading contractors comprised some twenty ring binders of technical minutiae, a couple of meters shelf space of documents, each of which had to be reviewed with care and attention.



Franco Emiliani (2007)



Michel Bouffard (1997)



Bruno Strim (1997)

Matra Marconi Space in Toulouse in France, under Michel Bouffard, was duly awarded the prime contract for the telescope, the detection system, and all the associated experiment parts. Alenia Spazio in Torino in Italy, under Bruno Strim, would be responsible for the rest of the satellite support systems, and the overall satellite integration. Incidentally, Matra was later known as EADS Astrium, and today, as Airbus Defence & Space; but its name at the time is retained throughout this account.

Industrial involvement

FROM ACROSS THE FAR-FLUNG nations of Europe, industrial teams with specific knowledge or distinct expertise bid, in their turn, for a lower-level task. Hundreds of contracts were signed off. In this way, around thirty different industrial teams from many countries pooled their expertise, and would become involved with the design and manufacture of the various components.

Across these industries, the workforce numbered around two thousand. Together, and orchestrated by the prime contractors, they then came up with drawings and descriptions of the overall system and its various subsystems—the power supply, the attitude control, the thermal control, the telecommunications, the telescope optics, the on-board processing, and so on. Manufacturing procedures were elaborated. Protracted negotiations on costing, construction, and testing edged forward.

The challenge of running a project of such complexity is firstly to find and recruit the army of workers with all the skills required. But even more crucially, to ensure

thereafter that all of the many and varied interfaces fit together, and that the whole effort is organised to come together on the schedule demanded. The launch contract, once signed, is rather immovable and, in any case, delays are expensive once a large team is in place.



ESA's Hipparcos project team (1985)

Over the next three years, the satellite progressed from a conceptual design on paper, to a detailed description of the overall system and its component parts. The system section built a detailed model of the predicted performances. This meant that we could see, at a glance, what would be the effect on the final accuracies of changing the mirror size, its reflective coatings, the spin rate, the amount of stray light falling into the telescope, and a whole host of other details.

Hundreds of meetings, thousands of documents, and countless reviews of the component parts were clocked up as the weeks and months passed. Major reviews were held to look over the entire system design. Contract and cost meetings between ESA and the various contractors paralleled the technical and performance meetings. All of the major steps followed the detailed schedule drawn up at the start—for the costs to be held in check, the schedule was paramount.

Eventually, around 1984, the blueprints were finalised. The project had moved from concept to detailed design. To mark such a major milestone, it was a tradition for the leading contractors to host a small party for the customer. Toulouse and Torino were, naturally, excellent cities for culinary celebration, and we could enjoy rare moments of more relaxed discussions outside of the meeting rooms.

THE DESIGN AGREED, it was then time for the various industries to start on the construction of the individual parts. Some components would be fairly routine. Others would represent challenges at the very limits of technical feasibility, and would sit on the critical path, thorns in our side, for the following three years. Once the parts were manufactured, they would be integrated to form the complete satellite. Detailed testing would take place along the way.

Satellite construction usually proceeds through a series of prototypes to test the design: in this case, Emiliani had agreed with industry that they would provide an optical model to verify the quality of the telescope and its alignment before final manufacture,

a thermal model to be tested in the conditions of solar illumination in space, and a mechanical model to be shaken to simulate the launch conditions. Once these different parts were validated, the flight model would be built, assembled and tested in its turn.

Industrial progress meeting,
Alenia (1986)

Franco Emiliani moved on from the Hipparcos project in 1986, his place as project leader taken by his spacecraft section head, Hamid Hassan, who thereafter held the post until launch. Hassan was a different character, whose distinct management style was equally well matched to this second phase of the development. Here, design creativity was no longer relevant and no longer sought. Schedules and deadlines, industrial contract obligations, instrument performances, and financial control were instead paramount. He built good relationships with the industry prime contractors, and he and his team got the very best out of them as a result.

Hassan also had great esteem for the scientists working on the project, and the two of us—he as project manager and me as project scientist—had an excellent relationship founded on trust and a respect for the very different, but equally indispensable jobs that we each had. Both in the same boat, we had to steer a common course. At weekly project meetings we would identify the challenges ahead, and agree on any compromises.

Hassan's wry sense of good humour and self-deprecating demeanour masked a sharp intelligence, and he would occasionally goad me with a favoured quip, each time telling me as if it were something witty and original which he had just thought up: "We project managers don't mind if we're told to launch a ball of wax on a piece of string; our job is to get it launched on schedule and within budget."

In reality, Hassan was immensely proud of the task he'd been given, the team of individuals that he had been asked to lead, and the place in history that he knew Hipparcos would occupy. The satellite was duly launched on schedule and within budget, all technical challenges resolved along the way, probably one of the very few of comparable size which could make that claim.

Here, I'd like to quote some words of mathematician and cosmologist Professor Sir Hermann Bondi:

Projects prosper if there is a powerful, centralised, unified project management team in place, with a project manager who is responsible for the project from cradle to grave. Once this manager has become familiar with the proposed task, the first essential job is to specify the resources of money, staff, time, and facilities required for completion and to offer milestones of achievement along the way. The whole undertaking is likely to take many years, during which period none of the key staff should change. If the task is successfully accomplished in the time and with the resources they specified, a double promotion should be the reward; if they fail to deliver, retirement may well be appropriate. By contrast, insufficient authority for the management team, with frequent changes of its personnel, is a sure recipe for disaster.

