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# Astrometry: The Foundation for Observational Astronomy

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## Abstract

Astronomy has seen unprecedented growth in the past century, due to the rise in multiwavelength observations. The foundation for multiwavelength astronomy is given by Astrometry; the science of position and motion determination of celestial bodies. We present a technique of determining equatorial coordinates of celestial bodies from their pixel coordinates. We also present the subsequent results of using this technique in achieving the initial few steps required for the multiwavelength studies of young open clusters.

**Keywords:** Astronomy, Astrometry, Astrophysics

## 1. Introduction

The science of measuring the positions and motions of celestial bodies is termed as Astrometry. This area, also known by the term positional astronomy, is highly valuable in modern astronomy because of its activities of determining positions of sources in different wavelength regions. This paves the path for multiwavelength observations and analysis of celestial bodies. In the present scenario, with the colossal amount of archival data available to the public, the most common way of performing multiwavelength analysis of celestial bodies is by cross-correlating the catalogs of stars in different wavelengths so as to

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obtain the complete information of each source in all corresponding wavelengths.

Previously, the position of stellar objects in the celestial coordinate system was mainly used by astronomers to record and understand the movement of the stars. Currently, apart from its importance to multi-wavelength astronomy, astrometry is used (i) to establish inertial rest frame in the local scenario, (ii) determine the proper motion of stars in order to investigate stellar kinematics, and (iii) study the motion of extragalactic objects for cosmological purposes [12].

## 2. Reference Frames and Fundamental Catalogs

Astrometry relies heavily on fundamental catalogs of celestial body positions to determine a frame of reference. Due to the relative motion of the Earth, planets, sun and the galaxy, the absolute reference frame must be established by studying their motions in exquisite detail. This gave rise to the creation of fundamental catalogs, in which the objects serve as fiducial points. The main difficulty in creating a fundamental catalog, say in a particular wavelength band, arises due to the dynamical range of the observation techniques. Creating a catalog containing objects with vastly different magnitudes is a complicated process [12]. In addition to this, the accuracy of the position measurements is extremely important since all the research conducted during that era will depend on them. This accuracy in astrometric measurements has improved by about four orders of magnitude since 150 BC [6], as shown in Figure 1.

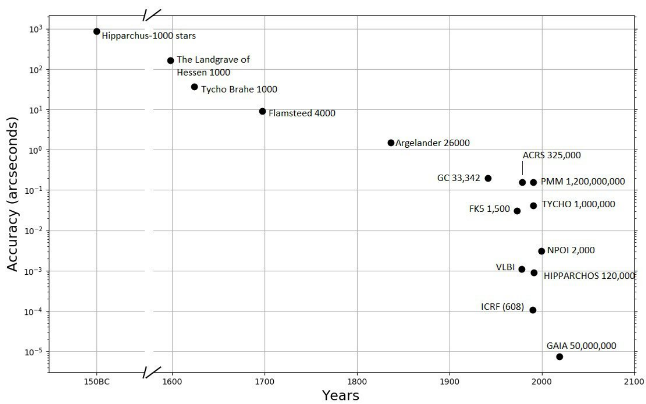


**Figure 1**. A graph showing the improvement in accuracy of astrometric measurements since 150 BC [6]

Coordinate systems are defined by the reference system which specifies their axes direction and the zero points. Furthermore, the positions of objects define the reference system. For all practical purposes, several fiducial points are employed in defining a reference frame. This gives everyone the clear advantage of being able to access the reference system from any location on the celestial sphere [6]. In more technical terms, according to Kovalevsky *et al.* [7], the main objective of setting up a reference frame is to establish a channel through which the reference system can materialize so as to quantize the positions as well as the motions of celestial bodies.

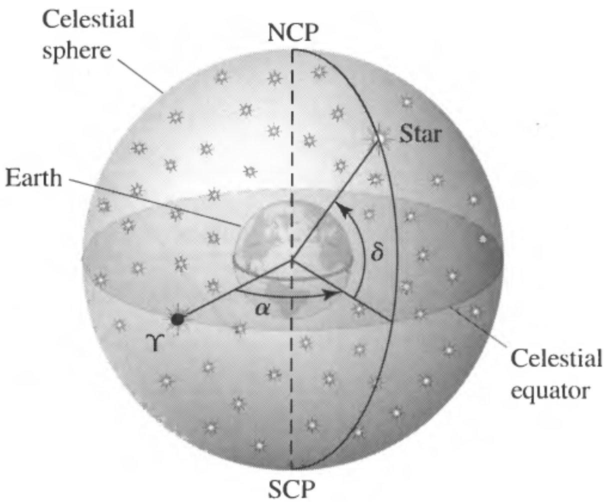


**Figure 2**. A representation of the Equatorial Coordinate System. The right ascension, declination and location of vernal equinox is represented by $\alpha$, $\delta$ and $\gamma$ [3].

In terms of an ideal kinematic reference system, the universe is assumed to be non-rotating. To achieve this, the International Astronomical Union adopted the International Celestial Reference Frame (ICRF), which is built on the positions of 212 compact radio sources, determined using Very Long Baseline Interferometric (VLBI) observations. Due to the large distances to these objects, the changes in their temporal positions are less than a few microarcseconds. The International Celestial Reference System (ICRS) derives the direction of its axes from the ICRF for the J2000 epoch, with a precision of about 20 microarcseconds [6].

## 3. Coordinate Systems

### 3.1 *Equatorial Coordinate System*

The Equatorial Coordinate system is based on three important concepts: Celestial Sphere, Celestial Equator and the Vernal Equinox. The Celestial sphere is a large imaginary sphere with Earth at its center. The stars appear to be projected onto the surface of this sphere. The plane of Earth's equator cuts the Celestial sphere forming a great circle known as Celestial Equator. Furthermore, the apparent motion of the Sun on the celestial sphere, due to the revolution of the Earth, describes a path known as the Ecliptic. The ecliptic is tilted by 23.5$^o$ with respect to the celestial equator (due to the tilt of Earth's axis of rotation) and cuts the celestial equator at two points which correspond to the Equinoxes [13]. The Vernal equinox ($\gamma$) is the equinox which happens on the 21st of March, when the Sun is traveling from the south of Celestial equator to the North. About 2000 years ago, the vernal equinox was located in the direction of the Aries Constellation, whereas, due to the precession of the Earth's axis, it is now in Pisces [14].

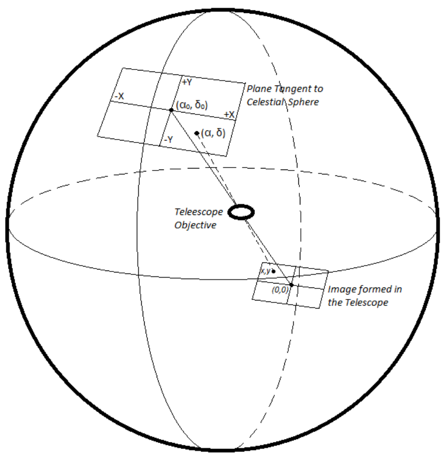


**Figure 3**. The CCD chip or the photographic plate of the telescope receives a projection of the Celestial Sphere. The Standard Coordinates on the plane tangent to the Celestial Sphere as well as the pixel coordinates on the CCD chip are shown [1].

The Equatorial Coordinate system is analogous to the longitude-latitude system of the Earth. Declination ($\delta$) or DEC is similar to latitude with the unit of measurement being degrees, arcminutes & arcseconds. Every object to the North of the celestial equator has positive declination, with the North celestial pole having the maximum declination of +90$^o$ 0' 0". Every object to the South of the celestial equator has negative declination, with the South celestial pole having the minimum declination of -90° 0' 0". Right Ascension ($\alpha$) or RA is similar to longitude and it is measured in units of hours, minutes & seconds, in which, 24 hours is equivalent to 360°. The RA of an object is measured by starting from the vernal equinox, moving eastward in line with the celestial equator, up until it intersects with the great circle that passes through the object and the north celestial pole [3].

### 3.2 *Standard Coordinates*

To define the Standard Coordinates, let us take a plane tangent to the celestial sphere at the point ($\alpha_o$, $\delta_o$), as shown in Figure 3. The X-axis coincides with the right ascension ($\alpha$), the Y-axis with declination ($\delta$) and the origin corresponds to the point of tangency.

A simple way to imagine this would be, to think of a flat sheet of cardboard in contact with a centrally illuminated hollow globe, at a point on the outer surface. Added to this, the opaque globe has small holes representing stars. The points on the flat cardboard, on which the light falls through the holes, represent the location of the stars in terms of Standard Coordinates. This geometry is known as the gnomonic projection [2].

Knowing the RA ($\alpha$) and DEC ($\delta$) of a star, we can determine the standard coordinates on the plane tangent to the celestial sphere at the point ($\alpha_o$, $\delta_o$) [1], using the equations:

$$X = \frac{cos(\delta)sin(\alpha - \alpha_o)}{cos(\delta_o)cos(\delta)cos(\alpha - \alpha_o) + sin(\delta)sin(\delta_o)} \tag{1}$$

and

$$Y = \frac{sin(\delta_o)cos(\delta)cos(\alpha - \alpha_o) - cos(\delta_o)sin(\delta)}{cos(\delta_o)cos(\delta)cos(\alpha - \alpha_o) + sin(\delta)sin(\delta_o)} \tag{2}$$

From the standard coordinates we can obtain the RA and DEC using:

$$\alpha = \alpha_o + tan^{-1}\left(\frac{X}{cos(\delta_o) - Y sin(\delta_o)}\right) \tag{3}$$

and

$$\delta = sin^{-1}\left(\frac{sin(\delta_o) + Y cos(\delta_o)}{\sqrt{1 + X^2 + Y^2}}\right) \tag{4}$$

## 4. Methodology

The method to determine the Right Ascension and Declination of objects in the observed field is a simple four step process but requires utmost precision and patience because all consequent analysis depends heavily on this step. The aspect of paramount importance in this process is the determination of the "transformation" between pixel coordinates of the image obtained by the telescope and their corresponding equatorial coordinates.

The process begins with the identification of a group of stars (reference stars) in the image for which the [RA, DEC] coordinates are already known accurately. Next, one must determine the pixel coordinates of these reference stars in the image, which will be in terms of [x, y]. Using the results from these two steps, we formulate the crucial transformation required to obtain the [RA, DEC] for a given [x, y]. Finally, we apply these transformations on the pixel coordinates of the objects of interest to determine their respective equatorial coordinates. [15]

### 4.1 *Plate Constants*

After taking an astrometric image, the computer reads the charged couple device (CCD) chip and the positions of stars is measured in terms of their pixel positions [x, y]. Ideally, there is perfect alignment between the RA & DEC axes and x & y axes. Added to this, the equatorial coordinates for the perfect center of the image ($\alpha_o$, $\delta_o$) is known. With the pixel dimensions available, one can convert the pixel positions into units of millimeter. Furthermore, in principle, if the focal length (F) of the telescope is known, one can easily convert these pixel coordinates into standard coordinates (discussed in §3.2) using:

$$X = \frac{x}{F} \ \& \ Y = \frac{y}{F} \tag{5}$$

After which by using (3) & (4) one can obtain the equatorial coordinates of the objects of interest.

Practically, it is difficult to obtain the exact center of the image and there are high chances of x & y axes being tilted with respect to the RA & DEC axes. Added to this, there might be a slight tilt in the detector with respect to the incoming light and the dimensions of each pixel may vary with changes in temperatures. Therefore, instead of accounting for every error that can exist, we can employ a general linear transformation between the pixel coordinates and the standard coordinates [1]:

$$X = ax + by + c \ \ \& \ \ Y = dx + ey + f \tag{6}$$

In these equations a, b, c, d, e & f are termed as the Pate Constants.

After identifying the reference stars in the image in terms of their pixel coordinates (x, y), their RA & DEC ($\alpha$, $\delta$) values are converted to the standard coordinates (X, Y) using (1) & (2). In principle, a minimum of three reference stars are required so that one can obtain (6) for each of those stars, which will give three equations for three unknowns. By solving these linear equations, the plate constants can be determined.

Practically, one must have a lot more than just three reference stars in their image. This allows for better accuracy in determining the plate constants by using the linear least squares method for an overdetermined system (the number of data points producing equations are higher than the number of unknowns). For the reference stars there will be a small difference between the actual standard coordinates obtained using the already known RA & DEC ((1) & (2)) and the standard coordinates obtained using the transformations (plate constants) on the pixel coordinates (6).

Essentially, in the linear least squares method, all reference stars are taken together and the plate constants are determined in a way such that the sum of the squares of the difference (between known and computed values) is the least possible value. After obtaining the new plate constants, using the standard deviation between the known and computed values of the standard coordinates of reference stars, the magnitude of errors can be calculated.

### 4.2 *Determining the Equatorial Coordinates*

After obtaining the plate constants, either by using three reference stars or by employing least squares method for more than three stars, the object positions in the equatorial coordinate systems can be determined from their pixel positions.

Taking objects in the image individually, in (6) all the quantities on the right hand side are known, hence X & Y can be determined.

Finally, by using the equatorial coordinates of the image center $(\alpha_o, \delta_o)$ and the standard coordinates (X, Y) of the objects of interest, their corresponding equatorial coordinates can be determined using (3) & (4).

## 5. Analysis

We employed this astrometric technique in our analysis of young open clusters, which is elaborated below.

### 5.1 *Young Open Clusters*

An Open cluster is a group of stars that originate in the same molecular cloud. Currently, they have meager amounts of molecular gas and are not forming new stars. Therefore, the term open cluster epitomizes a group of stars which have similar ages and are at approximately the same distance from Earth [11].

Young open clusters are the perfect laboratories to test our knowledge on star formation, including, the pre-main sequence evolution. Due to the common distance and chemical composition of the cluster members, it is relatively easier to determine the distance to the cluster as well as the average interstellar extinction, following which all other fundamental properties such as spectral type, age, stellar radius, surface temperature, etc. can be obtained. These fundamental properties of the member stars are crucial for further analytical studies on them.

### 5.2 *Astrometry on Young Open Clusters*

We used archival data to obtain information on young open clusters, so as to identify and study the evolution of pre-main sequence stars in them. We used the WEBDA [16] database to obtain their optical UBV magnitudes and the 2MASS database [10] to obtain their near-infrared (NIR) $JHK_s$ magnitudes.

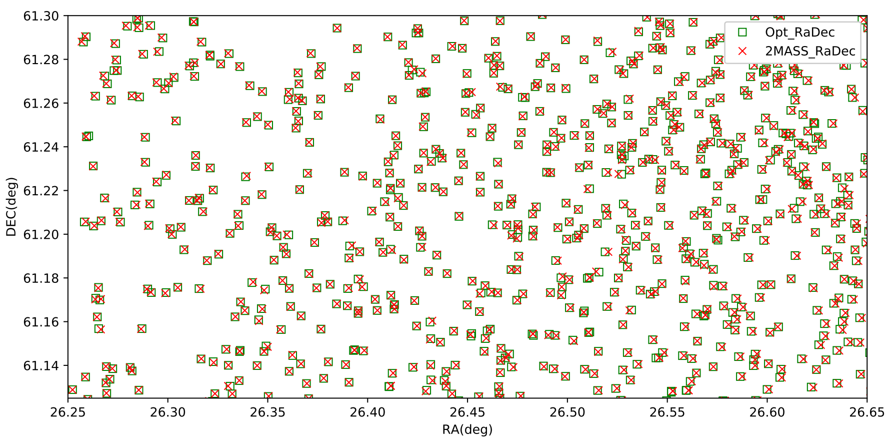


**Figure 4**. Result of cross-correlating optical and infrared sources for the open cluster NGC 663. Green squares are the equatorial coordinates of the optical sources obtained from their pixel coordinates using astrometric principles. Red crosses are the infrared sources obtained from the 2MASS catalog.

For many clusters, WEBDA gives us only the pixel coordinates of the cluster members. Moreover, 2MASS provides the equatorial coordinates for all the sources in the cluster field of view. To conduct any further analysis, we must first cross-correlate the positions of the optical sources (cluster members) with the NIR sources so as to obtain the complete information of each cluster member.

In order to cross-correlate, we must first convert the pixel coordinates of the optical sources from WEBDA into their corresponding equatorial coordinates. To achieve this we wrote a program using Python, incorporating the astrometric procedure, as explained above. After this, we cross-correlated the optical sources with the infrared sources and obtained the UBVJHK$_s$ magnitudes of the cluster members. In Figure 4, we show the results of such a cross-correlation for the cluster NGC 663, after converting the pixel coordinates of the optical sources into equatorial coordinates. We obtained the optical magnitudes for this cluster from Phelps and James [9].

This article is mainly written to make the reader appreciate one of the simplest methods of astrometry, so that he/she can realize the importance of every step involved in observing and then analyzing stellar bodies. Since this method employs linear transformation instead of accounting for every error that can occur during observations, it does not give milliarcsecond accuracy.

## 6. Conclusion

The principles of astrometry form the foundation upon which the field of observational Astronomy is built. Knowing the positions and motions of celestial bodies is essential to obtain their fundamental properties and develop a deeper understanding of them.

Reference frames play a crucial role in increasing the accuracy of our position and motion measurements. Since all bodies in the universe are in constant motion, it is imperative that we understand their motions and correct for the errors that arise in using them as fiducial points in our reference frames. Since the ICRF is based on 212 extragalactic compact sources, the motions of these bodies are negligible (few microarcseconds) when compared to the motion of bodies in the Milky Way. The current reference system has enough number of fiducial points spread across the entire celestial sphere which makes it possible to access the reference frame from any part of the celestial sphere.

Currently, since all telescopes use CCD chips for photometric observations, it is essential for the observer to understand the techniques by which one can obtain the equatorial coordinates from the pixel coordinates, so that one can calculate the appropriate errors involved. The key aspect of astrometry is to determine the most accurate transformation between the two coordinate systems. In determining this transformation, reference stars with the most accurate equatorial coordinates must be used.

**Acknowledgments**

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**References**

[1] R. Berry and J. Burnell, *The handbook of astronomical image processing*. 2005.
[2] M. R. Calabretta and E. W. Greisen, "Representations of celestial coordinates in FITS", *Astronomy and Astrophysics*, vol. 395, pp.1077–1122, December 2002.
[3] B. W. Carroll and D. A. Ostlie, *An Introduction to Modern Astrophysics*. 1996.
[4] W. Fricke and A. Kopff. *Fundamental Catalogue (FK 4)*. 1963.
[5] W. Fricke, H. Schwan, T. Lederle, U. Bastian, R. Bien, G. Burkhardt, B. Du Mont, R. Hering, R. Jährling, H. Jahreiß, S. Röser, H.-M. Schwerdtfeger, and H. G. Walter, *Fifth fundamental catalogue (FK5). Part 1: The basic fundamental stars*, Veroeffentlichungen des Astronomischen Rechen-Instituts Heidelberg, vol. 32, pp.1–106, 1988.
[6] K. J. Johnston and Chr. de Vegt, "Reference frames in astronomy," *Annual Review of Astronomy and Astrophysics*, vol. 37, no. 1, pp.97–125, 1999.
[7] J. Kovalevsky, I. I. Mueller, and B. Kolaczek, editors. *Reference frames in astronomy and geophysics*, Astrophysics and Space Science Library, vol. 154, 1989.
[8] B. G. Marsden, "How to reduce plate measurements," *Sky and Telescope*, vol. 64, pp.284, 1982.
[9] R. L. Phelps and K. A. Janes, "Young open clusters as probes of the star formation process. 1: An atlas of open cluster photometry," *Astrophysical Journal Supplement Series*, vol. 90, pp.31–82, January 1994.
[10] M. F. Skrutskie, R. M. Cutri, R. Stiening, M. D. Weinberg, S. Schneider, J. M. Carpenter, C. Beichman, R. Capps, T. Chester, J. Elias, J. Huchra, J. Liebert, C. Lonsdale, D. G. Monet, S. Price, P. Seitzer, T. Jarrett, J. D. Kirkpatrick, J. E. Gizis, E. Howard, T. Evans, J. Fowler, L. Fullmer, R. Hurt, R. Light, E. L. Kopan, K. A. Marsh, H. L. McCallon, R. Tam, S. Van Dyk, and S. Wheelock, "The Two Micron All Sky Survey (2MASS)," *The Astronomical Journal*, vol. 131, pp.1163–1183, February 2006.
[11] S. W. Stahler and F. Palla, *The Formation of Stars*. 2005.
[12] H. G. Walter and O. J. Sovers, editors. *Astrometry of fundamental catalogues: the evolution from optical to radio reference frames*. 2000.
[13] http://astronomy.swin.edu.au/cosmos/E/Ecliptic
[14] http://astronomy.swin.edu.au/cosmos/V/Vernal+Equinox
[15] http://www.gb.nrao.edu/ glangsto/SIP/astrometry.html
[16] https://www.univie.ac.at/webda/navigation.html