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TRADITIONAL CELESTIAL NAVIGATION AND UTC

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Traditional celestial navigation depends on accurate knowledge of some standard mean time. While transitioning to a time gradually decoupled from the Earth's rotation should present no serious problems for users who actively practice celestial navigation at sea, there are issues concerning possible confusion in the literature, textbooks, and other educational materials already published. Celestial navigation, though a backup of last resort, is still widely taught at maritime academies worldwide and in less formal classes. If DUT continues to be published and disseminated and identified as a simple "watch error," the continuity of textbooks and navigational practice will be maintained.

INTRODUCTION

Traditional celestial navigation is the science or art, or perhaps more properly the *craft*, of finding the position of a vessel at sea using handheld angle-measuring instruments to observe the positions of the Sun, Moon, and brighter planets and stars relative to the observer's horizon. Until about 1927, this subject was known as "nautical astronomy". Following the extension of the methods to air navigation, the less maritime and arguably more poetic name "celestial navigation" has become the preferred name for the subject.

This paper will address the impact of time standards and accurate time on "traditional celestial navigation" employing handheld sextants and non-electronic tools which reached a state of perfection and standardization circa 1960. It has declined drastically in importance in the past twenty-five years, and the overwhelming majority of marine navigation is now done by GPS. Note that automated electronic systems which use astronomical observations, usually in conjunction with inertial guidance systems (including classified military systems), can achieve much higher accuracies and depend more critically on exact time, but these are not the topic of this paper. Also note that astronomical surveying using theodolites and similar instruments achieved a level of accuracy an order of magnitude higher than traditional celestial navigation. While there are still a few practitioners of astronomical surveying, it is generally considered obsolete.

FUNDAMENTAL PRINCIPLE

The fundamental principle of traditional celestial navigation rests on the simplest connection between terrestrial coordinates and the celestial sphere. Any star or other celestial body at some given instant of time marks a specific location on the Earth's surface where that celestial body would be found in the observer's zenith. If we are fortunate enough to observe a bright star or planet, *e.g*. Jupiter, exactly at the zenith, and if we have ephemeris data giving us access to the

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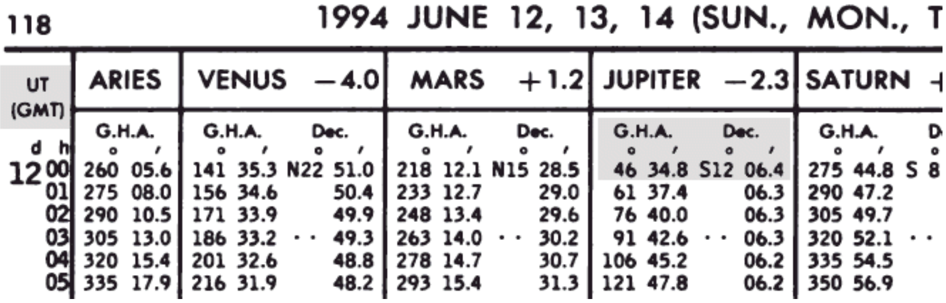
object’s Declination and GHA (Greenwich Hour Angle = the longitude, always measured west, where the celestial object is in the zenith at some instant of time) then we have determined our position without further calculation. The topocentric Declination is equal to the observer’s latitude. The topocentric GHA is equal to the observer’s longitude (Figure 1).



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UT (GMT)	ARIES	VENUS −4.0		MARS +1.2		JUPITER −2.3		SATURN +	
d h	G.H.A. ° ′	G.H.A. ° ′	Dec. ° ′	G.H.A. ° ′	Dec. ° ′	G.H.A. ° ′	Dec. ° ′	G.H.A. ° ′	D °
12 00	260 05.6	141 35.3	N22 51.0	218 12.1	N15 28.5	46 34.8	S12 06.4	275 44.8	S 8
01	275 08.0	156 34.6	50.4	233 12.7	29.0	61 37.4	06.3	290 47.2	
02	290 10.5	171 33.9	49.9	248 13.4	29.6	76 40.0	06.3	305 49.7	
03	305 13.0	186 33.2	· · 49.3	263 14.0	· · 30.2	91 42.6	· · 06.3	320 52.1	· ·
04	320 15.4	201 32.6	48.8	278 14.7	30.7	106 45.2	06.2	335 54.5	
05	335 17.9	216 31.9	48.2	293 15.4	31.3	121 47.8	06.2	350 56.9	

Figure 1. GHA and Declination. Note also that UT and GMT were formerly treated as synonyms.