Bondi had been Director General of ESRO (the forerunner of ESA) between 1967–1971, and thereafter the UK's Chief Scientific Adviser to the Ministry of Defence between 1971–77, Chief Scientific Adviser to the Department of Energy from 1977–1980, and Chairman of the Natural Environment Research Council from 1980–1984.

In an earlier life, as an accomplished mathematician and cosmologist, he had even written learned articles on magic squares. With this weighty portfolio, he might not have been able to claim that he had seen it all, but he had probably seen enough. His comments, in letter to *The Times* of 31 May 1995, targeted the massive cost and time overruns in recent Ministry of Defence projects that had been reported by the National Audit Office.

Bondi articulated that both cause and cure for such overruns were well known, and yet the solution often raised insurmountable difficulties for career structures which all-too-often presuppose frequent changes of post. In short, Bondi was critical of projects and organisations with changes of top-level managers engaged solely in career hops, moving on long before accountability caught up.

His principles were broadly followed for the development of Hipparcos, and we can look back on a decade of cutting-edge space engineering and say that it worked. It is regrettable that these simple and somewhat self-evident prescripts are not always adopted.

The Project Scientist

BACK TO 1980, A PARALLEL ARM of ESA's science directorate supplied the mission's scientific leader. In this capacity, my task was to ensure that the instrument worked as it had been laid down in concept, and to optimise the science that could be done within the budget assigned. To ensure that the scientific objectives remained paramount, I was not accountable to the project manager. My influence on the project was through scientific persuasion rather than fiscal authority.

In these aspects I worked closely with Maurice Schuyter's system group within the ESA project team. But I (in common with all ESA project scientists) also had the benefit of one extensive resource at my disposal, if only it could be coordinated and properly channelled: the European scientists and astronomers interested in the science, pushing the mission since its earliest awakenings, ready for deeper involvement in all of its aspects, and committed to work to its full success.

My task would be to marshal and coordinate their efforts, use their knowledge to guide the design, manufacture and testing of the satellite on ground, and to advise and assist with its operation once in orbit.

One example is sufficient to illustrate the process. The groups preparing the analysis of the data knew that they needed a knowledge of the spacecraft velocity at all moments to correct for the aberration of starlight.



Maurice Schuyter (2007)

Somebody would estimate how accurately this would be needed, and write a technical note giving their reasoning. Others would review the results. The resulting specification was passed to industry to make sure that the spin control could deliver the required performance, while the operations centre would propose a methodology for measuring it. At any one moment, hundreds of these scientific threads would be spinning their way across Europe, backwards and forwards between the relevant players to ensure convergence.

Something of a complication was that, in all of this scientific effort, no funding from ESA was available: each scientist or scientific team would be wholly dependent on their own funding, typically through university or national grants. They would have to petition for additional research positions, computer resources, travel funds, and whatever else they needed to do their work, and collaborate with others where funding was inadequate.

It may seem surprising that such a system can possibly work. How could an organisation coordinate the work of a large number of scientists, with no payment changing hands? It is a common feature of the ESA missions, and works for the following reason. Individual scientists with a commitment to the subject, would see Hipparcos as a once-in-a-lifetime opportunity for their particular field. A group with a track record in Galactic structure studies in France, an individual with a particular interest in stellar evolution models in Italy, a collaboration committed to improving the stellar reference frame in Germany, and countless others, understood that the project now starting up would provide frontline research opportunities for them in the years to come. They would lobby their own funding authorities, persuade their university astronomy or computing departments, and push their national technology institutes to get involved.

Funding might take years to fall into place, but the resulting resources mobilised can be enormous. The entire project being vastly more than any individual research group, or even nation, could begin to contemplate, collaboration, and notably with ESA, made enormous sense. In its turn, the credibility of affiliation with an international space mission would furthermore help their national funding requests. Indeed, delegates to ESA's advisory bodies all the way up to the Science Programme Committee were often senior figures within the decision-making structures in their own countries. Once a mission was underway in ESA, senior policy makers sympathetic to the cause would generally be keen to support further involvement by scientists in their respective countries. It was a fast way to gain further access to major cutting-edge research facilities.

Like a huge snowball gathering both mass and momentum, scientific and technical interest grew in the

member states. A key problem for me would be to keep all of this manpower prioritised, focused, on track, and especially given the unpredictable timelines so frequently encountered in research efforts, on schedule.

MY FIRST TASK AS THE PROJECT got into full swing in 1981 was to set up a scientific advisory group, the Hipparcos science team. This would be composed of scientists from universities around Europe who would together represent all of the many scientific disciplines needed to design the instrument, and make sure that no effect had been forgotten, no complication omitted or left to chance.

The *modus operandi* for such science teams had been established by other projects over the years. Once in place, it came together for a two-day meeting three or four times a year, under my chairmanship, to run through all of the scientific and technical issues which needed discussion, resolution, and agreement for the project as a whole to advance. Relevant engineers from the project team were also present. Tasks that needed to be investigated further were assigned to a relevant individual: perhaps someone from the project team who might in turn pass it as a task to industry, or one of the science team members best placed to work on the problem back in their home institute. To keep the project on track, a schedule for each task was agreed, and results were reviewed at the next meeting.

