POST-IAU-2000 NOMENCLATURE FOR THE TELESCOPE POINTING APPLICATION

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ABSTRACT. Pointing a telescope (or radio antenna) at celestial sources is, by the usual fundamental-astronomy standards, a rather low-accuracy application. Predictions of only 100 mas accuracy would in most respects be adequate, and this is well within the capabilities of even the pre-2000 models and procedures. However, the positional-astronomy part of the pointing application involves a long chain of transformations and corrections that has to be understood both by the astrophysicists who will use the telescope and by the engineers who will develop the control systems. These users, as well as being non-specialists in positional astronomy, have, with few exceptions, encountered only the old equinox-based methods. In addition, considerations of real-time computing efficiency usually make it necessary to calculate different effects and coordinates at different rates, rather than a straightforward end-to-end transformation for a given moment in time, introducing the need to label various "in-between" coordinates. All of these factors make telescope pointing a good test case for the post-IAU-2000 nomenclature. How easy is it to describe to a non-specialist how to point a telescope, and does the introduction of the new paradigm help or hinder this elementary task?

1. INTRODUCTION

Typical astronomical telescopes and antennas have mountings that consist of two rotating axes (generically *roll* and *pitch*) at right angles to one another, with the telescope or radio dish fixed to the pitch axis and at right angles to it. The most common configurations are *equatorial,* where the roll axis is parallel to the Earth's axis, and *altazimuth,* where the roll axis is vertical.

In essence, "pointing" means choosing roll and pitch angles—hour angle and declination in the case of an equatorial, azimuth and altitude in the case of an altazimuth—that bring the telescope or antenna into alignment with a specified celestial target. The process begins with *acquisition;* maintaining alignment as the Earth rotates is called *tracking.* Various techniques exist for high-accuracy acquisition and tracking, including dead reckoning, the use of finding charts, offsetting from an astrometric reference star, and autoguiding. The telescope's pointing control software also has to support the data acquisition system, by recording what part of the sky was being observed. This topic is called *world coordinate systems* (WCS), and in particular enables pixel coordinates (i, j) to be transformed into (α, δ) during subsequent data analysis. The accuracy requirements for WCS can be quite stringent, for identifying sources and overlaying pictures taken by different telescopes.

Telescope pointing is a good test case for positional-astronomy nomenclature schemes, for several reasons:

- The accuracy requirements, and hence the demands on the nomenclature scheme, are reasonable.
- On the other hand the application spans a wide range of transformations, with exposed intermediate stages.
- Typical users are not fundamental-astronomy experts.

2. THE APPLICATION AND ITS USERS

No existing groundbased telescope achieves dead-reckoning pointing better than about 2 arcseconds operationally, though some do considerably better than this in an *a posteriori* sense for the 1-2 hours it takes to perform an all-sky pointing test. Thus the control system's calculation of pointing direction could neglect effects below, say, 0.5 arcsec without much damage. However, relative accuracy needs to be better, say 1 mas, for reliable blind offsetting and to avoid digital noise when calculating tracking rates etc. In practice, there is a lot to be said for implementing the astrometric side of a telescope control system rigorously and completely. Validation is easier, there is more headroom and the application is future-proofed; moreover, with careful software design and modern computer hardware the extra computation is not an issue. However, for operational simplicity, most telescope control systems neglect polar motion (let alone IERS corrections to nutation); however, UT1−UTC is essential unless, for an equatorial mount, the old-fashioned "clock star" approach is taken to introduce an *ad hoc* hour-angle zero-point correction at start-up.

The target audience for the nomenclature scheme comprises:

- The telescope users themselves, typically astrophysicists but increasingly service observers. For the most part, the only celestial coordinates they use are ICRS, synonymous with FK5 and/or J2000 to the required accuracy. They also need to know in broad terms where their targets are, in particular the zenith distance (or air mass), so that scheduling decisions can be made in real time.
- The engineers and programmers who create and maintain the telescope control systems. They need to understand all the steps that lie between ICRS (α, δ) and telescope axis encoder readings.

Few of these people are will have heard of the IAU 2000 resolutions. They will have encountered only equinox/ST methods, even then with only a rudimentary grasp of the general principles, and will need to be persuaded that there are benefits in changing to a new scheme.

