SPACE ASTROMETRY PROSPECTS AND LIMITATIONS

J. Kovalevsky, F. Mignard and M. Froeschlé
C E R G A
Avenue Copernic
06130 Grasse, France

Abstract. Among the few parameters that describe the generalized space time metrics, astrometric techniques are essentially sensitive to the displacement of the apparent positions of celestial bodies. This includes the relativistic light deflection and aberration. The possibilities of small field and wide field astrometry in measuring these effects are described. The case of the second order aberration terms is considered with some detail from the theoretical point of view, both for stellar and planetary aberration. New results are presented in the latter case.

A section is devoted to a description of the existing space astrometry projects among which Space Telescope and HIPPARCOS are approved but will not contribute significantly to relativistic studies. Several "second generation" projects exist that aim at 2 or 3 orders of magnitude improvement in precision. They would yield results on second order relativistic effects and may be used to determine masses of some single stars. However, the present state of engineering of space astrometric missions has permitted to identify several limitations of the present and future missions. They will not all be readily suppressed and one should be very careful in assessing now their potentialities. It seems however that interferometric techniques have more chance to reach the 10^{-4} and 10^{-5} arc second precision than the imaging methods.

1. INTRODUCTION

Astrometry played a major role in the assessment of General Relativity as being the most adequate model describing the properties of space in presence of matter. If the non-Newtonian part of the motion of Mercury perihelion has been found owing to parallel progresses of Celestial Mechanics and Astrometry, the discovery in 1919 of the deflection of the light in the vicinity of the Sun is by all means an achievement of astrometry.

Since then, many other checks of General Relativity were performed and the knowledge of the parameters characterizing the generalized space-time metric has greatly improved. Astrometry played its role in this

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progress, but also spectroscopy, space probes, pulsar observations, lunar laser, etc...

As we shall see, the present limited accuracy of Earth-based astrometry prevents it from contributing any more to the field. But astrometry from space is now scheluded for a very near future aiming at improvements in accuracy by two orders of magnitude. Even more ambitious projects exist for which their authors expect a gain of another couple of orders of magnitude. How much could such future astrometric observations take the relay in investigating the relativistic effects on the apparent positions of celestial bodies? We have tried, in this paper, to collect some elements that may help to answer this question.

2. ASTROMETRY AND RELATIVITY

By definition, astrometric techniques are used to determine the relative positions of celestial bodies in terms of angular distances and orientations. Let us remark at this point, that these two components of the relative apparent positions of a pair of stars are accessed differently and, with a given instrument, the precisions of their determination may be quite different. However, when one is looking for a relative change of position, the variation of only one of the components may provide sufficient information.

Let us consider the main results connected with General Relativity as presently obtained and let us see whether astrometric techniques can contribute in their improvement (for more details, see Will, 1986).

- The measurement of the deflection of light by a mass gives access to the PPN coefficient γ. It is obtained in comparing the relative positions of celestial bodies at different configurations with the Sun. Presently, γ is known to about 0,1% and VLBI is the only Earth-based technique than can provide such an accuracy.
- The coefficient β is obtained through the analysis of the motions in the solar system: the tracking of space probes and landers overrule by a factor of 2 or 3 the results that may be derived from ground based observations of planets.
- The best test of the strong equivalence principle is presently made available by the interpretation of lunar laser ranging and by sending hydrogen masers on a high rocket orbit.
- The possibility of gravitational radiation seems to be now confirmed from the period variation of the double pulsar PSR 1913+16.
- The possibility of a time dependence of the gravitational constant is presently ruled out by the range data from Viking landers on Mars with a precision ten times better than that provided by lunar occultations and other astrometric methods.

In examining these various tests, one can see that the only possible contribution of stellar angular measurements to General Relativity studies is the determination or the use of the light deflection. Since there are two very different types of astrometric measurements, we have to consider them separately.

2.1. Small field astrometry

When observing the relative position of two stars in the same telescope field, only the difference between the deflections is observable. The effect is proportional to (1+γ) multiplied by a quantity of the order of the separation of the stars and cannot be determined accurately.