It is, I believe, of paramount importance that one person knows approximately what is going on in every part of a project of this size, maintaining a top-level picture of how all the puzzle pieces should fit together. This was one of my tasks. Like a conductor in a large orchestra, I couldn't play any of the instruments particularly well myself, and I had neither the aptitude nor time to learn. But I would have to maintain the synchronisation and set the tempo through to the final bar. Only then might the audience applaud.

Two related problems stood in my way in setting up the science advisory team. The first was that I had no background in the field and therefore no knowledge of the leading scientific exponents, nor of their specific skills and temperaments. Second, of which I was conscious at the time and perhaps more so in retrospect, was my age. At just 26, I could expect a rocky road ahead in gaining the confidence of the Europe's astrometric leaders. In both I landed on my feet, and for similarly related reasons. The leading astrometrists around which the studies had been structured were small in number, and as new to the opportunities of space as I was.



Henk Othof (2002)

At my first meeting with the leading players, in Paris, convened by the experienced and unflappable secretary of ESA's Astronomy Working Group, Dutchman Henk Olthof, I was greeted as a collaborator and, in showing my own commitment to the project, soon as a colleague. Catherine Turon, from the spectacularly situated Meudon campus of the Paris Observatory, Lennart Lindgren from Lund University in Sweden, Erik Høg from the Copenhagen University Observatory in Denmark, and Jean Kovalevsky from the CERGA institute perched in the hills of Provence above Grasse in France, were all hugely courteous and motivated only in moving the Hipparcos project forward. They welcomed me as the missing link of some grand overall plan, and we got down to work.

THE ADVISORY TEAM became the scientific voice of the project in Europe, and it was through their guidance that the scientific aspects—longer-term strategic problems as well as more day-to-day issues—were monitored, steered, anticipated and resolved.

The team would have to guide the project over the years to come, and it was crucial that I got the composition right. Expertise was needed to cover all of the major sub-fields of the project: optics, detectors, instrument design, calibration in orbit, astrometric needs, existing catalogues, and data analysis.

Such a team should not be too unwieldy in size—perhaps a dozen people at most. It should be selected according to competence alone, although as a pan-European project, broad geographical representation would be advantageous. The members had to be used to working to agreed schedules—in a team with many players, working in a project with many complexities, and comprised of scientists with other duties, this wouldn't be easy. It had to be a team that would work well together, and with the common aims and ultimate scientific objectives firmly in mind.

THE CHOICE, in reality, proved not too difficult: the scientists leading the studies carried out so far were relatively few in number, worked well together, and by-and-large covered most of the disciplines that would be needed. I talked to each, synthesised the totality of their own thinking, and assembled the guiding team.

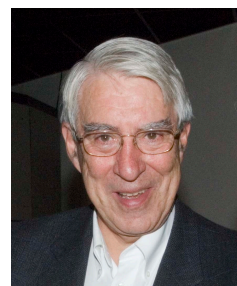
The first meeting was held at ESA's technology centre in The Netherlands on 28–29 April 1981. It remained in place for seventeen years. The thirty-ninth and last meeting was held on 9–10 October 1996, when it gave the go-ahead for the final catalogue release.

I met Sir Hermann Bondi, whom I quoted above, around the time of the catalogue publication. I should have mentioned this continuity of effort to him. He might have been interested. I'm sure he would have approved.

The Hipparcos telescope

THE TELESCOPE WAS CENTRAL TO HIPPARCOS, and I brought in an independent optical expert, Charles Wynne, at the very start. Then aged seventy, he was a significant figure in the design of optical instruments, and in that capacity had received the gold medal of the UK Royal Astronomical Society in 1979, its highest award. He was known for what was almost a monopoly of original designs for wide-field optics for large telescopes, for a series of scientifically elegant spectrographs, and systems to correct the effects of atmospheric dispersion. He had had nothing to do with the Hipparcos studies to date, which left him well placed to examine dispassionately the optical designs put forward by industry.

The telescope design and construction in reality represented the combined efforts of many different groups. René Bonnefoy in ESA led the part of the project team focused on the scientific instrument, and he had overall responsibility for making sure that the telescope design was plausible, that it could be built, polished and calibrated by the industrial teams, and eventually launched and operated in space.



René Bonnefoy (2007)

But getting the very basic design of the telescope correct was a tremendous challenge. There are many different telescope concepts—Newtonian, Cassegrain, and Ritchey–Chrétien amongst them. Named after their eminent designers, they differ in the details of how their various reflecting surfaces are polished and arranged. They nonetheless share a common objective: to create an image at their focus. The skill of the telescope designer's art is to consider what properties of the particular system are most critical—whether it be the largest field of vision, the smallest image distortion, the least colour imperfections, the highest throughput, the broadest wavelength response—and to design the system required.

Very often, as for Hipparcos, all of these are important, and it falls to the scientific and engineering teams to weigh up the various pros and cons before agreeing to a particular design. Whether it can be built, polished, and aligned, are additional practical considerations. Hipparcos needed to be able to look out in two widely separated directions at the same time, and to bring the images from the two fields to a common focus. Such a telescope had not been conceived of before, let alone built and deployed in space.

