56. Gaia: interferometer or monolith?

As briefly mentioned in the 2016 paper in *Astronomy & Astrophysics* describing the Gaia mission (Gaia collaboration 2016): *'In the early phases, Gaia was spelled as GAIA, for Global Astrometric Interferometer for Astrophysics, but the spelling was later changed because the final design was non-interferometric and based on monolithic mirrors and direct imaging'.*

But the choice (interferometer versus monolithic) was not at all straightforward. And, as I will explain, Gaia owes its very existence to its interferometric origins.

In late 1983, ESA made an open call for mission proposals to the European scientific community, based on an idea for a community-driven programme, Horizon 2000, as presented by Director of Science Roger-Maurice Bonnet to ESA's Science Programme Committee. The solicitation yielded 68 proposals: including 30 in the field of astronomy, and 34 related to solar physics.

An *ad hoc* committee led by Dutch Space Research Organisation (SRON) director Johan Bleeker was set up to assess the proposals. It comprised members of ESA's Space Science Advisory Committee (SSAC), CERN, the European Science Foundation, the European Southern Observatory, and the International Astronomical Union.

In early 1984, the committee formulated plans for a series of missions divided into three categories: 'cornerstones' costing a total of two annual budgets, medium-size missions costing one annual budget, and small-size missions costing half an annual budget. In broadly indicative terms, the annual budget was assumed to be around 200 M€ from 1991 onwards.

Three such cornerstone missions were assigned to a specific field of science that competing proposals would then aim to fill, while the science objectives of medium-size missions were left open for competitive selection.

Cornerstones selected were a comet sample-return (subsequently Rosetta), X-ray spectroscopy (later XMM-Newton), and a sub-mm mission (subsequently FIRST). Cornerstone objectives not selected due to financial and technical reasons, but noted as possibilities ('green dreams') beyond Horizon 2000, included a solar probe, a Mars rover, and... an interferometry mission.

Several concepts competed to occupy this interferometric 'slot' (within the follow-on Horizon 2000+), with an emphasis on establishing interferometric *techniques* rather than being driven by specific science goals.

One interferometric concept was Darwin, proposed in 1993, and studied by ESA for many years. It aimed to image Earth-like planets around nearby stars, with (in its final configuration) four free-flying telescopes. Despite a loose collaboration with NASA on their comparable Terrestrial Planet Finder, both missions were eventually abandoned due to technical complexity and cost.

Meanwhile Rømer, proposed by Erik Høg and Lennart Lindegren in 1993 as a medium mission in Horizon 2000 (100 million stars to 15–17 mag at 0.1–1.5 mas accuracies), was reviewed by ESA's Astronomy Working Group, but lost out to the microwave background mission Cobras/Samba (subsequently Planck).

There had, in fact, been ESA study teams devoted to space interferometry since the early 1980s. Under Sergio Volonté's direction, I had coordinated some of the work around 1988, leading to a report on a 'strategy' for space interferometry. My own notes from March 1995 read: *'I was unhappy with its immediate prospects – low throughput, a relatively small number of accessible targets, complexity, UV coverage, time variability – all seemed to undermine its scientific applicability.'*

On 9 September 1993, there was a lunar interferometry meeting in ESTEC. My notes from the meeting read *'Enjoyable talking to Chris Dainty. Useful in that it jogged me into putting a proposal in to post-Horizon 2000 planning, for a project which I called GAIA, for Global Astrometric Interferometer for Astrophysics'.*

In the evening, I met with Lennart Lindegren at the Camino Real, in Leiden. My notes continue: *'This is when Gaia was born – I believed that we could exploit the present interest in interferometry with a proposal for Horizon 2000+. A letter was duly prepared and submitted to ESA by Lennart; we prepared an outline proposal, added the names of interested people, and Lennart submitted it on 12 October 1993'.*

UNDERPINNING THE GAIA interferometric concept, as formulated and proposed by Lennart Lindegren and myself in 1993, were two distinct considerations. The first was programmatic: if an astrometry mission employed interferometry, it could hope to satisfy the open cornerstone slot in the Horizon 2000+ plan.

