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J. Kovalevsky

Modern Astrometry

With 137 Figures

Springer

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Series Editors

Cover picture: The most advanced instrument in modern astrometry is the satellite Hipparcos launched in August 1989 by the European Space Agency. This artist's representation shows the baffle aiming at one of the two simultaneous fields of view. The outcome of this mission consists of the positions, annual proper motions, and parallaxes of about 118000 stars with a mean accuracy of the order of 1 to 1.5 thousandths of a second of arc. (Photo: by courtesy of ESA)

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Preface

Astrometry is the domain of astronomy devoted to the determination of positions and their time-variations, and by extension, the apparent dimensions and shapes of celestial bodies. Although several books describe the theoretical foundations of positional astronomy, they touch only slightly on the description of instruments and the procedures for obtaining actual geometrical or kinematic quantities, which are among the basic observational data in the study of the Universe and of its components. The goal of the present book is, in contrast, to provide an up-to-date description of astrometric techniques, particularly the most recent and powerful ones, whether the instruments are on the ground or in space.

Until the end of the 19th century, before the development of physical astronomy, all astronomical observations were directed towards obtaining positions of celestial bodies. Since then astrophysics has become the most important domain of astronomy. With the extension of observations to almost all wavelengths from radio waves to gamma rays, with the use of very sensitive new receivers and the development of fast computers, remarkable progress has been made in the description and the understanding of the Universe.

Until about 1970, astrometry did not take part in this general development of astronomy, and yet trigonometric parallaxes, proper motions, and sizes of stars, which can be obtained only by astrometric techniques, are fundamental quantities in many domains of astrophysics. As a consequence, some basic domains of astrophysics became conspicuously uncertain in comparison with progess achieved elsewhere. Since 1970, astrometry has started to make up for lost time and its contributions to astronomy are disproportionately increasing. New techniques such as radio and optical astrometry, CCD receivers, astrometric satellites, chronometric methods, and computers have drastically changed astrometry, leading to gains of one, two, and sometimes several orders of magnitude in precision and accuracy. Thanks to them, astrometry has become a completely renovated science. It is this new science that is described in this book, which is a development of several years of postgraduate courses at Paris Observatory.

A first draft – in French – of the material presented here was published by Springer in its Lecture Notes series (Kovalevsky, 1990). However, the present book is not simply an enlarged and updated version of the latter. Several chapters are almost completely rewritten. New material is introduced in most sections and a chapter on future projects is added. Results from the Hubble Space Telescope and Hipparcos, now available, are presented as well as new developments in other techniques.

The first chapter is a general introduction to astrometry emphasiing its objectives and general methods. The next two chapters present a synthesis of the main results in physical optics necessary to understand the general properties of astrometric instruments and of the atmosphere – an unavoidable medium for ground-based astrometry which strongly affects the observations. Chaper 4 presents a resumé of the main results of spherical astronomy that are constantly used in the reduction of observations; this is not an attempt to write a new treatise in fundamental astronomy but this chapter was added to have at hand in the book all the necessary formulae referred to. The same concern led to a short presentation of the main tools for data reduction and evaluation of uncertainties as well as a sketch of the physical background of techniques used.

The next seven chapters are devoted to presentation of the instruments used in astrometric observations of celestial bodies and of the Earth–Moon system. The objective is to present a brief summary description of the instruments and of their principles, to discuss the origins of errors, to describe the calibrations, and to give some indication of the methods used to reduce the observations. Besides classical astrometric instruments such as astrographs, meridian circles, and astrolabes with their latest improvements, we present all the new techniques which appeared in the last 10–20 years, and contributed to the high precision of modern astrometric data (CCD receivers, Hubble Space Telescope, Hipparcos, optical interferometry, VLBI, laser ranging, GPS pulsar timing). In the last chapter, after a summary description of the main achievements of modern astrometry, we present the need for even better precision and projects which aim at meeting these requirements.