In practice, for the visual observer using a hand-held instrument, like the traditional marine sextant, stars are never observed exactly in the zenith, and instead zenith distances are acquired by measuring altitudes from the sea horizon. Observed altitudes are corrected for dip and refraction (and a few other corrections specific to the object in question) and then these corrected altitudes may be subtracted from 90 degrees to yield zenith distances. The zenith distance is the distance of the observer away from the tabulated location where the object is in the zenith. So an altitude measurement places an observer on a “circle of position”. At all points along the circle, the observed star would have the same zenith distance. A single altitude observation places the observer at some location along that circle of position. If we observe a pair of stars, then the locations where the circles cross yield the observer’s position fix. There is a minor ambiguity since two circles cross in two points, but these are usually separated by thousands of miles so this is not a practical problem; the navigator is never that lost (Figure 2). Note that the radius of the circle expressed in nautical miles is exactly equal to the corrected zenith distance expressed in minutes of arc. Thus, an error of one minute of arc in a measured altitude yields an error in position of the edge of the corresponding circle of position equal to one nautical mile.

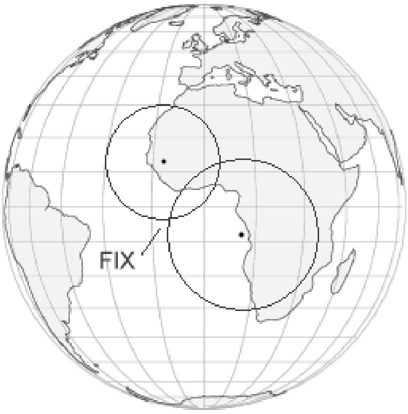


Figure 2. Two circles of position yield a fix.

The idea of the circle of position took hold relatively slowly in the history of celestial navigation. Although we can see that it is fundamental today and though mathematicians understood it from the mid-nineteenth century, practical navigators continued to picture latitude and longitude sights as distinct, separate operations. By contrast, the concept of the circle of position applies to all altitude measurements (Figure 3). Practical navigators began to think in terms of circles of position beginning at the end of the nineteenth century thanks in large part to one of the most influential books in navigation education, S. T. S. Lecky's "Wrinkles in Practical Navigation".[1] According to a reviewer of the third edition, "What Shakespeare is to the player, so is Lecky to the navigator."[2] The emphasis on circles of position was not entirely due to Lecky himself. There was a genius behind the curtain. Lecky was in close correspondence with an accomplished mariner and yachtsman who emphatically believed in the modernization of British navigation methods: the great physicist William Thomson, Lord Kelvin. Kelvin encouraged Lecky to use the language of circles of position, already standard among mathematically-inclined navigators, and to abandon the older explicit separation between latitude and longitude sights. Lecky, thanks to his light-hearted prose, made it palatable to working navigators.

