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Dr. R.M. Bonnet
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8–10 rue Mario-Nikis
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Dear Dr. Bonnet,

Global Astrometry and Photometry from Space
Proposal for an ESA Cornerstone Mission

With reference to your letter of June 29th, calling for mission concepts for the post-Horizon 2000 planning, I wish to draw your attention to the enormous and unchallenged advantages of space techniques for very accurate global astrometry and photometry. This is an area where Europe has now taken the leadership through the outstanding success of the Hipparcos mission. It would seem appropriate to build on this experience by selecting, for a future ESA mission, an instrument that will expand our knowledge of the Universe by another factor of the same order as provided by Hipparcos. This requires global astrometric measurements for millions of stars, with an accuracy substantially below the milli-arcsec level. The astrophysical value of such a programme would be truly immense.

The Roemer proposal, submitted this summer for M3, was designed to provide sub-milli-arcsec accuracy for 50–100 million stars, and is thus already in its present form a worthy candidate for such a follow-up mission. In the context of a Cornerstone Mission the Roemer concept could however be significantly improved, resulting in accuracies in the tens of micro-arcsec range. This could be achieved by increasing the aperture and focal length of the optical telescope, and possibly by using two telescopes instead of one.

As noted in the Roemer proposal, a Fizeau-type interferometer with a baseline of a few metres has the potential to do global astrometry at the 20 micro-arcsec level for very many objects. A modified Fizeau concept, better adapted to existing detector technology, is outlined in the attached proposal for a mission called GAIA (*Global Astrometric Interferometer for Astrophysics*).

The scientific justifications and potential performances are comparable for the 'large Roemer' and the GAIA concept. Roemer would have a fainter limiting magnitude, and could observe more objects, whereas GAIA would be more accurate. Many aspects of optical design, detector requirements, attitude control and data handling are similar. I propose that both concepts are considered for an ESA Cornerstone Mission and that they are initially studied together as options of a project aimed at very accurate global astrometry and photometry. Within the time-scale of a cornerstone mission it could be properly determined which option offers the best way forwards, without a priori excluding either.

Yours sincerely,

Lennart Lindegren

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Response to Call for Mission Concepts for Horizon 2000 Follow Up
Proposal for an astrometric interferometer as an ESA Cornerstone Mission

GAIA

Global Astrometric Interferometer for Astrophysics

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Summary

We propose that a small interferometer of the Fizeau type (baseline ~ 3 m), dedicated to global astrometry, should be studied as a possible concept for an ESA Cornerstone Mission. Positions, absolute parallaxes and annual proper motions could be determined with accuracies on the 20 microarcsec level. The observing programme could consist of all objects to a limiting magnitude around $V = 15$–16, or some 50 million stars, extragalactic and solar-system objects.

Introduction to ESA Activities in Interferometry

Within Horizon 2000, optical interferometry was identified as a 'green dream'—an important area for ESA involvement, but relegated to the distant future due to the demanding technical nature of such a mission. Since that time, several studies have been undertaken related to an interferometric mission, culminating in ESA SP-1135 'A Proposed Medium-Term Strategy for Optical Interferometry in Space'. The body that compiled that report, the Space Interferometry Study Team (or SIST), were able to reconcile the many and varied ideas related to interferometry existing in the late 1980's, and identified some of the key technological developments that would be necessary before a long-baseline imaging interferometer could realistically be considered. As a result of the SIST recommendations, a technical study was initiated within the ESA Technological Research Programme. This has already been beneficial in identifying solutions in critical areas such as delay lines and element co-phasing. Following on from this work came activities within the Lunar Interferometry Study Team (or LIST), who studied what type of interferometers could benefit from their location on the lunar surface, and what type of precursor mission might be necessary to demonstrate the feasibility of lunar-based interferometry. Subsequent studies, as summarized for instance in ESA SP-354 'Targets for Space-Based Interferometry', have identified *global astrometry*, next to UV imaging, as a high-priority area for space interferometry.