Many possible options were investigated, and their strengths and weaknesses circulated in technical documents for analysis and discussion. The solution finally proposed by the industrial leaders was daring. They

would first polish a single mirror to a special shape, carrying the profile of a Schmidt-type telescope specified by a detailed computer ray-tracing analysis. Just thirty centimeters in diameter, this main reflector at the very centre of the satellite would not be much larger than a decent-sized shaving mirror. They would then slice it in half without disrupting the surface quality, rotate the two halves by an angle demanded by the two viewing directions, and then glue the two pieces back together at this chosen angle.

Other mirrors in the telescope would have their own special shapes, all optimised by computer design. Once assembled, the two incoming light beams would bounce off the split mirror, be intercepted by the mirror next in the telescope's path, and then projected on to a common focus where more magic would be woven.

So simply described, the task was forbidding in practice. For a start the design demanded an assiduous polishing, accurate across its surface to a fraction of the wavelength of light. If we imagine inflating this modest-sized mirror to the dimensions of the Atlantic Ocean, the residual lumps and bumps of the scaled-up monolith could not deviate from the underlying smoothness by more than ten centimeters in height. The mirror slicing could not be allowed to affect this delicate surface either. And when it came to glueing the two parts together, it had to be with meticulous precision, and using an adhesive that would hold the two parts rigidly in place during the launch, and yet not deform the bonded surfaces as the satellite aged or 'out-gassed' once consigned to the almost perfect vacuum of space.

It was an even more complex approach to this mirror at which even the enormously competent French Space Agency CNES had baulked during its own studies a decade before. And it would not be the first time that a wonderful telescope designed on paper might not be possible to fabricate in practice. The famous Cassegrain reflector, developed by Laurent Cassegrain in 1672, had been invented independently

at least three times before that, including by Marin Mersenne, the 'father of acoustics' who also gave his name to an important family of prime numbers. All were prevented in their attempts to create the actual telescope by the available technology, Cassegrain included. Our success in transposing paper design to glass could not yet be guaranteed either.

When the industrial teams started the satellite design, it was their creative optical expert Pierre Hollier from Matra Marconi Space in Toulouse, graduate of the Ecole Supérieure d'Optique in Orsay, who stepped in with a feasible telescope concept, and Lennart Linde-

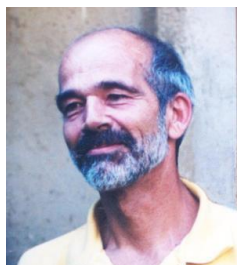
gren from Lund Observatory in Sweden who pointed out a particular trick which allowed the dissection and reassembly to work. The telescope images, Lindegren pointed out, could be improved by carving off and discarding a sliver from the two halves before re-bonding. I have heard it said that nobody is quite sure how Bernhard Schmidt came up with his practical method of making the difficult corrector plate in the revolutionary wide-field telescopes that he invented in the 1930s and which now bear his name. Sixty years later and I'm not sure any of us understood from which hat Lennart Lindegren plucked his slicing-and-dicing magic, but it was just one of a number of insightful and indispensable legacies that he brought to the mission. It typified the sort of scientific creativity that few can emulate, and yet which decides the fate of these complex systems. We could only read his technical note on the subject with admiration, and shake our heads with bemusement.

I have the very greatest regard for the skills of the high-technology industries who worked with us on Hipparcos. But they can be an optimistic breed, eager to get a concept pushed through, with the customer left to pick up the bill as mounting practical problems have to be ironed out later on. It can be useful to ask experts to stand back from their detailed involvement and give a top-level feeling of how things are going. Experience and intuition based on a lifetime's work are important.

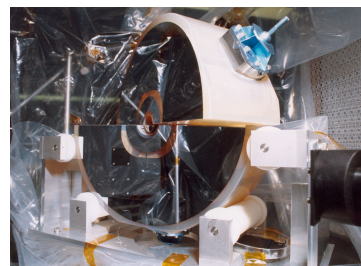
Early in the design phase, during one of the advisory meetings in Noordwijk, my insight at a loss to see whether the proposed mirror would serve its exacting purpose, I pushed Charles Wynne for an answer to a simple question "In your opinion, will Matra's telescope design work, yes or no?" He had clearly been thinking similar thoughts because his answer was out before my question was fully formed. "I'm not saying that it won't", he said, eyes twinkling mischievously as he hedged, "but I do know that seconds of arc don't split into milliseconds of arc very easily!"

It wasn't the answer I'd hoped for, but it was wise council nonetheless. Three further years of effort vindicated the design; it did work, and the telescope would eventually take up its sentinel position in space, peering out, skew-eyed, across the expanses of our Galaxy to scrutinise the stars.

Once designed on paper, by computer ray tracing, this complex mirror was polished by craftsmen of the French industrial company REOSC Optique, a group specialised in high-precision optics for science and in-



Pierre Hollier (1922)



The 30 cm diameter beam combiner

dustry. Based in Saint Pierre du Perray, south of Paris, REOSC's eventual hard-won success with this difficult mirror augmented the company's capabilities and consolidated its growing reputation. REOSC went on to polish some of the greatest mirrors in the astronomical arsenal at the turn of the second millennium, including the four gargantuan eight meter diameter mirrors of the European Southern Observatory's Very Large Telescope, now operating in concert on the sawn-off mountain top of Cerro Paranal, deep in the Atacama desert in Chile.