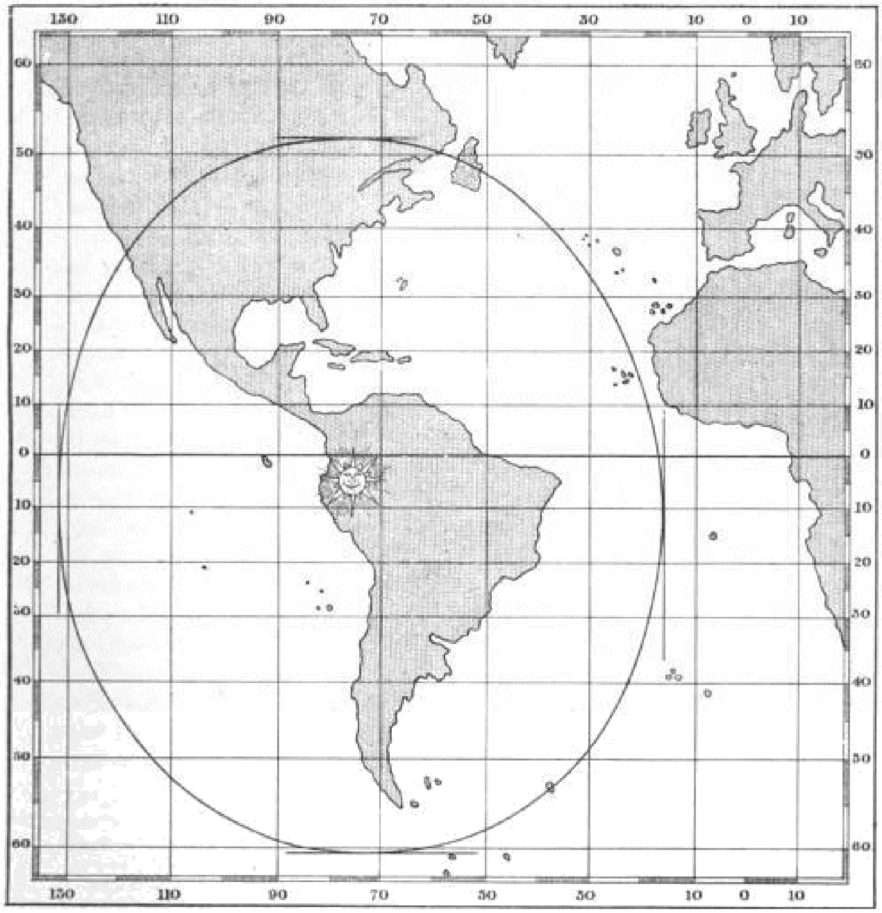


Figure 3. A circle of position from Lecky's "Wrinkles" (1885).

Clearly traditional celestial navigation explicitly depends for its operation on the connection between terrestrial coordinates and therefore Earth orientation and the coordinates of the celestial sphere. As the Earth rotates, the locations where the stars are directly overhead—the centers of those circles of position—travel west at a rate of one minute of longitude in four seconds of time. At the equator, this is equivalent to one nautical mile in four seconds:

$$\text{4 seconds of time} \rightarrow \text{1 nautical mile} \qquad (1)$$

ACCURACY AND ERRORS IN TRADITIONAL CELESTIAL NAVIGATION

Traditional celestial navigation never evolved into a high accuracy method. One nautical mile of accuracy has been considered a reasonable expectation of accuracy, and two or three nautical miles of uncertainty are not unusual or problematic. The accuracy of the method is limited by several factors, primarily terrestrial refraction and instrument errors.

The great majority of celestial navigation observations require the sea horizon as a reference. The sea horizon is typically some minutes of arc below the true horizon. The true horizon is the great circle 90 degrees distant from the observer's zenith while the sea horizon, where the sky meets the sea visually, is depressed below the true horizon by an amount which, in minutes of arc, is very nearly equal to the square root of the observer's height of eye in feet (a case where English units yield a simpler rule than metric units). While introductory textbooks often introduce this as a problem in pure geometry involving a simple plane triangle, this is really a physics problem. Rays of light travelling for some miles near the Earth's surface are deflected downward by refraction. Known as "terrestrial refraction", this has the effect of making the Earth seem larger in radius for all optical experiments performed near the Earth's surface. The terrestrial refraction is variable. It depends on the rate of change of the density of the atmosphere with height in the lowest level of the atmosphere and this in turn depends almost entirely on the temperature *lapse rate* -- the rate at which the temperature in the lower atmosphere falls with altitude. The lapse rate varies with the weather. Therefore the depression of the visible horizon, known to navigators as the "dip" of the horizon, cannot be known in advance. This is the single greatest limiting factor in the methodology of traditional celestial navigation. Altitudes can be measured to an apparent precision of 0.1' of arc using a sextant, but the accuracy is limited to about +/-0.5' depending on the weather. This variability is itself variable. Close to shore, where the navigator is most concerned about an accurate position, the variability of dip can be even greater. Dip anomalies of several minutes of arc are not uncommon close to land. These uncertainties in dip translate directly to uncertainties in position. They are unavoidable.

While the modern metal sextant can be read to a precision of 0.1' of arc, the practical accuracy is frequently lower. The instrument has to be properly adjusted. Mirrors should be set perpendicular to the frame, telescopes parallel to the frame. There are simple, well-known methods to make these adjustments. Many sextants, especially those dusted off in an emergency, will not be properly adjusted, but we will assume for now that they are properly adjusted.