However, let us assume that the stars are moving one with respect to the other and that, at some moment, their directions are so close that the light of the farthest star (let us call it B) is bent by the star A. Two cases may occur.

a) The stars A and B form a physical binary system. When the components are in conjunction, the apparent position of B is modified so that the orbit seems to be perturbed. This effect repeats itself at every revolution and does not modify the period of the system.

b) The stars A and B are not physically linked. The path of the foreground star A is straight, while the apparent motion of B bends in a well defined fashion, symmetrical with respect to the actual conjunction (figure 1). If one measures also the parallax of A, one can obtain the linear distance of the closest approach to A of the light emitted by B and deduce the mass of A (Chollet, 1979). This method, which would be accessible to very accurate small field astrometry, would give the first possibility of direct measurement of the mass of a single star.

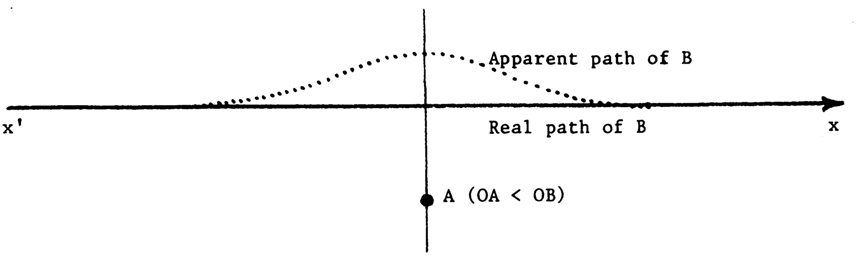

Figure 1. Apparent motion of a star B nearly a star A. If B is closer than A, the path is x'x. If B is further, the path is given by the dotted line.

2.2. Linking widely separated objects

Let us consider two stars A and B in the vicinity of the ecliptic and separated by a large angle. Their angular distance to the Sun will change with time as well as the value and the direction of the relativistic light deflection. If one can measure accurately the angle between A and B as a function of time, the variations will provide 1+γ. with the actual accuracy of the angular measurements.

The same measurements give also access to stellar aberration for which second order terms are of the order of the present uncertainties of γ.

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This problem of aberration merits some more development, especially in the case of planetary aberration. This is the object of the next section.

3. RELATIVISTIC EFFECTS IN THE ABERRATION

In astrometry aberration refers to the apparent displacement of a celestial object as a result of the motion of the observer or that of the object itself. The former situation alone, independent of the motion and distance of the object, is refered to as stellar aberration. It is by necessity the only part of aberration astronomers deal with in stellar astrometry. The second part, may be considered as a correction for light-time, taken into account to correct for the motion of a planet during the flight-time a photon needs for the one way trip from the planet to the observer.

The principle of relativity entails that no stellar aberration could be detected if the motion of the Earth were rectilinear and uniform. What Bradley did observe in 1725, was actually the change of stellar aberration due the variation in the Earth's velocity vector as the Earth proceeded on its orbit around the Sun. However, on purely theoretical grounds, one can think about the aberration in stellar position even for an observer in uniform motion. This notion is quite useful for the following development, even though aberration in that sense is not directly observed. To be more accurate we shall compare the position vectors of a celestial object from two distinct viewpoints First we consider a reference frame bound to the barycenter of the solar system. An astronomer located there would obtain for a star a position vector which should be the same as the star catalogue coordinates. If at the same time observations of the same star were carried out on the Earth, a different position vector would result, corresponding to the apparent star position. In the following we shall call aberration the difference between those two position vectors. In the case of a moving object in the solar system, we need to compare the proper direction of a body as observed by an observer whose heliocentric coordinate vector is known at time t_r, (the subscript r refers to the reception time of a photon that would be emitted by the source) to a certain direction of reference of the same body, which usually will be its geometric position as deduced from computed positions available in national or international ephemerides. Aberration in this case, known as planetary aberration, will be the difference between the two aforementioned position vectors. While in stellar aberration both vectors are defined unambiguously, the reference vector in planetary aberration may be chosen in different ways in the frame of special relativity.