The split mirror was just one of a number of exquisitely flawless mirrors inside the Hipparcos telescope. The others, more classical spherical mirrors, or perfectly flat 'folding' mirrors inserted to keep the overall telescope size down to its most compact, and drilled from the back with cylindrical holes to minimise weight, were built by the German optical masters, Carl Zeiss GmbH at Oberkochen. Once polished and assembled, this unusual split view telescope brought star light from the two viewing directions to a common focus, precisely as had been commanded.



Spherical mirror integration (1987)

The optical parts were assembled to form the complete telescope by the experienced integration team from Matra Marconi Space. Polishing each surface had been a tall order. Alignment of all the surfaces to the sub-micron prescription of the computer design posed its own tricky challenge.

Holding the mirrors precisely and rigidly in their designated positions thereafter was a whole specialised craft, and needed its own ingenious solution. Computer analysis showed that three support struts would be needed to hold the spherical mirror in its place during the hefty vibrations of launch. But once in space, the reduced gravity would change the forces on the mirror, and the three clamping points would cause the mirror to buckle. Another headache, another imponderable, another unexpected obstruction thrown in our path. The solution—there often is one if you assemble the right experts—was a small pyrotechnic device which would be detonated once in orbit, to cut the anchoring point of one of the struts, reducing the clamps to just the two.

At each place in the satellite where a clever design on paper had to be translated into practice, these kinds of complications invariably surfaced. The relationship between project scientist and project manager is always a delicate one for these reasons. My brief as chief scientist was to make sure we had the clever design in place that

thought of everything. Only by stepping through each consequence of every scenario would potential problems be anticipated. Emiliani's and later Hassan's brief as project manager was to translate these lofty ideals into substantive form, and to inspire and coordinate industry to deliver a working satellite, *sui generis*.

Only by bringing together the appropriate teams of creative and specialised experts could such a one-off experiment be designed and built. Yet always hanging over us was the perennial problem for a space mission: though fearsomely complex, the entire system could never actually be tested at the levels it would need to perform at in space—under zero gravity, in total vacuum, bathed in harsh ultraviolet light, and bombarded by high-energy particle radiation. Each problem was tackled rigorously, but we also kept our fingers crossed for several years nonetheless.

Much later, two years before launch, test engineers at the ESA centre in Noordwijk were examining the quality of the entire telescope before its final integration into the satellite. Designing and building the optics was far from easy, but setting up the testing equipment to demonstrate that performance was also a challenge. The telescope was cosseted in a 'clean room' to exclude even microscopic dust particles from contaminating the optics, and supported on massive granite blocks to minimise effects of external vibrations, however miniscule.

As the battery of tests proceeded, the team in charge were perplexed to find small, regular but quite unexpected motions of the star images being projected through the entire telescope. Like surgeons involved in a complex operation, the team in white coveralls, face masks and hairnets, consulted their battery of diagnostic machinery with consternation, eliminating the possible causes one by one. The source of the pulsating image motions was eventually traced to the regular impact of ocean waves pounding the beaches of the North Sea, seismic shocks felt more than a kilometer away across the coastal dunes of Holland.

Again, I could not help thinking about how this sensitive instrument would take to being launched. Had the vibration experts done their parts of the design correctly? Had the relevant launch team measured and communicated the spectrum of launch



ESA technology centre (ESTEC), Noordwijk

vibrations correctly? Damping vibrations is a crucial art in space projects, where resonant frequencies can wreak

the type of havoc seen in the Tacoma Narrows bridge collapse of 1940. Were there other malevolent celestial equivalents of the pounding North Sea breakers that we'd not thought of, lying in wait for us, high above?

Our science team meetings, usually held in ESA's research and technology centre in The Netherlands, were always an opportunity to brainstorm. It's an irritating word, but it nicely conveys what was a significant and crucial part of our collective scientific work. I would prepare the agenda for each meeting a couple of weeks in advance (in those days, circulated by telex) based on the main problems being faced or anticipated, and where scientific advice or compromises were debated and agreed. Members would come with the results of their own work, and perhaps recommendations or solutions, and usually with their own problems to lay on the table. Difficult issues would be lobbed back and forth until a possible solution could be sensed, and a way forward agreed. Project team members, operational team representatives from Germany, and industry experts from around Europe might attend for specific issues. Coffee breaks were times for more uncertain thoughts to be aired, or for one-on-one discussions to plan a way forward on some particular topic that didn't need to be discussed by all. A social dinner was mandatory at the end of the first day of the two day meetings: a respite from the difficulties of the day, more relaxed deliberation of the less technical problems, and an opportunity to inspire each other with thoughts of the next major milestone ahead.

Support functions

IF THE BASIC TASK of the instrument was to project the star images onto the telescope focal surface, the rest of the satellite had to supply it with its variety of support needs. We needed electrical power from the solar arrays and chargeable batteries, and demanded scrupulous shielding from scattered light from the Sun, Earth and Moon. High on the critical list was the ultra-rigid structure to hold all of its optical parts in sub-micron level alignment. All components had to be clamped down to prevent vibration, isolated from the effects of the launch and the boost motor firing, and stabilised against any thermal variations which might throw its highly-delicate measurement path out of alignment.

