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TELESCOPE SYSTEMS AT LICK OBSERVATORY AND KECK OBSERVATORY

Steven L. Allen [*]

The telescopes in active use at Lick Observatory and Keck Observatory were constructed over an interval spanning more than a century. All of the telescope systems were designed in an era when systems which provide civil time were based on the rotation of the earth. Existing software systems for the control of telescopes at Lick Observatory and Keck Observatory use UTC as a close approximation to UT1. If UTC abandons leap seconds then ongoing operation will require various strategies suitable for each different telescope.

INTRODUCTION

The 400 years of telescope history have seen huge changes in the practices and technologies. The pointing of telescopes has changed considerably. Early observers like Galileo casually aimed their small telescopes. Teams of laborers pulled ropes to hoist the framework holding their lord's large telescope and their lord himself. Iron workers produced large bearings and gears for precision equatorial mountings with clock drives that modelled the rotation of the earth. Now robotic control engineers build alt-az telescopes whose operation depends entirely on models in software. Obtaining the desired pointing results during interaction with the models in these systems involves algorithmic conventions about earth and sky.

COORDINATE REFERENCE SYSTEMS AND FRAMES

Human commerce is facilitated when all parties agree on the meanings of the words describing products and procedures. The late 1800s saw trans-continental railways and trans-Atlantic telegraph cables making new connections between communities with little previous contact. One of the efforts to standardize human endeavor was the International Meridian Conference of 1884.[1] The Prime Meridian at Greenwich was one terrestrial result of the conference, but the resolutions also prescribed conventions for the measurement of time as a subdivision of calendar days.

Technical details of the implied metrology were not specified by the diplomats at the conference. Among the practitioners of the metrology was Simon Newcomb who had the funding of the US government along with the data from the the American and European observatories. Before the end of the century he had overseen calculations to produce mathematical expressions of celestial motions[2] so impressive that all the directors of national ephemerides agreed to use them.

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[*] UCO/Lick Observatory, 1156 High Street, Santa Cruz, CA 95064

Astronomical changes over the past century

Shortly after the 1919 formation of the International Astronomical Union (IAU) the national ephemerides changed their tabulations of time to conform with the 1884 International Meridian Conference resolution that the Universal Day should be reckoned from midnight. In an effort to avoid confusion the American almanac engraved a warning paragraph on its cover.[3] To the chagrin of many, the British Admiralty insisted on keeping the same name, GMT, even though it had formerly been used for time reckoned from Greenwich mean noon. This resulted in an IAU decision to replace GMT with Universal Time (UT),[4] a change of nomenclature with no effect on telescope pointing.

Despite its non-relativistic basis, errors known at the time of adoption, and the discovery of earth rotation variations, time service bureaus used Newcomb's 1895 expression for UT across almost 90 years. Atomic chronometers, digital computers, satellite geodesy, very long baseline interferometry (VLBI), and Lunar Laser Ranging (LLR) contributed to new metrology technologies. These revealed serious deficiencies in existing models and motivated a new expression for UT1 starting in 1984, but its authors took great care to match the new definition to the old one.[5] Existing telescope systems did not need a large change in procedures for handling celestial coordinates.

At the turn of the 21s century ongoing measurements with high-precision technologies led to another, newer definition of UT1 that does not need the concept of equinox.[6] This change is accompanied by a complete change of the underlying concepts for celestial coordinates.[7] These IAU 2000 changes are essential for the precisions required with VLBI, LLR, interplanetary navigation, timing of phenomenon, etc. For the pointing requirements of optical telescopes, however, there will be little discernible difference before the end of the 21st century.

Pedagogical aspects

At the beginning of the 20th century the underlying concepts of astrometry had not changed much since Ptolemy. By the end of the 20th century the underlying concepts had been completely changed twice within the span of a productive career. A rate of change like that obsoletes procedures, software, and human expertise. It produces a strong need to review the pedagogical resources and their limits of validity.

The textbook from Smart contained the same kinds of haversine table look-ups used by navigators for the preceding century.[8] The *Explanatory Supplement*[9] encapsulated the early changes to procedures which preceded use of the FK5 system in 1984.

Texts from Murray[10] and Green[11] gave early treatments for new methods for computing and the FK5 conventions. The new *Explanatory Supplement*[12] covered the FK5 conventions in detail, but only a few years later those were replaced by the sweeping changes of the IAU 2000 conventions. Aside from the problem of old texts, some texts contain errors, and students who learned from any of these may continue to employ old concepts and algorithms for the duration of their career. This unfortunate truth is a strong argument for changes in the conventions and definitions to be as inconsequential as possible.

Calculations using the current IAU 2000/2006 framework are described by USNO Circular 179,[13] Wallace and Capitaine,[14] and in the IERS Conventions.[15] These are useful documents until such time as the next revision of *Explanatory Supplement* appears.