Throughout the book, we have used systematically the international system of units (SI). However, with the great increase in precision, the unit of angle, the second ($''$) is too large. Several notations for a thousandth of a second are found in the literature. It is either called milliarcsecond abbreviated "mas" or millisecond of arc (actually the correct term should be millisecond of degree or millisecond of angle since the quantity measured is not an arc but an angle). I have chosen to use millisecond of arc systematically and introduced the corresponding abbreviation "mas".

It is my pleasure to acknowledge the very competent and efficient typing by Mrs Jeanne Falin. I thank Dr D. Bonneau for his very thorough reading of the chapter on interferometry: actually some paragraphs were written by him. I thank Drs M. Froeschlé, F. Laclare, F. Mignard, and C. Thomas for reading several chapters, correcting errors, and suggesting pertinent modifications.

Grasse, May 1994 Jean Kovalevsky

Contents

1 Presentation of Astrometry

What is Astrometry? What are its objectives and its place in astronomy? By what means these goals are achieved? These are the questions that we are answering in this chapter before entering into the detailed description of the basic techniques of astrometry.

1.1 Astrometry in Astronomy

What is Astrometry? Astrometry is the part of astronomy which provides the positions, and by extension, the dimensions and the shapes of the celestial bodies. These quantities generally vary with time so that the primary goal of astrometry is to describe their motions. Once they are obtained, they are analysed essentially in two different manners.

(i) The description of the motions is an objective in itself. This is the kinematical approach. For instance, stellar kinematics is a domain in which relations or correlations between the components of stellar motions and some of their intrinsic properties (such as chemical composition, age, spectral type, etc.) are established.

(ii) One tries understand why the motions have the observed properties. This means that one studies the forces which govern them. This is the dynamical approach. For instance, in celestial mechanics, one interprets the motion of planets and satellites in terms of the various forces present in the Solar System. Similarly in galactic dynamics, one attempts to explain the structure of the Galaxy from the parameters of the motions of stars.

But even the knowledge of the positions of stars or galaxies, without any reference to their motion, has direct impacts on astronomy, as for instance the structure of clusters or the distribution of matter in the Universe.

In all these applications, astrometry is the observational component of the scientific results at stake. Should one then consider astrometry as an astronomical technique? Such a point of view is quite acceptable, provided that photometry, spectroscopy or radio astronomy are also considered under the same heading. However a better definition would be that astrometry is the application of certain techniques, which one may call *astrometric techniques*, to determine the geometric, kinematic, and dynamic properties of the celestial bodies in our Universe.

In the next section, we shall present some main goals of astrometry, although it is, by no means, an exhaustive list. When science advances, and the accuracy of astrometric measurements grows, new objectives appear. In Chap. 12 some of the expected future applications of astrometry are sketched together with techniques which are due to appear in the decades to come.

1.2 Goals of Astrometry

In very general terms, anything which is somehow distributed in the Universe, moves or has a dimension or shape accessible to measurements is within the domain of astrometry, provided that it has a scientific interest beyond a mere description. Modern astrometry has passed the descriptive stage of the development of science. There are too many problems related to the understanding of phenomena, or to the verification of various hypotheses on the structure and evolution of celestial bodies and their clustering, or to the actual physical laws in the Universe. It is no longer possible to use the limited and costly instrumentation devoted to astrometry merely to observe something because it is observable.

During the first half of this century, some astronomers used to say that any observation is capital which has a value for the future. This is no longer true. An observation must be aimed at solving some specific problem. When an observing programme is set up, one must ask oneself what is the usefulness of this observation, to what question will it bring an element of answer.

Astrometry definitely must obey this rule. Because for many years astrometry did not always follow it, the necessary means were not provided for its development and it was practically severed from the very quick progress of the other fields of astronomy. It got a reputation as an esoteric activity, somewhat dusty and turned towards the past. During the last 20 years, this has ceased to be the case and *modern astrometry* has started to progress. But it is and always will be necessary to ask oneself the question: what domains of astronomy need the knowledge of positions, motions, dimensions, shapes of celestial bodies and what for?

Let us give some answers to these questions and consider successively various classes of objects observable by astrometric techniques, starting from the most remote.