One adjustment always required of any sextant is the "zeroing error" known in celestial navigation as "index error". The sextant combines light from a direct and a reflected pathway allowing the observer to look in two directions at once. This reflecting principle makes the instrument immune to pitching motions, and is responsible for its remarkably high accuracy for a handheld instrument, despite the small errors under discussion here. When the two pathways, direct and reflected are pointed at the same object (distant enough to avoid parallax effects from the distance between the two mirrors) and the direct and reflected views coincide, the instrument should read zero. If it does not, the difference is applied as an "index correction" to all sights. Typical methods for estimating this index correction are accurate to approximately +/-0.25' based on group experiments that I have conducted with experienced students in navigation classes. There are methods for reducing the error in the index correction almost to zero, but they are not widely used.

The modern sextant also suffers from arc error. After the zeroing error or index error has been accounted for, observations may still show small variable errors along the arc. For example, all observations at 30 degrees may show a bias of +0.7' while all observations at 60 degrees may show a bias of -0.4 '. Formerly, these arc errors were tested on optical benches and recorded on certificates kept with each sextant affixed in its case, but today they are usually considered insignificant for practical use. Sextant certificates for some forty years have been ritually marked with strings of zeros and labeled "free of error for practical navigation." There is no meaningful statistical data on the extent of arc error. Unquestionably, it depends on the manufacturer. Anecdotal evidence and tests I have performed suggest that most modern metal sextants have arc errors less than 1.5' for most points along the arc. If measured and tabulated, arc error is a correctable error, not unlike the standard index correction.

Errors in dip and the instrument errors described above together guarantee that the standard deviation error in celestial navigation sights is around 1' leading to errors in the plotting of circles of position of 1 nautical mile. Most practitioners of traditional celestial navigation are happy with errors two or three times larger than this. In the middle of the ocean, such errors are inconsequential. Close to land, the navigator can see that far (when the weather is good, which is, in any case, a pre-requisite for traditional celestial navigation). Practical safety and economy are not compromised. In addition, the "system error" of celestial navigation might be considered much larger since the astronomical methods are only available when the sky is relatively clear and the horizon is distinctly visible. At all other times, the vessel's position is traditionally determined by dead reckoning. Dead reckoning or *DR* is simple, manual, two-dimensional integration of course and speed between fixes (*N.B.*: while the etymology is uncertain, this is not derived from "deduced reckoning" which has become a popular "folk etymology"). Given that skies may be cloudy for days, the combined method of celestial navigation + dead reckoning has total average "system error" at least several times larger than the purely celestial portion of traditional navigation.