Astrometric software

The original complexity of astrometric calculations was within the capability of a trained human navigator with a book of mathematical tables. The complexity of the current conventions exists because of digital computers but the algorithms require expertise not likely to be found in many programmers. As a result most current computations for telescope pointing rely on libraries of algorithms used widely across the astronomical community. One early example for the FK4 and FK5 systems is the Starlink Library for Astronomy (SLALIB).[16] For the IAU 2000/2006 conventions the IAU fostered the Standards of Fundamental Astronomy (SoFA) effort.[17][*] The USNO provides another implementation in its Naval Observatory Vector Astrometry Software (NOVAS)[18] which is completely free of intellectual property issues.[†]

TELESCOPE POINTING OPERATIONS

UCO/Lick observatory operates the telescopes on Mt. Hamilton in California and collaborates to oversee the operation of the Keck telescopes in Hawaii. Here is a quick survey of the effects we would see in the absence of leap seconds, along with some strategies for continuing operations.

Lick refractor

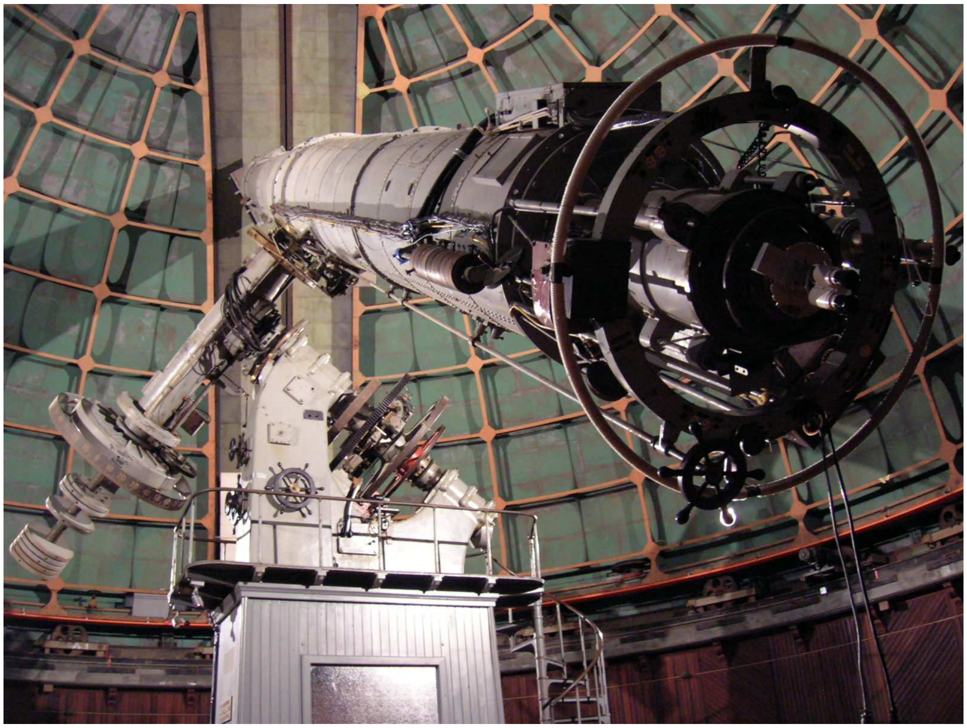

Figure 1. The 36-inch James Lick refractor is pointed by manual effort.

The James Lick telescope on Mt. Hamilton (Figure 1) has a 36 inch objective on an equatorial mount.[19] The Lick, other large telescopes from the 19th century, and many subsequent telescopes

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[*] `http://www.iausofa.org/`

[†] `http://aa.usno.navy.mil/software/novas/novas_info.php`

are pointed using the physical effort of the astronomer. The absence of leap seconds would have no effect on the operation of the Lick telescope.

Shane reflector

The Donald Shane telescope on Mt. Hamilton (Figure 2) has a monolithic 3 m primary in an equatorial mount. The Shane saw first light in 1959. Its original pointing relied on mechanical systems and analog electronics.[20] In the 1970s the analog pointing systems gained digital assistance from an 8-bit 6502 microprocessor. Recent upgrades to the Shane replaced the 6502 with Unix-based "POCO" software on computing hardware with roughly 1000 times greater capability.[21]

All Shane slewing remains under direct control of a Telescope Technician (TT). When a blind slew does not bring a target into the field of the guide camera the TT makes manual corrections based on experience with the telescope. In the absence of leap seconds the TTs could continue to point the Shane for several years without significant degradation.

The source code for POCO belongs to Lick Observatory. POCO employs SLALIB for its astrometry, so within a few decades POCO will need an upgrade to conform to the IAU 2000 conventions. The absence of leap seconds would trigger a need to spend manpower resources upgrading POCO within a few years instead of a few decades. In an era of tight state budgets this is not a welcome change.

Figure 2. The 3-m Shane reflector and the 1-m Nickel reflector have human operators who compensate for pointing problems.

Nickel reflector

The Anna Nickel telescope on Mt. Hamilton (Figure 2) has a 1 m primary in an equatorial mount. The pointing for the Nickel was designed early in the era of digital control systems.[22] For its first 25 years astronomers operated the Nickel from the dome or the adjacent control room. Astronomers slewed the telescope manually, and they could correct pointing errors using the finder scopes.