A typical order of magnitude of planetary and stellar aberration is $\sim v/c \sim 20''$ where v is the Earth's orbital velocity and c the speed of light. Both for classical and modern astrometry, such a large effect is of paramount importance, but only do the most refined tools of modern astrometry (VLBI, HIPPARCOS, Space Telescope) require the introduction of second order terms, in $(v/c)^2$, in the computation of stellar and planetary aberrations. Stumpff (1979, 1980) has already adressed the stellar aberration and derived a complete second order algorithm to perform the transformation from the geometric position of a star to its apparent position and vice-versa. He showed that second order correction in stellar aberration amounts to 1 mas (=10^{-3}"), which justify then introduction in all the reductions to be performed from HIPPARCOS observations. We shall present a relativistic derivation different from Stumpff's, which leads to the same final expression for the aberration. As for planetary aberration we present here only the results. For more details, see Froeschlé and Mignard (1986).

3.1. Stellar aberration

For stellar aberration we must compare $\vec{u'}$ the unit vector in an Earth-linked frame (O',X'Y'Z') from which a photon appears to come to the unit vector $\vec{u'}$ in a frame bound to the barycenter of the solar system (O,XYZ). O' is the center of mass of the Earth which is instantaneously moving with respect to O at about 30 km.s^{-1}. Let $\vec{r}$ and $\vec{r'}$ be the position vectors of a star in the two frames and t and t' the respective coordinate times. The coordinates of a space-time event are connected through the Lorentz transformation (Fock, 1976) :

$$\vec{r'} = \vec{r} + (\gamma-1)\frac{\vec{r}.\vec{\beta}}{\beta^2} - \gamma\vec{\beta}t \qquad (1)$$

$$t' = (t - \frac{\vec{r}.\vec{\beta}}{c}) \qquad (2)$$

where $\vec{\beta} = \vec{v}/c$, the Earth instantaneous velocity vector expressed in unit of the speed of light, and $\gamma = (1-\beta^2)^{-1/2}$.

Let us consider the following space-time event : the emission of a flashlight by a star at t=-r/c in the frame O. Due to the rectilinear propagation of light the apparent position vector of the star in O', is nothing but the space coordinates of this space-time event in O'. By inserting in (2) the fact that the photon was emitted at t=-r/c we obtain :

$$\vec{r}' = \vec{r} + (\gamma-1)(\vec{r}.\vec{\beta})\frac{\vec{\beta}}{\beta^2} + \gamma r\vec{\beta} \qquad (3)$$

By expanding Eq.(3) to the second order in β we have readily :

$$\vec{r}' = \vec{r} + (\vec{r} + \frac{\vec{r}.\vec{\beta}}{2})\vec{\beta} \qquad (4)$$

and dividing both members by r yields,

$$\vec{U}' = \vec{u} + (1 + \frac{\vec{u}.\vec{\beta}}{2})\vec{\beta} \qquad (5)$$

where $\vec{u}$ is the unit vector in the direction of the geometric position of the star and $\vec{U'}$ a non-unit vector for its apparent direction. Eq(5) has the same accuracy as Eq(35) in Stumpff (1979), even though the second order algorithm presented here is of a different form. By neglecting β^2 in Eq(5), the classical first order stellar aberration is recovered.

A normalization of Eq(5) leads to the correspondance between unit

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vectors,

$$\vec{U}' = \vec{u} + \vec{\beta} - \vec{u}(\vec{u}.\vec{\beta}) + \vec{u}\left[(\vec{u}.\vec{\beta})^2 - \beta^2/2\right] - \vec{\beta}(\vec{u}.\vec{\beta}/2) \qquad (6)$$

that is to say the same as Eq(35) in Stumpff's paper.

In order to make a comparison of the accuracy of the first order aberration (Eq(5) and (6) and the rigourous expression (3)) we have computed the difference between the apparent and geometric position of two fictitious stars with $\alpha=45°$, $\delta=30°$ and $\alpha=225°$, $\delta=30°$, and by greatly exagerating the observer's speed so as to make the aberration very significant. We have taken $\beta_x = 1/30$ ($v_x=10$ km.s^{-1}), $\beta_y = \beta_z = 0$. With the first order we expect no better accuracy than $\beta^2 \cong 0°06$, while equations (5) (6) should not depart from the exact result by more than $\beta^3 = 0°002$. Results are listed in table 1 below. It appears that second order expressions are more accurate than expected, a fact which may come from the presence of a small numerical factor in the term of third order in the expansion of Eq(3).