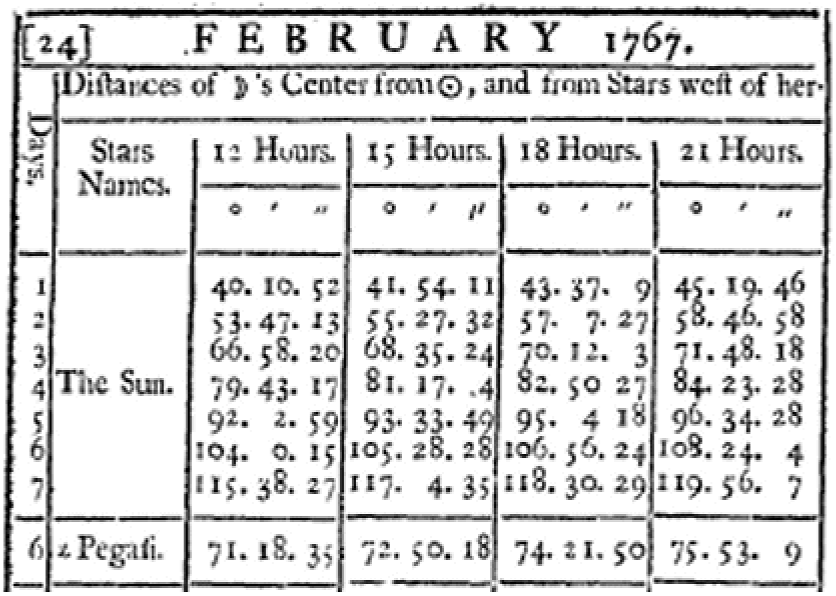
HISTORY OF TIME STANDARDS IN CELESTIAL NAVIGATION

Given the typical errors expected from traditional celestial navigation, errors in UT of one second or even somewhat more do not significantly affect the position fix. A one second error adds an error of 0.25' to the longitude or 0.25 nautical miles for points near the equator. Keeping or carrying time to this level of accuracy once it has been determined by an Internet time check or GPS of shortwave radio time source is a trivial matter today. Common watches can maintain accuracy for months without special care. In this sense, there is no such thing as a "marine chronometer" in the modern world. The care and feeding of the timepiece is a matter of purely historical interest. Cumulative error in a modern watch, once selected, can be ignored. The only error of concern to the modern navigator is drastic watch failure: a dead battery, saltwater in the case, etc. And here the modern navigator is advised to follow the traditional practice dating back to the early nineteenth century: bring two. With two good watches, the navigator can at least detect if one watch is in trouble. And of course, with three or more watches, a bad watch can be ignored or multiple watches can be averaged.

If leap seconds are dropped from UT, that time standard or its descendant under a different name, call it UT*X*, will gradually drift from the alignment required by celestial navigation. For a navigator, this could be counted as a simple "watch error". Before addressing this 21st century issue further, we can consider some of the changes in timekeeping standards that have impacted navigators in the past two hundred years.

Traditional celestial navigators once mastered a daily computation known as "calculating the true time." Today we recognize this as the calculation of Local Apparent Time or LAT. That it was known even in the middle of the nineteenth century as the *true time* reflects the long-standing importance of apparent solar time. This calculation, by the way, determined LAT from the altitude of the Sun measured with a sextant. In effect, it turned a sextant into a highly accurate sundial.

The ancestor of both the modern *Nautical Almanac* (NA) and the *Astronomical Almanac* (AA) was the *Nautical Almanac and Astronomical Ephemeris* (NA&AE) which was rushed into publication starting in 1767 to introduce and facilitate the new *lunar distance* method of determining longitude which had recently become practical thanks to the lunar ephemeris tables of Tobias Mayer and the indefatigable enthusiasm of Nevil Maskelyne. The NA&AE, remarkably, listed all ephemeris data, and especially the lunar distance tables, in terms of Greenwich Apparent Time, GAT (Figure 4). A navigator could directly compare the Greenwich Time derived from lunar observations with the LAT or "true time" observed in his longitude. The difference between the two was the longitude in units of time, and no correction for the Equation of Time was necessary. The tables did not switch to Greenwich Mean Time, the time naturally suited to marine time-keepers or chronometers, until 1834, though this was considered embarrassingly late in the era. The dominance of time by machine gradually led to the Sun being counted as *early* or *late* (as tabulated in the Equation of Time) rather than clocks being considered *fast* or *slow*.



[24] FEBRUARY 1767.

Diſtances of ☽'s Center from ☉, and from Stars weſt of her.

Days.	Stars Names.	12 Hours.	15 Hours.	18 Hours.	21 Hours.
		° ′ ″	° ′ ″	° ′ ″	° ′ ″
1	The Sun.	40. 10. 52	41. 54. 11	43. 37. 9	45. 19. 46
2		53. 47. 13	55. 27. 32	57. 7. 27	58. 46. 58
3		66. 58. 20	68. 35. 24	70. 12. 3	71. 48. 18
4		79. 43. 17	81. 17. 4	82. 50 27	84. 23. 28
5		92. 2. 59	93. 33. 49	95. 4 18	96. 34. 28
6		104. 0. 15	105. 28. 28	106. 56. 24	108. 24. 4
7		115. 38. 27	117. 4. 35	118. 30. 29	119. 56. 7
6	α Pegaſi.	71. 18. 35	72. 50. 18	74. 21. 50	75. 53. 9

Figure 4. All ephemeris data in the *Nautical Almanac and Astronomical Ephemeris* were tabulated by Greenwich Apparent Time from 1767-1833.