Recent upgrades to the Nickel added new encoders, motors, and the POCO software. These changes allow astronomers at remote sites to operate the Nickel using the Internet.[23] The field of view of the Nickel telescope guide cameras is about 7 arcminutes, so occasions when the telescope pointing is outside the guide field are uncommon. If the pointing does fail then a local observer or technician must use the finders. These conditions indicate that the requirement to upgrade POCO for the Shane would ensure that the Nickel telescope will never experience pointing problems due to the absence of leap seconds.

Keck reflectors

The Keck telescopes on Mauna Kea (Figure 3) have segmented 10 m primaries in alt-azimuth mounts. The Kecks saw first light in the 1990s. Keck pointing systems rely on software, but all telescope slewing is under direct control of an Observing Assistant (OA). In many cases the Keck telescopes slew to within 7 or 8 arcsec of the target. Pointing may rarely be as much as 40 arcsec off target; in such cases the OA typically locates a nearby catalog star before proceeding to target. Nightlog Tickets during 2011 indicate about 1 hour of observing time lost to pointing issues.[24]

Figure 3. The 10-m Keck reflectors have human operators.

Guide cameras for Keck instruments have fields of view around 3 to 3.5 arcminutes. The absence of leap seconds would begin to affect pointing procedures within a year. The skill of the Keck OAs should be able to handle pointing for several years after that, but in that time the celestial coordinates reported with the science data would become increasingly aberrant.

The pointing source code for the telescopes belongs to Keck. It employs SLALIB for the astrometry. As with the Shane telescope, the absence of leap seconds would trigger a need for Keck to spend manpower updating the pointing code within a few years instead of a few decades.

APF reflector

The Automated Planet Finder (APF) telescope on Mt. Hamilton (Figure 4) has a monolithic 2.4 m primary in an alt-azimuth mount. APF saw first light in 2009. It is intended to perform fully robotic observation without human attendants. The APF telescope and dome were purchased as a complete system of hardware and software. The specification required pointing within 10 arcseconds. The vendor achieved this specification using a commercial GPS receiver to provide time to the telescope software. Lick Observatory does not have the source code for the APF software.

Figure 4. The 2.4-m APF reflector is robotic. Its pointing software will cease to acquire targets within around a year if leap seconds are abandoned.

The robotic operation means there will be no humans on site supplying their skill to correct the pointing. In the absence of leap seconds the APF telescope will fail to meet its specification within the first year. There is no guarantee that the vendor will be available to provide an update for the software. In the absence of leap seconds and new software, several strategies are options for continuing operation of APF.

We could corrupt the input coordinates we provide to the APF telescope software, adjusting the right ascension by the number of missed leap seconds. This has a drawback because the coordinates supplied from the telescope software to the science data files will be wrong. Lick built the science instrument for APF, so we could remedy this by a second hack to our software which receives the output coordinates. Eventually the time offset would grow large enough to displace the notion of zenith, and that would affect the pointing model, but this would not happen during the expected lifetime of the telescope. The result, however, would be confusing if astronomers attempt manual use. Users would have to be trained to perform the right ascension offset before entering targets into the GUI and to expect the coordinates visible in the GUI to be wrong.

The design of the APF software provides a more desirable alternative for handling the absence of leap seconds. This technique relies on the concept of the Ephemeris Meridian originally proposed by Sadler.[25] Although the APF telescope relies on a GPS receiver for time, the telescope pointing software does not use the geodetic coordinates from GPS. The telescope software obtains its geodetic coordinates from a configuration file, and the coordinates are not exposed in any relevant fashion. This fortuitous aspect of the software design means that in the absence of leap seconds we expect to modify the specified longitude of the telescope by the amount of drift in the Ephemeris Meridian resulting from the missing leap seconds. This option is available for APF science because we are only concerned with one coordinate system, the celestial sphere. Many telescopes from the same vendor, however, are used for satellite tracking. The same technique would probably not work for satellite applications because they rely on knowing the relations between both celestial and terrestrial coordinate systems.

CONCLUSION

In the absence of leap seconds the significant difference for the operability of telescopes at Lick and Keck observatories is not the mount nor the software. The critical difference is the role of humans in the operation of the telescopes. The telescopes which remain operated by humans will not be affected for years after cessation of leap seconds. The telescope which is entirely operated through software will be affected within a year after cessation of leap seconds.

The cost of changing software and procedures for the human-operated telescopes will be unwelcome, but straightforward to absorb as a part of routine maintenance during the years before problems arise. For the APF telescope the concept of Ephemeris Meridian allows us to exploit a trivial "hack" to the software system inputs which will not be visible in the data stream. This hack, however, relies on the particulars of assumptions made by its software system designers and on the particulars of its operational goals. It is not reasonable to generalize these cost results to other telescopes and software systems. Every telescope pointing system needs its own analysis.

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