3. HOW TO POINT A TELESCOPE

Figure 1 shows the main components of a telescope pointing algorithm. The starting point is the catalog position of the science target, for example a star. Through a series of astrometric transformations, the *observed* azimuth and altitude (az,alt) are predicted, i.e. where a perfect theodolite would have to be pointed to see the star. The inputs to the transformation process include the time, UT1−UTC, the site location and the ambient air conditions (for refraction; for optical/IR the color is also needed). Once the observed (az,alt) is known, the mechanical properties of the telescope and mount can be allowed for—zero points, misalignments, flexures etc.—plus in more sophisticated control systems the desired focal-plane coordinates of the image.

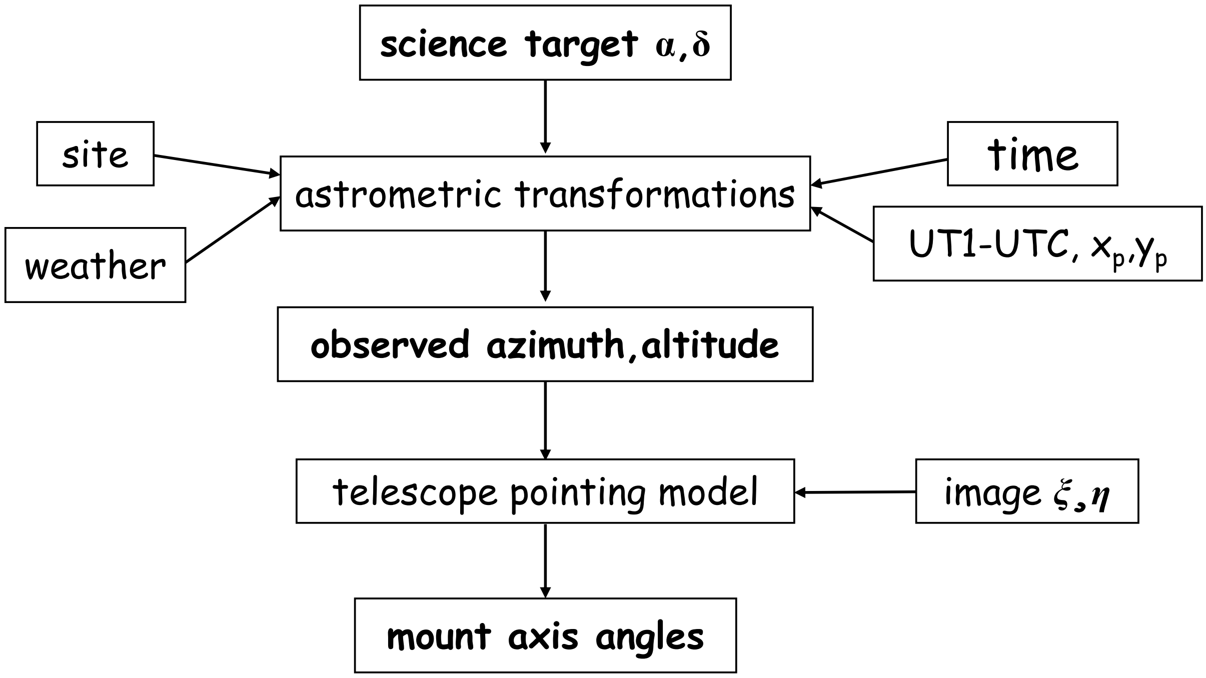

Figure 1: Telescope pointing algorithm.

The result is the mount-axis encoder readings required to acquire the image of the target. Final setting, and guiding, involves small *ad hoc* manual corrections either to the target (α, δ) or (usually more appropriate) to selected terms in the pointing model.

The entire transformation scheme has to be executed sufficiently often to keep the telescope tracking smoothly and responsive to guiding inputs, typically 10-20 times per second. Modern computers are so fast that the entire pointing calculation could be done at the full rate. But it is still usual to re-compute precession and nutation only occasionally, for example for each new target. In general, star-independent quantities—Earth ephemeris, precession, refraction etc.—can be refreshed infrequently; only Earth rotation is time-critical. All of this means that various sorts of interim coordinates are present in the software and must be clearly labelled.

4. ASTROMETRIC TRANSFORMATIONS

Figure 2 shows the sequence of transformations that take a star catalog entry and predict the where in the sky to point the telescope. Apart from certain preliminaries, the sequence corresponds to the box in Figure 1 labeled "astrometric transformations".

