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Excerpt
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Introduction

> The omniscient scholar would analyze climates of opinion and all their component ideas and idea-clusters. He would reveal their development in time, their action upon one another, and their relationship to the events of social and political history. He would psychoanalyze individual thinkers and study their thinking as expressions of group and class behavior. He would range easily through all fields of thought, from theories of physics to theories of art. He would study the function of language in the formation of ideas. He would expound the culture of elites and the culture of masses, the minds of nations and of whole civilizations, ancient and modern, Eastern and Western. . . . In the absence of such polymaths, intellectual history reduces in real life to a profusion of specialized studies employing many methodologies, fulfilling a variety of purposes, and based on conflicting definitions of the discipline.
>
> W. Warren Wagar[1]

The statement above gives a good indication of the theoretical scope of intellectual history, and why in practice all who write it fail. For intellectual history in its institutional setting, which is the subject of this volume, the task is at once more and less daunting. We have for our subject a single institution and a well-defined span of 170 years. We need not worry about the rise and fall of civilizations. On the other hand, we must take into account not only individuals and their interactions in an institutional context, but also the development of science, the roles of the federal government and the military, the history of technology, and some measure of political and social history, in addition to a host of other components.

Histories of scientific institutions are sparse among the literature of history of science, especially in the United States. In the case of astronomical institutions, only in recent years has this sparsity begun to be remedied; this study may be seen as part of that remedy. As one of the oldest scientific institutions in the U. S. government, the Naval Observatory is in many ways unique. It maintains the Master Clock of the United States, and hence provides time for the nation and is the chief contributor to world time; it is one of the premier institutions for positional astronomy, a field whose applications are essential but largely unappreciated; it determines Earth-orientation parameters needed for a variety of practical purposes; it compiles a variety of almanacs

[1] W. Warren Wagar, *World Views: A Study in Comparative History* (Dryden Press: Hinsdale, Illinois, 1977), p. 4.

for navigation, geodesy and astronomy; and it continues to make signal contributions to astronomy even outside of its rather circumscribed mission. Each of these aspects has its history. With its unique time span as a Federal astronomical institution in the United States, it is hoped this history of the U. S. Naval Observatory will serve as a foundation toward a better understanding of the history of astronomy, and the history of science in general, especially in its American context. As the Prelude makes clear, this study is also an important part of the broader history of national observatories, and forms a seldom-recognized part of the history of the U. S. Navy and navigation. It is the American story of the long-standing relationship of astronomy in the service of navigation; thus the title *Sky and Ocean Joined.*

I have divided this study into three parts: the founding era, the golden era, and the twentieth century. While the twentieth century might have been broken into several eras, the overriding organizing principle is a continuous story in three main areas: positional astronomy, time and navigation. Of course these areas are interrelated, and thus, while documenting their unique aspects, I have also tried to make clear their connections, as well as to place the sum total in its institutional context.

The founding era of the Naval Observatory encompasses three foundings: the Depot of Charts and Instruments in 1830, the permanent Depot and *de facto* Naval Observatory in 1842, and the Nautical Almanac Office in 1849. The development of the permanent Depot and its supposedly "small observatory" into the first National Observatory of the United States is the subject of the first chapter; the origins of the Nautical Almanac Office (closely related to the Naval Observatory but not officially incorporated into it until the turn of the century) are the subject of the third chapter. In addition to the three founding events, the founding era is given coherence by the four men who successively headed the Depot and the Observatory: Louis M. Goldsborough, Charles W. Wilkes, James Melville Gilliss, and Matthew Fontaine Maury; two other chapters concentrate on the administrations of two Superintendents, Matthew Maury and James M. Gilliss. The resignation of Maury to join the Southern cause at the beginning of the Civil War, and Gilliss's death at its end, mark the termination of the founding era of the Naval Observatory.

The golden era is marked by the tenure of Asaph Hall, Simon Newcomb, William Harkness, and other Naval Observatory astronomers, by the discovery of the moons of Mars, the far-flung transit-of-Venus and solar-eclipse expeditions, and by progress in the more routine work of positional astronomy and celestial mechanics. During this era the Naval Observatory acquired the largest telescope in the world, excelled in most of its activities, and achieved worldwide fame as a result. However, the realm of astronomy was rapidly growing, and this was the last era in which worldwide prominence in classical astronomy could be equated with worldwide prominence in astronomy.

The twentieth century is actually grounded in events that began in 1893, when the Observatory moved to its present site, with new buildings and instruments, a new lease on life, and new opportunities in a rapidly growing discipline now fully engaged in incorporating astrophysics and photography. We will find here that, despite its continuing excellence and innovation in specific areas such as radio time dissemination, the Observatory did not immediately take advantage of astrophysics, and did not make full use of new techniques in photography. Sometimes this tardiness resulted from issues of mission and targeted government patronage beyond its control. The issue of military versus civilian control of the Observatory, and whether government astronomy would be better undertaken in a different branch of government, also came to a head early in the century, sapping the energies of the institution. The promise of a new lease on life expected from new buildings and instruments was overtaken by external changes to the field, to which the Observatory did not respond rapidly.