But a key reason to consider an interferometer was related to the accuracies achievable. If λ is the wavelength and D the overall size of the instrument aperture (diameter or base length), then the characteristic angular size of features in the diffraction pattern that can be used to localise a star image is of order λ/D radians. If a total of N detected photons are available for the image location, then the theoretically achievable angular accuracy is of order $(\lambda/D) \times N^{-1/2}$ radians.

In a scanning instrument, with the astrometric accuracy determined by the star's centroid position *along-scan*, it follows that for a given mirror mass, astrometric accuracy can be gained by extending the mirror in the along-scan direction. Which is why, today, the Gaia primary mirrors are rectangular, 1.45 m × 0.5 m in size, with the longer dimension in the along-scan direction.

GIVEN THAT the baseline launch vehicle, Ariane 5, had a fairing diameter of about 4.5 m, an interesting possibility presented itself: a rigid interferometer, housed within the Ariane 5 fairing, could employ circular primary mirrors of, say, $D = 0.6$ m, with a baseline length of around 2.5 m, and an astrometric accuracy significantly superior to a much smaller diameter monolithic mirror of comparable mass.

Although later changed to a Soyuz launch vehicle, these considerations led to the original design of GAIA as a stacked pair of interferometers, and to the mission's original accuracy goals of 10 micro-arcsec at 15 mag.

Working through the numbers led to an astrometric mission substantially more performant than Rømer. And with other features including multi-colour photometry and bright star radial velocities, the Astronomy Working Group and SSAC found the resulting science case compelling. In this form, rather crucially, GAIA also satisfied the letter – if perhaps not necessarily the spirit – of the Horizon 2000 interferometer placeholder.

NOT ALL OF ESA's advisers were happy with this astrometric juggernaut which appeared out of left field. Arguments against included the fact that ESA had only just completed one astrometry mission, Hipparcos, and that it was the turn of another scientific discipline.

Others expressed the opinion that astrometry was not what the Horizon 2000 architects had in mind for an interferometry mission. There was scepticism, too, that the required technologies were attainable. But the scientific case for this high accuracy astrometric survey, extending as faint as 19 mag, duly won the day.

THE INTERFEROMETRY CONCEPT underpinning GAIA (note the capitals!) was the initial baseline. But during subsequent system studies between 1997–1999, two industrial teams (Alenia, Torino; and Astrium, Toulouse) undertook a more detailed technical evaluation.

Alenia continued to focus on, and advocate, the interferometric design. But as the studies progressed, multiple problems became apparent. One was the technological challenge of maintaining the required 10 pm optical stability over the 2.5 m baseline. Associated with this was the formidable challenge of the in-orbit spatial alignment, complicated by the multiple optical components all along the two interferometric arms.

A further difficulty followed from the smaller Airy profile: the CCD pixels would have to be reduced, along-scan, to a dimension matched to the higher spatial frequency of the star images, with problems both for manufacturing, as well as for the pixel charge capacity. This led to other penalties including a brighter limiting magnitude, and a much higher data rate to Earth.

THE ASTRIUM TEAM, in contrast, soon discarded the interferometric option, and concentrated their efforts on a monolithic primary mirror design, albeit with a penalty in achievable astrometric accuracy.

When the time came for the technical evaluation of the two industrial proposals – covering all mission aspects including technical, managerial, schedule, risk and cost – the ESA evaluation team unanimously recommended acceptance of the monolithic design. The trade-off is detailed in the Gaia Concept & Technology Report (ESA–SCI(2000)4, Appendix B).

One could argue that, by discarding an interferometric concept, the Horizon 2000+ implementation plan should have been revisited. But by this stage the scientific impact of Gaia (no longer an interferometer, and so no longer capitalised as its original acronym!) was widely appreciated and fully endorsed by ESA's scientific community as represented by its advisory committees.

My own record of this technologically and politically charged period, extending over nearly 10 years, with its many actors, and its lobbying, meetings, reports, deadlines and frustrations, runs to many pages. But this outline picks out the key points in the transition from its interferometric origins to its final monolithic design.

IN SUMMARY, interferometry was eventually dropped for objective technological and associated cost/risk reasons. But I suggest that, had Gaia not started as an interferometer, it would never have been accepted within ESA's scientific programme in 2000.

And by not capitalising on the scientific expertise carried over from Hipparcos, it might have been a very long wait until the right circumstances for the flourishing of microarcsec astrometry re-emerged.