1.2.1 Extragalactic Objects

With the exception of changes of position of emission, quasars and remote galaxies are fixed to better than 10^{-5} arcsec per year. So, it is generally not useful to observe motions of such objects. Closer galaxies, such as Magellanic Clouds and members of the local group, may be moving at speeds that might be measurable with the present capabilities of astrometry. But to measure such small motions one needs to materialise a reference system which is fixed on the sky. The problem of reference systems and frames is presented in Sect. 4.1. It is a necessary tool for determining any apparent motion freed from spurious effects such as a global rotation and, in dynamics, the appearence of Coriolis accelerations.

Quasars and distant galaxies are ideal fiducial points for a celestial reference frame. Therefore continuous astrometric observations giving accurate positions are a fundamental objective of astrometry which has indirect effects on all other measurements of motions of celestial bodies: any rotation of the reference system is wrongly interpreted as a motion of the bodies under study

Another issue for astrometry is the distribution of galaxies in the Universe. A description of the large structures is a precondition for the understanding of the early stages of the Universe when these structures were formed.

1.2.2 Stars

There are many reasons to determine apparent kinematic properties of the stars. One can distinguish three main domains of application.

(i) Stellar astrophysics

The most important parameter that can be obtained from astrometric measurements is the *parallax* (Sect. 4.2.2). Trigonometric parallaxes are at the origin of all other methods to determine distances in the Universe which are based upon the principle that two stars having otherwise the same physical characters (spectrum, temperature, variability, etc.) have the same intrinsic luminosity. However, this analogue method assumes that the actual luminosity of some stars in each category is calibrated. This is possible only if its distance is known: it is the role of trigonometric parallaxes to determine the primary distances of the chain.

The problem is not to determine the parallax of all stars. At a distance of 100 parsecs (316 light–years) the parallax is only 0.″010 or, using the millisecond of arc as a unit (denoted mas = milliarc second), 10 mas. So one can obtain significant values of distances ($D = 1/\varpi$ where D is expressed in parsecs and ϖ in seconds of arc), only in the solar environment, a tiny fraction of the whole Galaxy. Among the closest stars, an observing programme will depend upon the astrophysical importance of the stars.

Several other parameters are determined by astrometric techniques:
• The orbital motion of double or multiple stars,
• The apparent diameters of stars,
• The proper motion, representing its apparent path on the sky. Although this is essentially useful in studying clusters or the Galaxy itself, it may happen that one finds a non–linear proper motion. This leads to discoveries of unseen companions of stars.

Among the consequences of the knowledge of distances of stars, of utmost importance is the fact that the actual values of parameters otherwise observed become expressed in physical units used in laboratories. It is only under this condition that one gets the necessary constraints in physical models of stars, including their internal structure and evolution. Among such quantities are:
• Apparent luminosities of stars in any narrow or wide–band spectral domain (visual, radio, infrared, ultraviolet) which are transformed into absolute luminosities and energy outputs.
• Apparent diameters of stars which become actual diameters expressed in kilometres.
• Apparent dimensions of orbits of double stars which are transformed into astronomical units from which one can deduce the sum of the masses of the components in units of solar mass. In addition, binary pulsars are indicators of the properties of strong gravitational fields, used to verify consequences of general relativity.
• The proper motion of stars are expressed in kilometres per second along the plane perpendicular to the direction of the star. If, in addition, radial velocities are measured using spectroscopic techniques (Sect. 5.6), one obtains the actual velocity of the star with respect to the observer.

(ii) Kinematics and dynamics of stellar groups

The important parameters are proper motions and/or radial velocities. They allow one to study the motions in clusters (and indirectly their distance), to detect stellar associations (stars having a common birth–place), to analyse the motions within the Galaxy and derive relations between the kinematic and astrophysical properties of stars (chemical composition, spectra, variability type, age) which lead to an understanding of the evolution of the Galaxy.

The interpretation of kinematical properties of clusters lead to studies of the force field that keeps them from disrupting and of their evolution in time (for instance, the proportion of runaway stars and the formation of double stars). Similarly, as inputs to galactic dynamics, proper motions and radial velocities are the basic observational data to determine the galactic structure, the galactic gravitational field (existence of dark matter and of an internal bar) and its evolution (stability of spiral arms).