Three solar arrays would give power for the satellite to operate in orbit, its electricity generated by incident sunlight. All three panels would be folded flat against walls of the hexagonal satellite body, hinged and clamped for launch, to be opened out once in orbit by ground command. This panel opening would be another tense moment, scheduled for several days after launch. Deployment failure of one or more panels would

be another death sentence, for not only would the power supply be curtailed, but the smooth spinning motion of the satellite would be lost.

On-board computers were needed to calculate which stars were to be observed as the satellite rotated slowly in space. Swift and accurate calculations had to be done in a flash to pilot the sensitive detectors to the chosen star images, and then to queue the data acquired for transmission to the ground. Specially designed antennae were needed for this too. As the satellite turned in space, different parts would face the Earth, and two antennae were needed for full coverage. The data had to be switched between the two antennae depending on which of the pair were on the sight-line to the ground. All these calculations had to be done autonomously on-board the satellite, for there was insufficient time to send data to the ground, perform some calculations, and send the results back up. The round-trip travel time for the radio waves to propagate would alone take a quarter of a second, and that was too long.

All of these systems were complex and intricate, usually demanding a specific development and manufacturing effort within the relevant industrial groups. Most components that are used in space rely on decades of space engineering experience and heritage, in materials, integration procedures, and testing methods. Items that had been 'space-qualified' in the past gave no particular cause for concern. Yet the reason that industries relish space experiments is to extend their own expertise by doing something new, gaining new knowledge, and extending their own competitive advantage. This is why cutting-edge science and high-tech industries make such a rewarding partnership. It's also one of the reasons why space experiments are so risky.

ONE OF THE SUPPORTING TASKS of the satellite was particularly challenging, and absolutely crucial to the mission's success: how would we spin the satellite to sweep out the circles on the sky? The whole satellite had to rotate slowly but precisely, following an accurate pre-defined and endless loop around the celestial sphere, on and on for three years. Several challenges had to be mastered: once set in its delicate slowly spinning motion, small adjustments would be needed to keep the two directions of view on their pre-defined track. These adjustments would need to be carried out most gently, without transmitting unwanted vibrations through to the rest of the measurement system. The designers needed to figure out how to follow where the satellite was pointing, and needed to find a way of adjusting the motion so that it could continue to point to where it needed to be over the coming seconds and minutes of its sky scanning.

The solution had the feel of something precarious if not preposterous. We would know the approximate positions of the stars that we would be measuring. We

needed a way of recognising the star field that the satellite was pointing to, and thereafter making adjustments to its scanning to point it where it needed to go next. Implementing this required a plethora of sensors, monitors, and methods for the attitude adjustment, which would work together to get the job done. Once the satellite had been placed into its final on-orbit location, a coarse sensor would detect the light from the Sun, and allow the solar arrays to be pointed roughly in that direction. The satellite would then be spun-up to its required spinning rate. This motion would be sensed by gyroscopes, and adjusted to give precisely the desired spin. Next, the entire satellite would be slewed so that its spinning axis was offset by the chosen forty three degrees from a line to the Sun.

Thus gently rotating, star images would pass steadily across a star sensor at the telescope's focus. This star tracker would sense the passage of stars across the focal plane in both coordinates on the sky. The signals would be analysed by the computer on-board. The computer would interpret the pattern of stars flowing across the two telescope fields, comparing it with the known star positions. It would then know which stars were passing across the telescope's sight lines.

So informed, tiny pulses of gas would then be fired, every thirty seconds or so as needed, to tweak the telescope viewing directions so as to point, very precisely, to the stars next in line to be observed. And so on throughout the life of the satellite in space. If and when the satellite was hit by tiny micrometeorites flying through space, the accurate pointing had to recover from these unexpected nudges also.

If this sounds somewhat of a circular logic—star images used to determine the viewing directions, themselves then used to adjust the attitude—it was a concern that we all shared and which we were most anxious, after launch, to see demonstrated. The tiny gas jet thrusters issued tiny puffs of gas, on computer demand, to nudge the satellite by just a fraction. They would have to work, reliably, for the full duration of the mission.

If knowledge of the spin rate or the pointing direction were lost, the only way to recover would be to reposition the satellite to its Sun-pointing mode using the coarse sun sensors, then repeat the acquisition steps. The entire procedure would take several hours. It would demand a full turn-out of the operations team—orbital engineers, flight dynamics experts, and instrument operation and satellite attitude groups—and was a delicate and stressful procedure. When first executed, it took over the main control room of the operations centre due to its size, its complexity, and its criticality.

In the detailed unfolding of the technical design of Hipparcos, the complex attitude control system always remained central to the project's feasibility. That it did work was testament to the expertise of the Matra Mar-

coni Space team at Velizy in France who designed it, ESA project team members Hamid Hassan and Kai Clausen who supervised it, and science team members Erik Høg from Copenhagen and Rudolf Le Poole from Leiden who sat in on various confidential closed meetings with the industrial teams to optimise it for the specific demands of space astrometry.