In parallel with all of this work, it has been demonstrated that important advances are still possible from ground-based observatories, through techniques such as closure phase and the use of laser guide stars. These developments indicate that great caution is needed before a full imaging space interferometry mission is embarked upon. In the most optimistic scenario, ground-based techniques may over the coming years be able to outperform any realistic imaging space interferometer, unless the UV capabilities of space are exploited (which brings its own complications).

Another important consideration, and indeed a very serious reservation, about long-baseline imaging interferometry is the very low throughput of a plausible space-based interferometer, and the corresponding very long integration times necessary to create useful images by significant coverage of the *uv* plane. Exposure times of days or even weeks would be necessary for 100 m baselines and for any reasonable number of small-aperture telescopes, restricting the number of observations made to only several tens per year.

The Resurgence of Interest in Astrometry

The dramatic success of ESA's Hipparcos astrometry mission has meanwhile opened the way to European involvement and leadership in fundamental astrometry, and a strong awareness of the scientific potential of sub-milli-arcsec accuracies. It is evidently expected to foster substantially new research possibilities, and a resurgence of interest in this important science.

Already, for M3, a follow-up astrometry mission has been proposed to ESA. Referred to as Roemer, this would provide a considerable advance in astrometry, basically by replacing the Hipparcos detector and focal plane system with a CCD array. The consequent improvement in efficiency could lead to sub-milli-arcsec astrometry for many millions of stars down to significantly fainter magnitude limits than was possible with Hipparcos. As noted within the M3 Roemer proposal, a further advancement even over the Roemer concept could be made by the introduction of a small interferometer within the payload. This option was not much elaborated in the Roemer proposal, as it would clearly go beyond the constraints of a medium-size mission, but it is the starting point for the present proposal.

The Proposal

Our preliminary studies indicate that an instrument consisting of two mechanically connected Fizeau interferometers, each with two 30 cm apertures on a 3 m baseline, could (if a sufficiently wide field of view can be achieved) yield positions, annual proper motions and parallaxes to the level of some 20 micro-arcsec, or *two orders of magnitude improvement over the Hipparcos accuracies.* The limiting magnitude would be around $V = 15$–16, and the observational programme could consist of all objects down to this limit, or *some 50 million stars and numerous extragalactic and solar system objects*, compared with the 120 000 observed by the main Hipparcos experiment.

We consider that this potential could be realised within ESA in the very near future. Furthermore, in view of the tremendous astrophysical importance of such a programme, we consider that a careful feasibility study is timely, for the following reasons:

- the recent Hipparcos experience underlines that a continuously scanning instrument is the optimum, and possibly the only way, to achieve a dense global reference system and, as a consequence, positions and proper motions for a large number of stars significantly below the milli-arcsec level. Many of the technical and scientific solutions adopted for the Hipparcos (and also for the M3 Roemer) mission could be directly applied to a global interferometric mission, for example, the scanning 'law', the tools for the accuracy assessment, etc;
- stabilization of a Fizeau interferometer with such a small baseline should be feasible, given experience with comparable apertures (Hubble Space Telescope) and comparable stability requirements (Hipparcos);
- ESA, and the scientific community that it represents, could be confident that the scientific goals of such a mission would be very substantial, and could not be achieved from the ground;
- the mission would give direct experience for possible longer baseline instruments, also for imaging interferometry, ultimately positioned in space, or on the moon. However, it is important to note that the moon *cannot* be considered as an optimum location for astronomical programmes requiring all-sky visibility, such as a global astrometric instrument.