Navigators through the middle of the nineteenth century frequently dealt with another peculiarity of time-keeping known as the "nautical day" or the "sea day". At sea, the work day and the logbook day began at noon, and that was when officers and crew adjusted the day and date. Monday, June 7 turned to Tuesday, June 8 at noon as observed from the deck of the vessel. Upon arriving in any port for any length of time, the vessel's time-keeping would be switched to the civil standard leading to the curiosity of days of "twelve hours" and days of "thirty-six hours" duration, and these were sometimes recorded in logbooks.[3] Note that this day beginning at noon is very similar to the old concept of the "astronomical day" but one calendar day offset. The nautical day overlapped the corresponding civil day in the morning hours while the astronomical day overlapped in the afternoon and evening hours. The "nautical day" was eliminated by decree in the British Royal Navy in 1805, but it continued in common use on commercial vessels until it faded out after 1850.

The concept of the nautical day created some curious issues in daily life at sea. Respecting the Sabbath among crews which, in American and British shipping, were almost universally Christian until the modern era, was a source of enduring confusion. In general, the captain or master of the vessel had the last word on declaring the date. Similarly in the Pacific, when the date was changed from western hemisphere reckoning to eastern hemisphere reckoning (known in modern euphemism as "crossing the date line," though this is a recent notion), ships' crews had to decide when to observe the Sabbath if Sunday was doubled in the account of days or, worse yet, dropped from the calendar. Here, too, the captain had the last word. Nathaniel Bowditch of Salem, Massachusetts, famous as the author/editor of the *New American Practical Navigator* was one of the first Americans to face this issue when his ship sailed into Manila in 1796. At that time, the Philippines and other Spanish outposts in the western Pacific maintained the date consistent with the western hemisphere in order to remain synchronized with Mexico. Travelling via the Atlantic and Indian Oceans, Bowditch arrived with the western hemisphere accounting of days. As good Yankee Protestants, Bowditch and the other New England traders made do. They kept the date onboard unchanged (since they would be sailing back to Massachusetts the way they came rather than circumnavigating). And so they worked on "our Sunday", as he put it, in order to make the most of their short time in Manila.[4] I would add with respect to the idea of dropping leap seconds from civil time-keeping that if word gets out that civil time will be allowed to drift away from Earth rotation and might, in a few thousand years, effectively turn Saturday into Sunday, there will be confusion at best, and potentially outrage, among the faithful around the world.

The introduction of standard time zones in the late 19th century (in 1883 in the US) had little significance for celestial navigation since navigators already dealt with these issues (time zones do, however, cause lingering confusion for modern navigation students). Following the introduction of time zones, jurisdictions have generally tended to shift their time-keeping east. In the US, Ohio, Michigan, most of Indiana, most of Georgia, were not originally on Eastern Time but have legislated themselves east for economic and cultural reasons. With Daylight Saving Time now in effect for 238 days out of the year in the US (since 2007) equal to 65% of each year, the Eastern US and much of the Midwest now maintain a civil time which would correspond to actual solar Mean Time far out in the Atlantic, east of Bermuda, at 60 degrees West longitude. We are already culturally disconnected from the time implied by the Earth's orientation to an extraordinary extent.

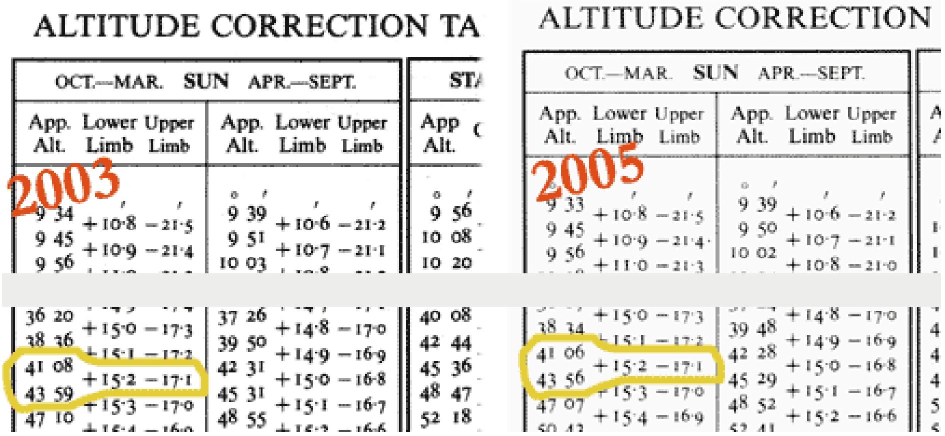
In the early twentieth century, the "big bang" in almanac time-keeping occurred on January 1, 1925 when the astronomical day was abandoned and the almanacs adopted the civil standard of initiating each calendar day at midnight instead of noon. Anecdotal evidence suggests that this may have caused some brief confusion for navigators at sea, uncertain whether to take, e.g., the Declination of the Moon, from the column for 0 hours or 12 hours. I have found no direct evidence of such confusion in actual primary-source materials such as logbooks.