Le Poole played a key role on the science team. Ten years my senior, he was a bundle of energy. Rarely did he put pen to paper, or in later years, fingers to keyboard. He worked by catalysis. His knowledge of physics was impressively broad, and he had a lightning insight into how things worked and why. He did not design an instrument like Høg could, nor work through the precise mathematics like Lindegren, but he revelled in probing everything, and he made sure that the rest of us questioned any possible missing links. He advised the industrial teams on the attitude control, the grid, the detectors, and the gyroscopes, advised the project team on the alignment and calibration, sat on the science team, and on the steering committees of the input catalogue and one of the data analysis teams. He laughed a lot, and we talked late into the night when I had problems to discuss. We skated long distances together when the canals froze in Holland, which they did a plenty in the 1980s but rarely thereafter, although a splendid freeze in January 2009 saw us back on the ice together for a reunion.

In the wonderful Boerhaave Museum of science in Leiden, sits Philips' first electron microscope, and I spotted that a label on it credits the design to another Le Poole. "Yes," he said, "he was my father." It is interesting how traits propagate down through the generations.

The focal plane

ONE FINAL PIECE OF THE EXPERIMENT which I have side-stepped so far merits examination in a little more detail. We have seen the intricate telescope with its two viewing directions which creates images of the stars at the common focus. And we have looked at the marvels of an attitude control technique capable of spinning the satellite in a carefully controlled manner to point to the stars. The remaining decisive step is how to actually measure the angles between the stars along the circles being scanned on the sky. How to sense and collect the very angles necessary to feed into the processing system on ground which would spit out the positions, motions, and parallaxes of each star measured at the finale of the three year observing period.

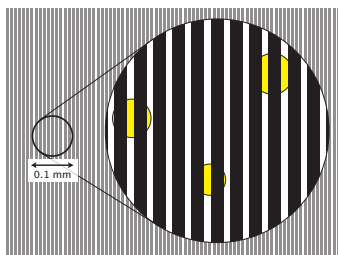


Rudolf Le Poole (2006)

Our star surveyor pre-dated CCD technology. The only light-sensitive detectors that could be used were types of photomultiplier tube, which convert light falling onto them into an electrical current. The basic phenomenon—the photoelectric effect—was first described in the opening years of the twentieth century. Explaining what was happening had proved problematic at that time, because the detailed behaviour disagreed with James Clerk Maxwell's wave theory of light. Albert Einstein solved the paradox by thinking of light as discrete particles, or photons, rather than continuous waves. His explanation led to the quantum revolution in physics, and it was this piece of work, rather than relativity, which duly earned him the Nobel prize in 1921.

So it was that photomultiplier tubes located behind the focus recorded the pattern of light bursts as star images entered the telescope's sight line as it scanned the heavens. The images passed across a special asymmetrical slitted mask in the focal plane. This gave rise to an electrical signal which encoded the satellite's directions in space, information used to adjust its path on the sky.

In the central part of the focal area was something even more remarkable. Etched onto a three centimeter square mask, Swiss engineers fabricated a tiny grid of nearly three thousand alternately opaque and transparent parallel slits. The grid, so microscopic in pitch that the pattern printed on it was quite invisible



Part of the tiny grid, much enlarged, with star images crossing behind it

to the naked eye, was constructed and laid down with masterful and painstaking precision.

The size of a matchbox, it was the result of a difficult and dedicated technology programme that had extended over more than three years. It was the very heart of the instrument—star images passing across it gave the pulsating signals that encoded their positions.

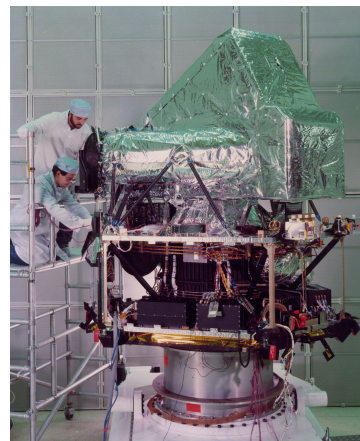
As light from the stars crossed this tiny grid, the detector sensed the regular train of peaks and troughs transmitted. Just like looking through a picket fence at a moving light beyond, the source would appear to fluctuate in intensity as it moved, but with a regular uniformity. The positions of the peaks and troughs of different stars gave the information used to pin down their angular separations. Stars from the same telescope viewing field had exactly these separations. Stars from the two different fields differed additionally by the known angle between the two lines of sight. This angle was rigidly fixed by the beam-combining mirror, its own stability ensured by tiny heaters surrounding the telescope providing meticulous thermal control.

Converted to electrical signals, digitised, labeled by the on-board computer, and sent to ground, the data processing teams preparing themselves far below would have all the information needed to re-assemble the pieces of this massive celestial jigsaw.

Satellite integration and testing

AS ALL OF THE VARIOUS PIECES of hardware, designed, constructed and tested in various high-tech industries throughout Europe came together, they were shipped to the integration centres in Matra Marconi Space in Toulouse in France and in Alenia Spazio in Torino in Italy. Industrial leaders Michel Bouffard in Toulouse and Bruno Strim in Torino took charge of these final steps. Another jigsaw of hardware pieces was being assembled, final testament to the specifications and detailed design steps which had been set up by ESA and the industrial prime contractors over the preceding years.