TABLE 1

	Star A $\alpha = 45°$, $\delta = 30°$		Star B $\alpha = 225°$, $\delta = 30°$	
	$\alpha_{ap}-\delta_{geom}$ (deg)	$\alpha_{ap}-\delta_{geom}$ (deg)	$\alpha_{ap}-$ geom (deg)	$\delta_{ap}-$geom (deg)
First order	- 1.5177	- 0.6703	1.6023	0.6794
Eq. 5	- 1.5328	- 0.6771	1.5858	0.6725
Eq. 6	- 1.5333	- 0.6773	1.5863	0.6727
Exact formulae	- 1.5336	0.6775	1.5870	0.6728

3.2. Planetary aberration

In dealing with planetary aberration one must distinguish carefully between the two following parts : light-time effect on one hand, and stellar-like aberration on the other hand. Light-time stems from the motion of the planet during the time $\tau = r/c$ the photon takes to travel from the planet to the Earth. This effect does not depend upon the motion of the Earth. Once this correction is performed we obtain the astrometric position of the planet. For both Pluto and some minor planets astrometric positions are published so as to render them directly comparable with the mean places of stars as given in star catalogues.

So to obtain the planet's apparent position at t_r we must first compute the geometric heliocentric position at the emission time $t_e=t_r-(r/c)$ where r is the actual distance covered by the photon between the emission time t_e by the source and its reception at t_r on the Earth. Then r does not correspond to the Earth-planet distance neither at t_e , nor at t_r. More exactly r is the distance between the place occupied by the planet at the emission time and the Earth at the reception time,

$$r = r(t_e, t_r)$$

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To the heliocentric planet's position at t_e one adds the Sun's position at t_r to get the astrometric position of the planet. The computation to the second order is detailed in Froeschlé and Mignard (1986) and yields for the planet's astrometric position relative to the Earth,

$$\vec{EP} = \vec{EP}(t_r) - \frac{\vec{V}_P}{c} r + \frac{\vec{V}_P}{c}(\vec{EP}(t_r).\frac{\vec{V}_E}{c}) - \frac{1}{2}\left(\frac{V_P}{c}\right)^2 \frac{r^2}{a_p}\vec{n} \qquad (7)$$

where $\vec{EP}(t_r)$ is the geometric position vector of the planet relative to the Earth where both bodies are considered at t_r. $\vec{V_P}$ is the heliocentric velocity vector of the planet, a_P is the planet's semi-major axis and $\vec{n}$ a unit vector along the Sun-planet radius vector, and $r = |\vec{EP}(t_r)|$ is the so called true planet's distance. The last term in the right hand side of Eq(6) follows from our taking account of the curvature of the planet's orbit. In current ephemerides astrometric positions are not computed with the help of Eq(7), but by forming a geometrical ephemeris for the mean equinox and equator chosen. Then one applies the full correction for first order planetary aberration as if it were a star (Explanatory Supplement of the Astronomical Ephemeris, p. 127).

By noticing that the astrometric position must replace the true stellar position in the computation of aberration, we can now proceed through Eq(4) to determine the planet's apparent position $\vec{r'}$, in term of its geometric position $\vec{r}$, with $\vec{r}=\vec{EP}(t_r)$; one obtains,

$$\vec{r'} = \vec{r} + \frac{\vec{V}_E - \vec{V}_P}{c} r + \frac{V_E}{c}\left(\frac{\vec{r}.\vec{V}_E}{2c} - \frac{\vec{r}.\vec{V}_P}{c}\right) + \frac{\vec{V}_P}{c}\left(\frac{\vec{r}.\vec{V}_P}{c}\right) - \frac{1}{2}\left(\frac{V_P}{c}\right)^2 \frac{r^2}{a_p^2}\vec{n} \qquad (8)$$

We can also work by using the unit position vector for the geometric position and a non-unit vector in the direction of the apparent position we have,

$$\vec{U'} = \vec{u} + \frac{\vec{V}_E - \vec{V}_P}{c} + \frac{V_E}{c}\left(\frac{\vec{u}.\vec{V}_E}{2c} - \frac{\vec{u}.\vec{V}_P}{c}\right) + \frac{\vec{V}_P}{c}\left(\frac{\vec{u}.\vec{V}_P}{c}\right) - \frac{1}{2}\left(\frac{V_P}{c}\right)^2 \frac{r^2}{a_p^2}\vec{n} \qquad (9)$$

When only the first order is retained in Eq(8)(9), we see that to this level of accuracy, one can account for planetary aberration by antedating the ephemeris of a quantity $\tau = r/c$, that is to say by taking as the apparent position the same as the geometric position that the object occupied at time $t-\tau$ relative to the position that the Earth occupied at $t-\tau$.