The starting point, **CATALOG** $(\boldsymbol{\alpha}, \boldsymbol{\delta})$, may include proper motion and parallax (and radial velocity) in addition to the star's coordinates at the catalog epoch[1]. The first step in the sequence of transformations is needed only for the case where the catalog epoch is not already J2000, and allows for space motion from the catalog epoch to J2000, to give the **INTERNATIONAL CELESTIAL REFERENCE SYSTEM** $(\boldsymbol{\alpha}, \boldsymbol{\delta})$**, epoch J2000**. A position from, say, the Tycho-2 catalog is already in this form. This step would be part of the preparation for acquiring

[1]ICRS is assumed here; demand by observers for FK4, FK5, and equinoxes other than 2000.0 has in practice all but disappeared and can in any case be dealt with pre-observation. Catalog epoch is normally J2000.0, but the Hipparcos catalog and the original Tycho catalog are epoch J1991.25, a fruitful source of mistakes. Proper motions are another minefield: both annual and centennial values are found, while RA proper motions may use time or arc measure and can either be $\dot{\alpha}$ or $\dot{\alpha}\cos\delta$.

CATALOG [α,δ]
proper motion, catalog epoch to J2000
INTERNATIONAL CELESTIAL REFERENCE SYSTEM [α,δ], epoch J2000
proper motion, J2000 to date
(barycentric) ICRS [α,δ] of date
annual parallax
ASTROMETRIC [α,δ]
light deflection
annual aberration
GEOCENTRIC ICRS [α,δ]
frame bias
precession
nutation
CELESTIAL INTERMEDIATE REFERENCE SYSTEM [α,δ]
Earth rotation
TERRESTRIAL INTERMEDIATE REFERENCE SYSTEM [λ,φ]
polar motion
ITRS / GREENWICH [h,δ]
site longitude
diurnal aberration and parallax
TOPOCENTRIC [h,δ]
h,δ to az,alt
TOPOCENTRIC [az,alt]
refraction
OBSERVED [az,alt]

Figure 2: The ICRS-to-observed transformation sequence.

a new target and would be performed just once. The same is in practice true for the second step, where proper motion from J2000 to date is applied, though on some telescopes it is part of the tracking loop for the sake of rigor. In Figure 2, the resulting coordinates are called the **(barycentric) ICRS (α, δ) of date**. There is at the time of writing some disagreement about whether such coordinates can be labeled "BCRS". I have taken the view here that it is unwise to use this term outside its metric tensor meaning, and to recognize that there is no preferred spatial axis directions in BCRS (Soffel et al., 2003). Using the ICRS label also has the advantage that telescope users and engineers will recognize the term, whereas BCRS (and GCRS) will be new to them. The next step is to allow for annual parallax, thereby changing the viewpoint to the geocenter and producing the *coordinate direction* of the target. Note that this step has eliminated the final distinction between the star and any other source outside the solar system. It is useful to label the result the **ASTROMETRIC (α, δ)**. even though this has a tautological flavor.

The coordinate direction is next transformed into the *natural direction* by allowing for the path of the light ray through the solar system. For telescope pointing applications, only the Sun's gravitational field need be included, and even then the effect becomes appreciable only very close to the Sun. Finally, the star's direction as seen by a geocentric observer is obtained by allowing for annual aberration. In Figure 2, the resulting *proper direction* is labeled **GEOCENTRIC ICRS (α, δ) of date**. The alternative would be to say "GCRS", but the same arguments apply as for BCRS (see above). The adopted term *geocentric ICRS* may not be destined to receive official recognition but is at least self-explanatory: compared with plain ICRS, the orientation of the coordinate triad has not changed, but the viewpoint has.

We now reach the set of transformations that reflect the attitude and orientation of the Earth in space. The first step is to rotate the coordinate triad so that it aligns with the celestial intermediate pole (CIP) of date and the celestial intermediate origin (CIO) of date[2]. The components of this transformation are the frame bias, precession and nutation, and there are various ways of computing it (Capitaine et al. 2004). The result is the **CELESTIAL INTERMEDIATE REFERENCE SYSTEM** $(\boldsymbol{\alpha}, \boldsymbol{\delta})$ of date.