And then in they flowed, the synchronised culmination of five years of technological development across Europe: the beam-combining mirror from REOSC Optique at Saint Pierre du Perray; the spherical, folding and relay mirrors from Carl Zeiss GmbH in Oberkochen; the straylight-suppressing baffles from CASA in Madrid; the modulating grid from CSEM in Neuchâtel in Switzerland; the mechanism

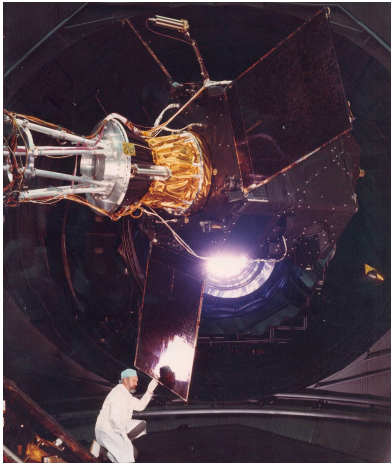


Final satellite integration (1987)

control system and the thermal control electronics from Dornier Satellite Systems in Friedrichshafen; optical filters, the experiment structures and the attitude and orbit control system from Matra Marconi Space in Velizy in France; instrument switching mechanisms from Oerlikon-Contraves in Zurich; the image dissector tube and photomultiplier detectors assembled by the Dutch Space Research Organisation, SRON in The Netherlands; the delicate refocusing assembly mechanism designed by TNO-TPD in Delft; the electrical power subsystem from British Aerospace in Bristol; the structure and attitude control system from Daimler-Benz Aerospace in Bremen; the solar arrays and thermal control system from Fokker Space System in Leiden; the data handling and telecommunications system from Saab-Ericsson Space in Göteborg in Sweden; and the apogee boost motor from SEP in France.

Groups from the Institut d'Astrophysique in Liège in Belgium and the Laboratoire d'Astronomie Spatiale in Marseille masterminded the optical performance, calibration and alignment tests; Captec in Dublin devised the calibration sequences to be run through in orbit, and Logica in London programmed the on-board computer software.

Everything was now on a critical path to launch. There were many tense moments, many crises, many difficult decisions, and many long meetings and too many late nights.



*Testing in the Large Solar Simulator
(ESTEC, Noordijk, February 1988)*

Kai Clausen tells how, in the final stages of integration, he had been summoned to Madrid to hand-carry a replacement part for an antenna which had broken during tests, and which was now needed urgently in Toulouse. He was dropped at Barajas airport with the flight unit reposing securely in a multiple layer metal suitcase, protected from shocks and from any possible contamination. An

escort through the airport had even been arranged with the Guardia Civil. The duo marched swiftly and importantly through to customs, at which point Clausen with no knowledge of Spanish, and the policeman with no knowledge of English, both found themselves at a loss to explain to the vigilant officer as to exactly what each was doing in the other's company. The officer insisted on seeing what was in a case which demanded an armed escort. Clausen, still unable to communicate what was going on, had no option but to resist the officer's strenuous attempts to pick up the antenna part for closer examination. He had, he said later, visions of invalidating the strict cleanliness requirements, a simple finger print which might domino down to a launch cancellation and a penalty fee of many millions. Before the situation got completely out of hand, Clausen produced a fistful of documents in Spanish, which happily included adequate customs declarations thoughtfully prepared in advance.

With these intense and delicate activities carried out in various companies and many countries over several years, the Hipparcos satellite was finally assembled and tested. It was passed from IABG in Munich for tests

of the thermal properties, to Liège for further extensive checks and measurements under vacuum conditions, to Intespace in Toulouse for vibration stresses to simulate the vigorous shaking that would be experienced at launch, and on to the vacuum chamber of ESA's Large Solar Simulator at its technical centre in Noordwijk. There it was gently spun at five revolutions per minute under a flood of intense optical and ultraviolet light, simulating the harsh and varying conditions of solar illumination that it would be subjected to in space.

It was during a night time test in this Large Solar Simulator that engineers were alarmed to find the satellite starting to vibrate when the spin rate was lowered. Test facilities were at a premium, and a fix was urgent. No time was lost in calling out mechanical experts from TNO-TPD, fifty kilometers away. They arrived at 3 am, and quickly traced the problem to damaged teeth of the coupling gearbox. In an unparalleled stroke of efficiency, the report was on Hassan's desk first thing the following morning. So too was the bill.

Eventually signed off by industry as all present and correct, confirmed by the ESA project team leader Hamid Hassan, approved by myself as project scientist and through the fiat of the science team, acknowledged as ready for action by the flight operations team in Germany and for launch by the Arianespace authorities, and in turn by an independent launch readiness review panel under the authority of the Director of Science, Roger-Maurice Bonnet, the work on ground was at last completed.

ALL OF US WERE CONSCIOUS that each piece would have to do its work in orbit for the satellite to take its place in history. The most perfectly polished mirrors in the annals of astronomy would have to work together with exquisitely sensitive detectors operating in the harsh environment of space. Featherweight thrusters would gently spin the satellite to survey the heavens. Computers and transponders and solar panels and temperature controls would all need to operate flawlessly. Optics, baffles and filters would have to remain in perfect alignment. There could be no rehearsal once the satellite was put into space, no possibility of adjustments or fixes if anything went wrong.

The satellite was crated, sealed, and shipped to French Guiana for its launch into space on Tuesday 8 August 1989.

The basis of this account originally appeared in my popular book describing the Hipparcos project: The Making of History's Greatest Star Map, 2010.