(iii) References for astrometry

To do correct astrometry, one needs to have a reliable and accessible celestial reference system. To materialise such a system one has to construct a reference frame consisting of positions of fiducial points in the sky which may be stars, galaxies, or quasars. It is the task of astrometry to provide such a reference frame and maintain it by determining the motions of the reference stars which represent it.

1.2.3 Objects in the Solar System

Just as with stars or galaxies, it is not useful to observe systematically all the objects of the solar system. One should limit oneself to those observations which have a practical or theoretical interest. Let us give some examples.

(i) The Sun

Among the celestial bodies, the Sun is the most difficult to observe for its position. Nevertheless, it is very important to do so, because its motion defines the equinox. Another parameter is the diameter of the Sun and its time variations. One would also like to find out whether its shape is or is not spherical. Both results have an important impact on the theory of the internal structure of the Sun.

(ii) Major planets

The dynamics of the Solar System remains an important object of study: it is a laboratory in which general relativity effects in weak fields may be analysed. The motion of planets is the basis of the definition of a dynamical celestial reference system which has been in use until now as the fundamental system (FK5 system) and should continue to be maintained for comparison with the extragalactic reference system – a major theoretical objective. Only very precise observations are useful for this goal, which is also true for the preparation of space missions and their operational fulfilment.

(iii) Planetary satellites

Practically every satellite is a particular problem for celestial mechanics. Therefore, the observation of their motion is very useful for theoretical reasons. The preparation and the accomplishment of space missions to some satellites demands frequent and very accurate positional observations.

(iv) Asteroids and comets

These objects are too numerous to be followed in totality with the utmost precision. Actually, it would not be useful: some sparse observations are sufficient to compute ephemerides precise enough not to lose the objects. However, there are cases where precise and numerous observations are needed, for instance the following cases:

• The preparation and accomplishment of space missions to a given comet or minor planet.

• A few minor planets have a particular interest for celestial mechanics: Trojan planets, some members of families of asteroids which are subject to strong resonances, and Earth grazers. This is also the case of comets which undergo strong perturbations by major planets.

• A few minor planets can affect the orbit of some other asteroids. The precise trajectory of the perturbed body allows one to determine the mass of the disturbing planet.

• Some very well observed asteroids contribute, together with major planets, to the definition of the dynamical reference system.

• Some asteroids may sometimes occult a star of comparable magnitude. Precise positions are necessary to predict exactly the phenomenon, whose photometric observations are analysed to determine the dimensions and the shape of the asteroid.

1.2.4 Earth–Moon System

The Earth–Moon system is a unique dynamical system in the sense that it can be very accurately analysed and presents many observable phenomena (tides, resonant rotation of the Moon, deceleration of the lunar motion, exchange of angular momentum with the Earth). Precise observations of the position of the Moon are particularly important since they are the way to access the dynamics of the system. However, they must be very accurate (lunar-laser ranging) so that older methods have become obsolete. Similarly, for the same reason, measurements of the limb irregularities have lost their importance.

Other indicators of the dynamical behaviour of the system – and particularly of the Earth itself – are artificial satellites. Their trajectory is a very sensitive indicator of the Earth's gravitational field and of other forces present in the terrestrial environment, mainly tidal forces and air drag. Not all the satellites are fit for accurate position observations and only those which are accordingly designed are to be observed (satellites with laser retroreflectors, radio transponders or precise timing emissions). Among the applications of precise observations of artificial satellites from the ground, the most important are :

• A very detailed determination of the gravitational field of the Earth,

• The monitoring of the parameters describing the rotation of the Earth,

• The monitoring of the position of observing stations, leading to the measurement of tectonic plate motions,

• The precise trajectography of a satellite needed to accomplish its missions (altimetry, time transfer, geodesy).

In some way, by including artificial satellites in astrometry, we incorporate a significant part of space geodesy. This is not an arbitrary choice, but is justified by several reasons: