Observational Astrophysics
14. Astronomical coordinates

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Autumn/Winter 2021/2022

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1 Introduction

The coordinates of the object(s) are obviously of central importance in planning observations. Without coordinates, and catalogs of coordinates, we would not be able to observe the majority of astronomical sources, since most are not visible to the naked eye. Positions are also essential for studying the motions of celestial bodies.

Astronomical objects appear as if they were distributed on the so-called celestial sphere. This is an abstract, arbitrarily large sphere with the Earth (or the observer) on its center. System of astronomical coordinates use two spherical coordinates, defined in a similar way as the terrestrial latitude and longitude coordinates. Several coordinate systems have been defined on this sphere for astronomical use. This includes the equatorial, galactic, ecliptic, and horizontal systems.

To complement the system of coordinates one needs a catalog of reference objects, with well determined positions. In other words, a reference frame needs to be defined. A set of object with well measured positions, distributed all over the sky, will help in determining the precise coordinates of other objects discovered/observed in specific locations of the sky (you can think of the reference frame as the set of standards that allow the differential positioning of other objects into a certain coordinate system).

2 Read this text

For a general overview of astronomical coordinate systems and reference frames, please read Chapter 3 of the book "Astronomy Methods: A Physical Approach to Astronomical Observations" (Bradt 2004)[1]. The last part of the Chapter also talks about catalogs and names of astronomical objects.

[1] See https://www.google.com.br/books/edition/Astronomy_Methods/hp7vyaGvhLMC?hl=en&gbpv=1&dq=astronomy+methods&printsec=frontcover for a preview.

3 Summary of concepts

- The North and South Celestial Poles are the projections of the Earth poles on the celestial sphere. Note that the elevation of the visible Celestial Pole above the horizon gives the latitude of the observer (positive if you are looking at the North Celestial Pole, negative if you are looking at the South Celestial Pole instead).
- A great circle is a circle with same center as the sphere that divides the sphere in half. The name comes from the fact that it is not possible to define greater circles on a sphere.
- The great circle halfway between the North and South Poles is the equator, called like this because it is equally distant from the two poles. The celestial equator is the projection of the Earth's equator on the celestial sphere.
- The point where the Sun crosses the celestial equator going northward in spring is called the vernal equinox or vernal point.
- Zenith and nadir are the points on the celestial sphere that are above and below the observer, respectively.
- The local meridian is the great circle that connects the poles, the zenith, and the nadir.
- The ecliptic is the great circle of the apparent annual path of the Sun on the celestial sphere. Or the other way around, it is the projection of the plane of the Earth's orbit on the celestial sphere. The plane of the ecliptic is inclined by 23.4° with respect to the celestial equator.
- The horizontal (or horizon, or altitude-azimuth) coordinate system: it has the two angular coordinates called altitude (a or h) and azimuth (A). The azimuth is measured along the horizon, usually from the North point turning to the East (but note that the ESO convention is to count it from the South and increasing westward). Altitude is then measured from the horizon to the object, along the vertical circle which passes through the object and the zenith. The altitude is positive for objects above the horizon and would be negative for objects below the horizon. The zenith angle (or zenith angular distance) is the complement of the altitude (i.e., measured from the zenith towards the object).
- The equatorial coordinate system: it has the two angular coordinates called right ascension (α) and declination (δ). Right ascension is measured on the celestial equator, from west to east, in units of time (hour, minutes, and seconds). The zero is counted from the vernal equinox. The declination is the angle measured from the celestial equator, positive in the northern direction (varying from 0° to $+90^\circ$) and negative in the southern direction (varying from 0° to -90°). The hour angle is defined as the angle between the local meridian and the circle that connects the object and the celestial poles. So the hour angle is zero when the object being observed is at the local meridian. It changes from negative to positive values with the object moving from the East to the West.
- The ecliptic coordinate system: it has the two angular coordinates called ecliptic (or celestial) latitude (β) and ecliptic (or celestial) longitude (λ). The ecliptic latitude is measured from the ecliptic plane and the ecliptic longitude is measured from the vernal equinox toward the East. The ecliptic system is useful for describing the motion of solar system objects.

- The galactic coordinate system: it has the two angular coordinates called galactic longitude (l) and galactic latitude (b). The galactic longitude (from 0° to 360°) is measured along the galactic equator, starting from the direction of the galactic center. The galactic equator is defined as the great circle of the intersection between the Galactic plane and the celestial sphere. The galactic latitude is measured from the galactic equator (from 0° to ±90°). To establish this coordinate system, the IAU defined the coordinates of the Galactic Center and the Galactic North Pole to be exactly $(\alpha,\delta)_{\rm GC}$ = (17h42m34s, $-28°55'$) and $(\alpha,\delta)_{\rm GNP}$ = (12h49m, $+27°24'$) in equatorial coordinates in epoch J1950 (Blaauw et al. 1960)[2].

- The location of the spring and fall equinoxes on the celestial equator are slowly changing at a rate of $50''$ per year, a shift that is called the "precession of the equinoxes". The precession is caused by the action of the Sun's gravity changing the orientation of the Earth's rotation axis with respect to the ecliptic (the axis is inclined by about $23°26'$). The period of the precession is of about 26 000 years. Because of precession, the equatorial coordinates change and need to be defined with respect to a reference position of the axis orientation at a given moment. That is why the epoch is given when talking about right ascension and declination.

- A reference frame is a practical realisation of the coordinate system in space. The idea being to define a set of standard objects spread throughout the sky that can be used to determine the coordinates of your source. For that, we need not only the accurate positions of the standards at the time the catalog was done, but also to have knowledge of the motion of these standards across the sky. Then, this information can be used also at other times, before and after the catalog was established. Determination of fundamental positions in the equatorial system require the simultaneous observation of both the Sun and the stars, so that their right ascension can be directly linked to the that of the Sun, and thus to the vernal equinox. The observations have to be repeated at different epochs, so that the variation of the positions can also be determined. To obtain a catalog of objects in the Northern and Southern sky, a coordinated effort among several observatories is needed.

- Several fundamental catalogs have been defined, each containing precise coordinates and motions for a limited (but always increasing) number of standard stars. The German series of fundamental catalogs is one of the most used. The first fundamental catalog (FC) containing only Northern stars (539 of them) was published by Auwers (1879)[3]. The second fundamental catalog (NFK), extended the sample to 925 stars, including Northern and Southern objects, and was published by Peters (1907)[4]. The third catalog (FK3) was published by Kopff (1937, 1938)[5]. The next ones, FK4 (Fricke et al. 1963) and FK5 (Fricke et al. 1988) were lead by

[2] `https://ui.adsabs.harvard.edu/abs/1960MNRAS.121..123B/abstract`

[3] See `https://opacplus.bsb-muenchen.de/Vta2/bsb11382237/bsb:BV019921404?page=3` for the original in German. Arthur von Auwers was a German astronomer. For a biography see `https://link.springer.com/referenceworkentry/10.1007/978-0-387-30400-7_85` and the other texts linked therein.

[4] Scans are hidden inside ADS, at `https://articles.adsabs.harvard.edu//full/journal=VeKAB&volume=0033&type=SCREEN_THMB`. About the author, I am not completely sure. It seems to be a German astronomer and mathematician named Johann Theodor Peters, who was also known as Jean Peters. An obituary note, in German, can be found in Kopff (1941), see `https://ui.adsabs.harvard.edu/abs/1941AN....272...47K/abstract`. The connection between Johann and Jean Peters was made in page 168 of this document `https://www.jstor.org/stable/pdf/2002639.pdf`. But neither the obituary nor this last document mention the catalog.

[5] A scan of the first part of the catalog is, again, a bit hidden in ADS at `https://articles.adsabs.harvard.edu//full/journal=VeABD&volume=0054&type=SCREEN_THMB`. The second part I could not find yet. August Kopff was a German astronomer. For a biography, see `https://link.springer.com/referenceworkentry/10.1007/978-0-387-30400-7_793`.

Walter Fricke[6] and are available in Vizier[7]. All of these catalogs made use of observations made with ground-based optical instruments. The next installment, FK6 (Wielen et al. 1999, 2000)[8] incorporated also results from the Hipparcos satellite (ESA 1997)[9].

- A problem with fundamental reference catalogs based on stellar positions is the proper motion of the stars. This motion is not random, combining effects of the Galactic rotation and the stellar orbits. Even taken as a whole, the total motion of the stars does not average to zero, preventing the definition of fixed directions and leaving the frame with residual rotation. To overcome this limitation, the IAU decided to adopt a new system, the International Celestial Reference System (ICRS, Arias et al. 1995)[10] to be realized on the basis of quasars, extragalactic compact radio sources with proper motions that should be negligibly small (not on distant galaxies visible in the optical, as they have angular sizes that prevent the precise measurement of their photometric centers). The bright quasars for the system are observed with Very Long Baseline Interferometry (VLBI). The technique can precisely monitor the variable Earth rotation and orientation (Schuh & Behrend 2012; Nothnagel et al. 2017)[11]. The origin of the system is at the solar system barycenter and the axes defined by extragalactic sources should be fixed with respect to the stars. For the sake of continuity, the axes were defined to be as consistent as possible with the FK5 definitions at epoch J2000.0.
- The current realization of the ICRS is the third international celestial reference frame (ICRF3, Charlot et al. 2020)[12]. For ICRF3, it was decided to adopt J2015.0 as the reference epoch.
- The second data release of Gaia included astrometric parameters for > half a million quasars and allowed the creation of a new reference frame that realizes the ICRS. The Gaia Celestial Reference Frame (Gaia-CRF2, Gaia Collaboration et al. 2018)[13] is the first optical realization of a reference frame based on extragalactic sources with sub-milliarcsecond precision.

4 Additional reading

See also Section 5.1 in Volume II of the book "Astrophysical formulae" by Lang (1999)[14]. This text gives the math for correcting coordinates from the effects of precession, nutation, astronomical aberration and atmospheric refraction. For a history of older fundamental catalogs see Fricke (1985)[15], including information up to the observations that were used for the Fifth Fundamental Catalogue (FK5). About the FK6, see also Wielen et al. (1998)[16]. For a review on the (current

[6] Walter Fricke was a German astronomer. For an obituary see Wielen & Lederle (1990) in https://ui.adsabs.harvard.edu/abs/1990QJRAS..31..515W/abstract.

[7] See https://cdsarc.cds.unistra.fr/viz-bin/cat/I/143 and https://cdsarc.cds.unistra.fr/viz-bin/cat/I/175

[8] See the catalog at https://cdsarc.cds.unistra.fr/viz-bin/cat/I/264.

[9] https://www.cosmos.esa.int/web/hipparcos/catalogues

[10] https://ui.adsabs.harvard.edu/abs/1995A%26A...303..604A/abstract

[11] See https://ui.adsabs.harvard.edu/abs/2012JGeo...61...68S/abstract and https://ui.adsabs.harvard.edu/abs/2017JGeod..91..711N/abstract

[12] See https://ui.adsabs.harvard.edu/abs/2020A%26A...644A.159C/abstract. The catalog can be accessed here: https://hpiers.obspm.fr/icrs-pc/newwww/index.php

[13] https://ui.adsabs.harvard.edu/abs/2018A%26A...616A..14G/abstract

[14] https://link.springer.com/book/10.1007/978-3-662-21639-2

[15] https://ui.adsabs.harvard.edu/abs/1985CeMec..36..207F/abstract

[16] https://ui.adsabs.harvard.edu/abs/1998AcHA....3..123W/abstract

and future) science with astrometric catalogs, see Kopeikin & Makarov (2021)[17].

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[17] `https://ui.adsabs.harvard.edu/abs/2021FrASS...8....9K/abstract`