The transition from slowly-changing celestial coordinates to rapidly-changing terrestrial coordinates occurs when the coordinate triad is turned about its z-axis through the Earth rotation angle (ERA) to produce the **TERRESTRIAL INTERMEDIATE REFERENCE SYSTEM** $(\boldsymbol{\lambda}, \boldsymbol{\phi})$. After the small supplementary re-orientation to take into account the tiny quantity s' and the polar motion, the resulting vector is in the **INTERNATIONAL TERRESTRIAL REFERENCE SYSTEM** and corresponds to the point on the Earth at which the star is in the zenith or, equally well, the **GREENWICH** $(\boldsymbol{h}, \boldsymbol{\delta})$, with due regard to the hour angle sign convention. By rotating the triad about z through the site longitude, and, depending on accuracy objectives, the diurnal aberration,[3] we reach the **TOPOCENTRIC** $(\boldsymbol{h}, \boldsymbol{\delta})$. Transformation from equatorial coordinates to azimuth and altitude requires the site latitude, ϕ, to give **TOPOCENTRIC** $(\boldsymbol{az}, \boldsymbol{alt})$. and finally atmospheric refraction (a function of pressure, temperature and humidity at the telescope and, in the optical/IR case, color) is applied to give the **OBSERVED** $(\boldsymbol{az}, \boldsymbol{alt})$. This is the direction in which the telescope or antenna must be pointed. It differs from the actual settings of the mount because of mechanical misalignments and distortions, and the location in the focal plane to which the image is to be delivered. These corrections are typically some tens or hundreds of arcseconds in size. See Wallace (2002) for details.

5. CONCLUDING REMARKS

The scheme outlined above complies for the most part with the latest nomenclature recommendations, is as complete as the application requires and is no harder to grasp than its classical predecessors. But there are a few reservations:

- At the time of writing, opinion is moving towards adopting "BCRS" and "GCRS" as labels for the respective spatial coordinates. These names really apply to metric tensors and are about the computation of intervals in spacetime: applying them to spatial coordinates is at best informal and at worst misleading.

- The term "astrometric place" is used here in a way which corresponds to a plain-English meaning but not to published definitions, which mention aberration but not light deflection. There is a need to change the official definition so that future astrometric places include stellar light deflection, even for nearby objects such as minor planets. The concept is that the astrometric place is the point on the distant background occulted by the nearby object.

- In "CIRS", the word "intermediate" is weak. Although it identifies the link to the CIP and CIO, it fails to highlight the most noteworthy aspect of these coordinates, namely that

[2]It is equally valid to use the true equinox instead of the CIO, in which case apparent sidereal time will replace Earth rotation angle later on.

[3]. . . and in principle the diurnal parallax. Note that transforming from barycentric to topocentric with no intermediate geocentric stage would remove the need for a diurnal aberration step; however, from some points of view, general-purpose software and almanac tabulations for example, working via the geocenter has advantages.

they are moving because of precession-nutation. Some form of words such as "the CIRS place, i.e. the RA,Dec of date" can be employed to augment the bald label. Or perhaps the word "instantaneous" could be revisited, by a happy coincidence also beginning with "I".

- In the scheme presented, "geocentric ICRS" is taken to mean that the effects of parallax, light deflection and aberration have been included (similarly GCRS versus BCRS if these labels are eventually adopted). Is this acceptable given that the spatial axes and the path of a light ray are really quite separate matters? Would it perhaps be better to label the triad (ICRS) and then identify the light direction (coordinate, natural, proper) separately?

However, it should not be forgotten that the classical names, though familiar, are baffling to beginners. Are "mean place", "true place", "apparent place" really self-explanatory, and how many practising astronomers could give a convincing definition of each of them? What about "virtual place"? How frequently is "epoch" used when "equinox" is meant? What do students make of the "equation of the equinoxes". Or "uniform equinox"?

Whatever the relative merits of the classical and new paradigms, there is no doubt that "selling" will be needed before the new paradigm becomes properly established. Existing descriptions of the new paradigm tend to focus on the CIO, which because it is kinematically defined is a subtle and confusing change to existing approaches. A better idea is to start instead with Earth rotation angle. The superiority of the two-coefficient ERA(UT1) formula over the complicated and messy GAST(UT1,TDB) expressions is quite obvious; the fact that adopting ERA requires a change in the definition of the RA zero-point no surprise; and the actual location of the CIO, for telescope pointing purposes (in fact to better than 0.1 arcsec for another century) where the ICRS prime meridian crosses the equator of date, easy to remember.

Further reassurance comes from realizing that if the observatory's sidereal clock is set to local ERA, and CIRS coordinates are used instead of apparent places, everything still works as expected. Moreover, whereas observers at present can get a rough estimate of the hour angle from $h \simeq LST - \alpha_{J2000}$, they will in fact get a slightly better result from the new-paradigm equivalent, $h \simeq LERA - \alpha_{ICRS}$.

6. REFERENCES

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