Finally the reader should convince himself of the lack of symmetry in the part played by the Earth and the moving object by studying with Eq(8) the aberration of the Sun for an Earth-based observer, and the aberration of the Earth for a fictitious observer located at the barycenter of the solar system.

4. SPACE ASTROMETRY PROJECTS

Two types of projects presently exist corresponding to small or wide field astrometry.

4.1. Small field astrometry

In this case, the observed stars are not separated by more than half a degree, sometimes only a few seconds of arc. The observations are performed quasi-simultaneously using the same optics. The determination of angular separations depends only upon the optical properties of the instrument and of its stability during the time of the observation. The relative orientation of the stars is obtained through trilateration techniques, while the absolute orientation is accessible only with a very poor precision. Among this class of techniques, one may quote all photographic or related (like CCD) methods and space interferometry.

The only actually approved mission of this kind is the Space Telescope, and namely, the use of its fine guidance sensors or of its wide-field camera. The precision of relative positioning is expected to be of the order of 2 milliarc second (Duncombe et al., 1982). This has many applications in stellar studies (parallaxes, search for invisible companions, double stars, etc...), but none of them refers to General Relativity.

In order to have some relativistic applications one has to reach accuracies at least one hundred times better. The most interesting application is the one described in 2.1.2. The value of the total deflection of the light due to A is :

$$\psi = 2(1+\gamma)\ \frac{GM}{rc^2}$$

where M is the mass of A and r the minimum distance of the light to the center of A. Let us call d, the distance of A in parsecs, the observed angular distance between A and B and the deflection both expressed in seconds of arc. One has the following expression :

$$\psi = \frac{0''.00812\ M}{(\theta - \frac{\psi}{2})\,d}$$

or, with a sufficient accuracy if θ is not of the order of ψ :

$$\psi = \frac{0''.00812\ M}{\theta d}$$

Let us assume that the goal is to obtain the mass of the star A with accuracies ε=10% or ε=1% of the solar mass. If the distance of A is 50 parsecs, table 2 gives, in function of the minimum apparent distance of the two stars, the precision with which the relative positioning of stars must be realized.

It is clear from these results, that this effect can be detected only with relative positioning of stars to accuracies of the order of micro-arcseconds. If the star is closer than 50 parsecs, larger θ would give the same accuracy, but the probability of close approaches is much smaller.

Actually several proposals have been made that aim at such few micro-arcsec accuracies that would, among other applications, be able to reach the double star relativistic effects.

TABLE 2

θ	ε	
	η = 0.1	η = 0.01
2"	10 arcsec.	10 arcsec.
1"	2.10 arcsec.	2.10 arcsec.
0.1	2.10 arcsec.	2.10 arcsec.
0.05	4.10 arcsec.	4.10 arcsec.

The most ambitious is a Space long focus telescope proposed by G.D. Gatewood (1986). The focal plane would include a field of view split into four quadrants equipped with a large CCD and a guiding detector for a bright central star. The star image is retrieved by moving a large grid that modulates simultaneously the light of all stars present in the field and a detector that resolves the stars. The final precision of a ten hour observation is optimistically presented as being in the micro-arcsecond range. But even a 10^{-5} arc second accuracy would be a remarkable achievement because of the numerous causes of biases such as instrumental unstabilities and deformations, chromatic effects that exist even in all reflective telescopes at this level of precision (see section 5), etc...

A less sophisticated project has lately been proposed to NSF by York et al. (1984). It would be an astrometric telescope designed to measure half a thousand objects to 10^{-4} arc second accuracy. If the technical difficulties are still great, they are significantly smaller than in the preceding project, and to one tenth of a milliarc second level they should be reasonnably under control. Indeed, the technology is fastly improving and the engineering of Hipparcos or the Space Telescope shows that they are controlled to a milli-second of arc accuracy with the 1985 technology. This means that the state of the art of the 1990's might allow an order of magnitude improvement.