Scientific Justification

Knowledge of stellar distances is fundamental to all astrophysical investigation. The trigonometric parallax is the only known method to obtain such distances truly independent of the models of stellar atmospheres, structure and evolution. But the usefulness of parallaxes depends strongly on the level of their errors, or specifically on how many objects of a certain type can be found within the 'parallax horizon', i.e., the maximum distance for a given relative accuracy in parallax or distance ($\sigma_r/r = \sigma_\pi/\pi$). The volume of space within the parallax horizon, and therefore often also the number of interesting objects, increases as σ_π^{-3}. Thus, while the majority of ground-based parallax determinations reach distances (at the 10% accuracy level) of only 10 to 20 pc, Hipparcos has enlarged this volume by one or two orders of magnitude, providing for the first time direct access to the more massive (and therefore rarer) stars. At the 20 micro-arcsec error level, the accessible volume is further multiplied by a million. This will for instance allow direct distance determination of all galactic Cepheids and a complete sampling of the main sequence with respect to masses, ages, metallicity and helium content. Indirectly this will profoundly impact the determination of the cosmic distance scale.

Annual proper motions become estimable with a comparable accuracy, corresponding to a precision on the transverse stellar velocities of 1 km s^{-1} at around 10 kpc. The determination of stellar motions with such a precision, and within such a large-scale reference frame, will extend the distance horizon for kinematical and dynamical studies *to the entire Galaxy*, by allowing a determination of the rotation curve, the scale height, and the mass density throughout a major portion of the Galaxy. The dynamical features of the Galaxy/Magellanic Cloud interactions become accessible, as well as the *internal* kinematics of the Magellanic System and of large stellar aggregates throughout the Galaxy.

Despite the current intense observational and theoretical efforts devoted to cosmology and the large-scale structure of the Universe, our own Galaxy remains the unique case where the complete scenario of galaxy formation and evolution may be traced back to the protogalaxy epoch through the physical and kinematical study of stars of all generations and birthplaces. The parallax and proper motion data, combined with radial velocities and colours, would allow a thorough discussion of the various galactic populations, such as the halo, the old disc, the bulge and the young disc. Such data would provide a *massive and guaranteed* scientific return.

It should be noted that *absolute* parallaxes are required for all kinds of study. At present, ground-based parallaxes are determined with respect to what is believed to be distant background stars within a small field. The residual correction from relative to absolute parallax is computed using distances estimated from spectroscopic and photometric criteria. Such a technique has been acceptable because the background stars usually have parallaxes of a few milli-arcsec, which is less than or comparable to the error of the ground-based measurements. But when much higher parallax precision is aimed at, this small-field technique is no longer useful, because the uncertainty in the corrections will be much too large (except if one can be sure to use only quasars as background objects). Absolute parallaxes can however be obtained directly if measurements are not confined to a small field, but extend over a large part of the sky. It is therefore essential that *global* astrometric measurements can be obtained.

Several proposals have been submitted for M3 related to fundamental physics and, in particular, determination of the metric, and possible violations of general relativity. It should be noted that metric determinations become possible as a by-product of the extremely accurate global reference system that would be generated. At the micro-arcsec measurement level, GR predictions can be subjected to very stringent tests, and a variety of other relativistic effects may become discernible.

General Technical Considerations

Global astrometry means that a coherent and reasonably dense system of positions and proper motions is built up to cover the entire sky. This must be achieved by direct measurements of long arcs ($\sim$ 1 rad), lest the accumulation of the errors of many small arcs should destroy the coherence on a global scale. Global measurements also allow to determine absolute trigonometric parallaxes by utilizing the different sun–observer–star geometries at the endpoints of each long arc. The most demanding technical requirement for any global astrometric instrument is the necessity for an extremely accurate calibration of the long-arc measurements. We believe that this is most easily achieved with a continuously scanning instrument in which the calibration parameters, as a function of time, are determined from the observations themselves as part of the global adjustment of the astrometric data.