The official almanacs used by most celestial navigators in the first half of the twentieth century were the British *Abridged Nautical Almanac* (AbNA) and the *American Nautical Almanac* (AmNA). Both of these had been spun off, originally as extracts, from the more complete and progressively more astronomically-oriented *Nautical Almanac & Astronomical Ephemeris* and the *American Ephemeris and Nautical Almanac*. By mid-century, the publication known widely as the *Nautical Almanac* (NA&AE) was not nautical except in name. Economy and international good-will suggested the unification of the AbNA and the AmNA and eventually a renaming of these as the international *Nautical Almanac*. This unification of content occurred in 1958 close to the plateau of the standardization of modern celestial navigation. This publication has been remarkably stable in its run. In terms of time-keeping the time standard for the Nautical Almanac changed from GMT to UT *c*.1980, but navigators take little notice of this. Indeed, it is normal among celestial navigators to use GMT and UT interchangeably. The difference has no practical significance, and the world's best navigation schools continue to use the terms interchangeably.

Will the Nautical Almanac exist in another fifty years? As I noted in my presentation on the history of the Nautical Almanac at Mystic Seaport in 2008, I would bet against it. But we can, with some confidence, assert that "nautical almanacs" published by various sources will still exist, even if only to serve a dwindling community of enthusiasts. There are a number of online sources for nautical almanac equivalent data, including my own. Geoffrey Kolbe, of Scotland, publishes a fifty-year *Long-Term Almanac*.[5] As he noted recently on the "NavList" message boards, "In the second edition of the LTA, it is specifically noted that the time system to which the ephemerides are referenced is UT1, and that a decision may be taken sometime during the period of validity of the tables to cease inserting leap seconds into UTC to keep it aligned with UT1. So, if DUT continues to be published as it currently is on the Internet, there should be no problem."[*] Unlike the official *Nautical Almanac*, his almanac already addresses this issue.

NAVIGATION EDUCATION AND SOLUTIONS

As noted, traditional celestial navigation reached a state of near perfection and high standardization some fifty years ago. It is stable, almost ritualistic. Small, even insignificant changes in authoritative data can cause confusion and lead to cynicism if not handled properly. In 2004, the refraction tables in the *Nautical Almanac* were recomputed. The changes are minor and unnecessary (Figure 5). For practical computation, they present no problem, but for pedagogic purposes, they created the impression that some published examples and sample problems were slightly incorrect.



ALTITUDE CORRECTION TA

OCT.—MAR. SUN App. Alt.	Lower Limb	Upper Limb	APR.—SEPT. App. Alt.	Lower Limb	Upper Limb	ST App Alt.
° ′	′	′	° ′	′	′	° ′
9 34			9 39			9 56
	+10·8	−21·5		+10·6	−21·2	
9 45			9 51			10 08
	+10·9	−21·4		+10·7	−21·1	
9 56			10 03			10 20
36 20			37 26			40 08
	+15·0	−17·3		+14·8	−17·0	
38 36			39 50			42 44
	+15·1	−17·2		+14·9	−16·9	
41 08			42 31			45 36
	+15·2	−17·1		+15·0	−16·8	
43 59			45 31			48 47
	+15·3	−17·0		+15·1	−16·7	
47 10			48 55			52 18

ALTITUDE CORRECTION

OCT.—MAR. SUN App. Alt.	Lower Limb	Upper Limb	APR.—SEPT. App. Alt.	Lower Limb	Upper Limb
° ′	′	′	° ′	′	′
9 33			9 39		
	+10·8	−21·5		+10·6	−21·2
9 45			9 50		
	+10·9	−21·4		+10·7	−21·1
9 56			10 02		
	+11·0	−21·3		+10·8	−21·0
	+15·0	−17·3		+14·8	−17·0
38 34			39 48		
	+15·1	−17·2		+14·9	−16·9
41 06			42 28		
	+15·2	−17·1		+15·0	−16·8
43 56			45 29		
	+15·3	−17·0		+15·1	−16·7
47 07			48 52		
	+15·4	−16·9		+15·2	−16·6

Figure 5. Small changes can lead to confusion: a minor change in the refraction tables in 2005.