A number of versions of interferometers in space have been recently proposed. All are described in the proceedings of the Workshop on High Angular Resolution Optical Interferometry from Space (Boyce and Reasenberg, 1984). A very wide diversity of use and design exist. For instance, the proposed baselines range between a few meters and a few kilometers. Some interferometers are designed to be embarked on the Space Shuttle or some other space platform (Shao et al., 1984, Faucherre et al., 1984). The expected accuracies also range from 10^{-4} to 10^{-6} arc second in function of the adopted base-line. The stability or baseline measurement requirements are not assessed for the most ambitious projects. However as in the case of the astrometric telescopes in space, the present technology or its foreseeable progress (Silverglate, 1984) permit us to be optimistic as far as the 10^{-4} arc second accuracy is concerned.

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4.2. Wide field astrometry

When determining the angular distances of widely separated points, it is necessary to refer the measurements to some calibrated object. In the case of ground base astrometry it may be a divided circle or the rotation of the Earth. In space astrometry, the angular standard is materialized by a prism. The absolute value of this standard may not be known, but its stability in time or the possibility to monitor its variations with great precision is fundamental.

Presently, HIPPARCOS is the only approved project of this type. The principle is to observe simultaneously two fields of view separated by a basic angle of 58° and to determine the relative distances of the star images in the combined field by letting them drift through a grid (Kovalevsky, 1984). A general reduction of continuous observations throughout a 2 year mission is expected to yield a mean precision of 0"002 for positions and parallaxes and 0"002 per year for proper motions of more than 100 000 stars.

At this level of precision, it is necessary to correct for the relativistic light deflection with the present best knowledge of this phenomenon. It is also necessary to introduce in the computations the second order effects for the aberration (see section 3 above): even if it is still below the expected accuracy, this should be done in order to avoid possible systematic errors. However, it does not appear that any meaningful improvement of γ could be achieved from the reduction of the HIPPARCOS data (Soderhjelm and Lindegren, 1986).

To really contribute significantly to relativistic studies it is necessary to gain another couple of orders of magnitude in the positioning of widely separated objects. This is the objective of the projects POINTS or MINI-POINTS described in several papers (Reasenberg, 1984 and 1986; Reasenberg and Shapiro, 1986). This project alloys the interferometric techniques with the double field observations of HIPPARCOS. If the expected accuracy can indeed be reached, it would be possible to conduct second order relativistic experiments. A direct observation of these terms would have a great impact on the understanding of the physics in the vicinity of dense masses, regions where second order relativistic effects become predominant, though not directly measurable.

5. LIMITATIONS

The technical difficulties that will encounter the realization of these "second generation" space astrometry projects are very far from being negligible. The kind of limitations that such instruments will undergo can be somewhat extrapolated from the very detailed error analyses that were performed in preparation of HIPPARCOS. Let us simply describe what has proved to be the main sources of difficulty in engineering this first purely space astrometric mission.

5.1. Shape and dimensions of the image

Since the aperture of the telescope is not expected to be very large (1 meter in the most audacious project), the diffraction pattern that is to be used for the measurements will be larger than 0"1 or 0"2. In HIPPARCOS, it ranges from 0"4 for the blue to 0"7 in the red. Already in the latter case, its photocenter will have to be determined with 1% precision. Even if it is possible to do better, a gain of two or three orders of magnitude seems to me very unlikely for the following reasons :

5.1.1. Numerization of the image. The dimension of the image will generally not exceed 10μm. The HIPPARCOS numerization is one dimensional and the step is about 1.2μm. The next generation of imaging type instruments should do at least 10 times better in both directions. This means a pixel size of one tenth of a micrometer. Even with such a small size, it will be necessary to have thousands of successive measurements to reach 10^{-5} arc second.

5.1.2. Optical imperfections or misalignments. They are unavoidable and will inevitably skew the diffraction pattern by some small amount that will introduce almost undetectable but not negligible systematic effects. In the case of HIPPARCOS, although the optics are good to λ/60, they displace the photocenter by several milliarc seconds as a function of the position in the field. This is partly due to the large field of view of HIPPARCOS (about 1°). However, very small fields are not efficient for linking stars between them, so that this type of effect will inevitably subsist.

In addition, the necessity of rather large fields makes it necessary to have either a complex optical design or to accept a Schmidt type configuration. In the first case, the misalignment problem becomes major and chromatic errors increase very quickly with the complexity of the optics. In the second case, there remains a coma whose shape and position are wavelength dependent: there is a diffraction chromatism (or chromaticity effect) which, in HIPPARCOS, amounts to several milliseconds of arc and is largely dependent on the position of the star in the field of view.