Continuous scanning necessarily implies a large observing programme, so that there are always several objects within the instrument's field of view. It also restricts the maximum integration time on any object to $\tau \sim T\Omega/4\pi$, if T is the mission duration and Ω the total solid angle of the detector(s). Since the astrometric errors are proportional to $\tau^{-1/2}$, and given that T is limited to a few years, we are thus motivated to maximize Ω and consequently the field size. This must however be balanced against optical aberrations and the availability of detectors with a sufficient spatial resolution. For instance, if we contemplate to put a CCD directly in the focal plane, then the pixel size (at least in one direction) must be at most a quarter of the fringe spacing, or $\lambda/4L$, if λ is the effective wavelength and L the baseline. With $L = 3$ m, a one degree field requires of the order of 300 000 pixels in the scanning direction, and perhaps 30 000 in the perpendicular direction. Moreover, this must be squeezed into an area of reasonable linear dimensions (a few decimetres), requiring a pixel size of ~ 1 μm. This is clearly beyond present-day CCD technology. To match existing detectors we must either reduce the field diameter or the baseline by a factor ~ 10, which in both cases increases the astrometric errors by the same factor ~ 10. Thus it appears that with a given, realistic number of pixels ($\sim 10^8$), the maximum useful baseline (if the detector is to be placed directly in the focal plane) is about 0.3 m. This corresponds roughly to the M3 Roemer proposal.

While these limitation may be overcome with future generations of solid-state detectors, it is necessary to consider an alternative solution here. The use of a modulating grid comes naturally to mind, and a concept along this line is outlined below.

Elementary considerations indicate that an accuracy of the order of 20 micro-arcsec at the 15th magnitude can be reached with a baseline of $L = 3$ m and a total integration time of $\tau \sim 1000$ s per object. This requires a field of view of $0.7 - 1.0$ degree diameter. Such a wide interferometric field can only be realized in a Fizeau configuration (Fig. 1). The requirements in terms of design aberrations, manufacturing tolerances and alignment are extremely severe, and active stabilization of pathlengths is probably a prerequisite for the attainment of fringes at all points in the field.

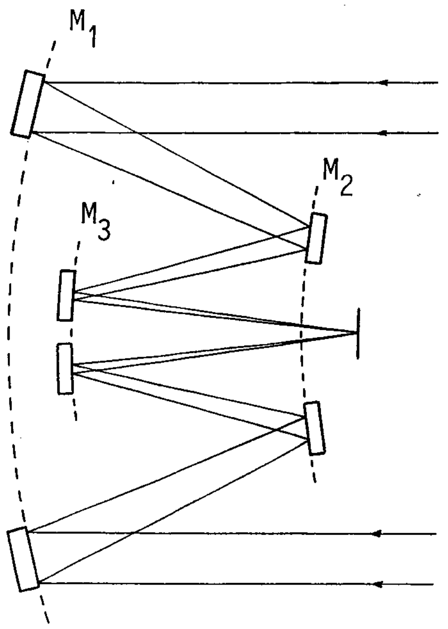
A Concept Using a Modulating Grid

As noted above, exploitation of the information at the fringe frequency in the absence of a modulating grid would require a prohibitively large detector array at the focal surface. This requirement, and the corresponding tolerances on the detector performances, can be relaxed dramatically with the inclusion of a modulating element, resulting in a data collection analogous to that employed with Hipparcos.

In this concept the focal surface is covered by a mosaic of perhaps 25 grids, with different grid periods but manufactured on a single substrate. Each grid is equipped with its own colour filter, such that the fringe spacing $\lambda_{\rm eff}/L$ matches the grid period, and a CCD to record the intensity modulations. The use of different periods (and effective wavelengths) is necessary to resolve phase ambiguities. It also adds some limited *uv* coverage for resolved objects in addition to multicolour photometry, including the additional information required for estimating double star parameters. Behind each grid a two-dimensional array of some 20×20 small field lenses images the two interferometer apertures onto the CCD (Fig. 2). The resulting intensity modulation of the subaperture images is recorded by shifting the charge image back and forth in synchrony with the modulation. The full CCD images must be read out at intervals corresponding to the travel time of star images across the subfield defined by each field lens. The satellite would automatically transmit data for all objects whose modulated component exceeds a certain threshold, corresponding to a limiting magnitude in the range $V = 15$ to 16. On average there should be less than one such object per subfield.