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[*] http://fer3.com/arc/m2.aspx?y=201108&i=116958

Navigators who practice celestial navigation tend to be highly independent to the point of distrusting authority, despite their dependence on the published tables. Small changes cause consternation. Celestial navigators tend to have strong aesthetic attitudes with respect to maintaining the link between mean solar time and civil time. More importantly, very few navigators remain in practice. This is the conundrum of the ultimate backup. GPS and other electronic systems work with great reliability, but eventually a navigator may need to fall back on traditional tools. If the navigator only vaguely remembers the methodology, any changes in the rules, such as a change in the meaning of the tabulated time, could lead to crippling confusion in a crisis situation. In the event that a time standard replacing UTC gradually drifts from Earth orientation, after fifty years the accumulated drift might amount to some forty seconds, equivalent to a ten nautical mile error in a celestial navigation fix near the equator. This problem can be avoided by the formulation and publication of extremely concise and clear rules carefully cleared of pedantic terminology irrelevant to the *craft* of celestial navigation. Celestial navigators are smart; they will figure it out. But they are not scientists, by and large, and any solution must respect the nature of rapid, non-technical education.

I have recently surveyed some of the most prominent textbooks, almanacs, and other resources used in traditional celestial navigation including recent editions of the *American Practical Navigator* (1962, 1995, US National Geospatial-Intelligence Agency, formerly authored by US Navy Hydrographic Office),[6] *Celestial Navigation in the GPS Age* by John Karl (2006),[7] the *Long-Term Almanac* by Geoffrey Kolbe (2000)[5], *Practical Celestial Navigation* by Susan P. Howell (1981),[8] and the *Primer of Navigation* by Mixter (1943)[9] seeking out exceptional cases or other problems that might arise if “leap seconds” are dropped. I am convinced that the most economical solution for traditional celestial navigation is the continued publication of DUT, identified as a cumulative “watch error”, and inserted on an annual basis as a prominent separate page with brief instructions in the official *Nautical Almanac* and similarly in any un-official nautical almanacs. Such instructions might read, for example, “For the year 2025, subtract 8.0 seconds from broadcast time before entering these tables”. Ephemerides for navigation would continue to be calculated on the basis of UT (UT1). Navigators would acquire the leap-second-free civil time, which I am calling for the purpose of this paper UT*X*, from the Internet, GPS receivers, shortwave time signals, etc. and then apply this simple correction, equivalent to a traditional “watch error”, before entering the tables. All textbook problems and examples would remain valid even in publications that are decades old.

Navigators and navigation enthusiasts that I have emailed and interviewed (all informally) appear convinced that there should always exist a non-Internet, non-digital, plain language, in-the-clear announcement of the time offset from the established international civil time standard if leap seconds are dropped. The system of doubled ticks presently used by WWV is neither obvious nor necessary, and few celestial navigators are even aware of the significance of the doubled ticks. Announce it in plain English. For example, WWV in 2025 might announce, “UT1 for navigation today differs from UT*X* by 8.3 seconds.” An announcement once an hour, similar to the tropical weather updates, should be more than sufficient for the needs of celestial navigators. The watch error or DUT need not be more accurate than the nearest second though there could be some small benefit in terms of confidence-building by providing this offset to the nearest tenth of a second.

CONCLUSION

The impact of dropping leap seconds on traditional celestial navigation would be small and manageable. The expected accuracy of celestial navigation, about one nautical mile under good conditions, is low enough that an error of a second or two would not be counted as significant.

The greater risk arises from the potential for confusion in a subject that is, at best, a rare backup. A single, concise, clearly-labeled page published in the annual Nautical Almanac and a simple, plain-language, hourly shortwave radio announcement will satisfy the needs of celestial navigation. The tools and the textbooks will continue to work. Beyond that, it is merely a matter of education.

ACKNOWLEDGMENTS

Many thanks to the members of the *NavList* navigation community who offered their opinions and advice. *NavList* discussions related to all aspects of traditional celestial navigation including issues of time standards, UTC, and leap seconds, spanning over fifteen years, are archived online at *http://www.fer3.com/arc*.

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