For all these reasons, and taking into account that the realization of the optical surfaces can scarcely reach λ/100, residual errors will always remain above the milliarc second level. Their calibration to 10% seems feasible, but it becomes very problematic at higher accuracies. In addition, the colour of the star will have to be known to a very high precision that is presently impossible to obtain for faint stars.

5.2. Mechanical jitter of the satellite

This is a mixture of various periodic oscillations of the satellite, mostly at the proper resonance periods of the structure. It produces quick motions of the image that blur the actual image. The mean amplitude is expected to be 7 milliarc seconds in Space Telescope, 2 or 3 milliarc seconds in HIPPARCOS, a satellite that is very specifically studied to reduce the jitter. The jitter is produced by the gyroscopes, by the mechanical setting up of the satellite on the object to be observed or by the guiding mechanisms. One cannot count on an indefinite averaging of this effect. Because of the non-isotropic character of the guiding actions, there will inevitably be a non-isotropic component in the motion of the images that will introduce some kind of systematic error. So, the reduction of the jitter to submilliarc second amplitudes does not seem to be presently acheviable and this effect will be a major limitation to all types of observations, especially for the short exposures.

5.3. Deformation of the structure

Even in absence of gravity torques, external and internal torques or constraints will introduce deformations of the structure and of the optical alignment. Thermal effects are one of the main causes. Even if all the structure is controlled in temperature to 0°1 - a very difficult problem indeed - the residual deformation on a one meter structure will be of the order of 10 Angströms, representing an angle of 10^{-4} arc second or more. Let us remark that POINTS and MINI-POINTS projects require a monitoring of the deformations to 0.1 Angström! One may doubt if this has any physical significance. To all these effects, one should add also calibration unstabilities or errors, guiding errors, parasitic light (stray light or Cerenkov radiation), receiver's inhomogeneities, etc., etc... In adding up all these causes of random and above all systematic errors, the ultimate limit in the coming couple of decades of space imaging astrometry should be of the order of 10^{-4} arc second. This is not sufficient to get the second order relativistic terms and the masses of single stars. If it is a global astrometry concept, one can only expect to obtain γ to a relative precision of about 10^{-4}.

5.4. Space interferometry

If we now consider interferometric measurements, some of the disturbing factors may have a less important impact on the final accuracy. This concerns essentially jitter and the size of the image. The systematic effects, on the other side, remain just as dangerous. Since presently, we have no experience in space interferometry, one has no ground on which one could extrapolate already observed limitations. One may make a parallel comparison with ground-based astrometry. In round numbers, the limitation of ground based astrometry is 0"1, while ground based Michelson interferometry has capabilities of the order of 10^{-3} arc seconds as proved by the Labeyrie interferometric measurements in CERGA. Space will permit to gain two orders of magnitude in imaging astrometry (HIPPARCOS, Space Telescope). One may guess that similar gain could be reached in space interferometry so that 10^{-5} arc second would be accessible. This seems not unreasonable since fringes are much better defined - especially in narrow spectral bands - than a diffraction pattern. In addition, assuming that jitter plays in space a disturbing role analogous to scintillation in ground-based interferometry, the fact that it has an amplitude that is one hundred times smaller, the alleged limiting precision of 10^{-5} arc second is consistent with such an extrapolation. However, the deformation problem remains the same for all techniques and may be actually the most important limitation in space astrometry.

If this 10^{-4} arc second precision is somehow reached, the second order relativistic terms will be observable and a number of single star masses may be determined. My conclusion is, therefore, that astrometry in space may still play an important role in the domains ruled by General Relativity, but only if interferometric techniques in their small field and wide field options fulfill the above described expectations.

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DISCUSSION

Alley :is there any program of using aperture synthesis in optical astrometry?

Kovalevsky : on ground-based interferometry, there is such a program by Labeyrie in CERGA. It is presently in its first phase of implementation. In space, there exist very general ideas, but no approved program.

Chechelnitsky : what are the prospects of observing planetary systems of other stars ?

Kovalevsky : if an accuracy of 10^{-5} arc-second is achieved, planets of the size of Jupiter could be detected.

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