Adjacent to the modulating grid there must be some CCDs set directly in the focal surface which will integrate star images at a lower resolution (corresponding to the Airy disk of each 30 cm subaperture). These are used for approximate (~ 2 milli-arcsec) attitude determination, as required by the data reductions, for a mapping of star images to be used as a starting approximation for the interferometric mapping, and for active control of the secondary mirrors (by superposing the two Airy disks).

Two identical interferometers, with optical axes set at a large angle (1 to 2 rad) to each other and perpendicular to the spin axis, are required to bridge the long arcs in a sufficiently short time to overcome intrinsic variations of the instruments. In Hipparcos, two 'viewing directions' at 58° separation were superposed in a common field of view. This superposition is not essential for the measurement principle and is not proposed for the present system. A crucial question is what the actual requirements are in terms of the short-term stability of the 'basic angle' between the two interferometer axes. Experiences with the Hipparcos data have shown that significant short-term variations of the basic angle can be eliminated in the data reductions without significantly reducing the coherency of the global results. We believe that this is true also for the present concept, and that the stability requirements are therefore substantially relaxed compared with the final accuracy. Further study is required to determine the precise stability requirements and whether they can be achieved by purely passive means.



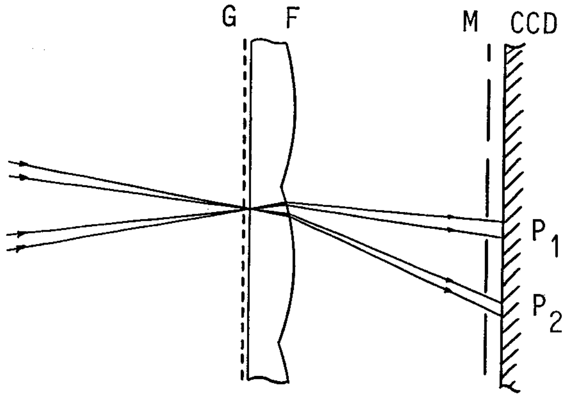


Figure 1 (left): Each interferometer consists of two off-axis telescopes (as if cut out of a single large telescope), with a common focus. Three mirrors are probably needed to obtain a sufficiently wide field.

Figure 2 (right): Part of the modulating grid (G) with an array of field lenslets (F) and detector (CCD). The two circular pupils of the interferometer are imaged on the CCD at P_1 and P_2. Diffracted (and unmodulated) light is masked off (M). The modulating grid may consist of a phase hologram, which doubles the light throughput; in this case P_1 and P_2 are modulated in anti-phase. (Not drawn to scale.)

Technological Reservations

The feasibility of the proposed concept depends critically on the following two requirements:

1. that a sufficiently large field (0.7–1.0 degree diameter) with full interferometric resolution can be achieved for a Fizeau interferometer of a few metres baseline;
2. that the two interferometers can be mechanically or optically connected so as to ensure a sufficient stability, or precision of monitoring, of the basic angle between their optical axes.

Mission Requirements

The suggested design should be consistent with an Ariane 5 launch mass and volume. From a science point of view the choice of orbit is not critical, although the relatively high and continuous data rate (some 100 kbit s^{-1}) probably makes a geostationary orbit the preferred choice. The orbital velocity must be known *a posteriori* to an accuracy of about 1 cm s^{-1}. Telemetry rates are considered acceptable. A minimum lifetime of 3 years is required to obtain annual proper motions to an accuracy matching that of the parallaxes.

Conclusion

We consider that a small interferometer in space dedicated to global astrometry could be undertaken in the near future, with relatively modest technical advances necessary over current capabilities, capitalizing on the recent experiences with Hipparcos, providing secure and outstanding scientific returns, and underlining Europe's leading role in fundamental astronomy.