Yet, during the course of the century, in the areas of time, positional astronomy, and navigation, the Observatory gradually not only carried out its duties, but also once again became preeminent in its field. Throughout the century, the Observatory both affected, and was affected by, many other major landmarks of American political and scientific history. Its time and navigation functions proved essential through both World Wars. The first operational Ritchey–Chrétien telescope (the optical design now used for many telescopes including the Hubble Space Telescope) was built for the Observatory in the midst of the Great Depression. Responding to the inexorable growth of light pollution in the Washington area, during the 1950s a major field station was established in Flagstaff, Arizona; a smaller station was built in Florida, and far-flung stations operated temporarily at the Southern-Hemisphere sites of Samoa, Argentina, New Zealand, and Chile. The Space Age and the computer revolution also shaped events at the Observatory, as at other scientific institutions. The 61-inch astrometric telescope dedicated in 1964 would never have seen the light of day had the space race not freed funds for science. Although the problems of navigation were now expanded from the oceanic to the interplanetary regime, at first the Observatory made a conscious decision to limit its connections to NASA; newer institutions, such as the Jet Propulsion Laboratory, filled the space navigation gap. Nevertheless, the technological necessities of war and peace in the Space Age became drivers for new accuracies in the traditional functions of positional astronomy, time determination, and celestial mechanics.

Lest the reader lose sight of the forest for the trees, it is important to emphasize that only a finite number of problems dominates Naval Observatory history; they reappear again and again in ever more subtle and expressive forms. The determination and dissemination of time; the definition of an increasingly accurate and dense stellar reference frame; the determination of the astronomical constants; the closing of the gap between observation and gravitational theory as applied to the motions of the planets, satellites, and other solar-system objects; and the uses of all these aspects for navigation, all set in the American context, are the main subjects of this book. That is not to say that there were no unexpected developments. The discoveries of the moons of Mars and Pluto, of interstellar polarization of starlight, of the first asteroids found by a U. S. institution, and cutting-edge work in charge-coupled devices, infrared astronomy, and optical interferometry, are all part of Naval Observatory history.

Six generations of scientists carried out this work at the Naval Observatory. For many of them, their efforts are documented here for the first time, and bringing these scientists and their work back to life has been one of the pleasures of writing this history. A few, including Asaph Hall, Simon Newcomb, Wallace Eckert, and Gerald Clemence, have entered the pantheon of American astronomy because of their contributions. Others, such as Lt James Melville Gilliss, George W. Hill, William Harkness, William Eichelberger, H. R. Morgan, C. B. Watts, and Edgar Woolard, among many, deserve to be better known. Some of them find a place in this history; others remain for future research.

For the reader who wishes to follow developments thematically, sections 2.2 and 5.3 as well as chapter 11 cover developments in time determination, timekeeping, and time dissemination over 170 years. Nautical Almanac Office history is found in chapters 3, 8, and 12. Positional astronomy is dealt with primarily in sections 2.2 and 5.2 and in chapter 10. The Observatory's administrative history after the founding era is covered in section 5.1 and chapter 9. For purposes of perspective I have felt it necessary to cover the last two decades of impressive progress in positional astronomy, time, and navigation at the Observatory. While this provides a context for the previous 150 years, it is more difficult to see how the future will judge the last 20 years; the reader will therefore find that the more recent years are covered in less detail than the rest of the history.

No history covering a subject expansive in space and time can claim to be exhaustive in detail. While clearly many avenues could be explored using the approaches mentioned at the head of this chapter, I have sought to capture in this volume the major institutional themes spanning more than a century and a half of unparalleled progress in astronomy.

Prelude. Perspectives and problems: The nation, the Navy, the stars

> It is with no feeling of pride, as an American, that the remark be made that, on the comparatively small territorial surface of Europe, there are existing upward of one hundred and thirty of these light-houses of the skies; while throughout the whole American hemisphere there is not one.
>
> President John Quincy Adams, 1825[1]

Before we plunge into the history of one of the oldest scientific institutions in the United States, it is essential to gain a perspective from at least three points of view: the history of astronomy, the history of science in America, and the history of navigation in the context of the U. S. Navy. These perspectives are not mutually exclusive; indeed the links between astronomy and navigation, particularly in the U. S. Navy, and their place in the history of science in America, are major themes of this study. They serve not only to provide the essential context of our story, but also to highlight some of the problems with which we will be concerned.

1. History of astronomy

The U. S. Naval Observatory must ultimately be placed in an international context. Specifically it falls squarely within that genre of astronomical institutions known as "national observatories." What happened in the United States in the 1830s and 1840s had already happened in other countries: a need was perceived for an astronomical observatory, not so much to advance the pure science of astronomy, but to serve practical purposes essential to national interests. Indeed, although the details differ in each country, a global perspective on the history of astronomy reveals that the Naval Observatory is part of what we may term a "national observatory movement," a 300-year pattern of government support for astronomical observatories. This movement gave rise to some of the longest-lived scientific institutions in the world. Throughout those three centuries the number of national observatories has increased, and the idea of "the national interest" has broadened to include pure research and national prestige, in addition to more practical concerns. National observatories are not immortal, however, as witnessed by one of its most venerable members, the Royal Greenwich Observatory, which ceased to exist as a scientific institution in 1998.

Table P.1 shows some of the more important national observatories, and

[1] John Quincy Adams's first annual address to Congress, December 6, 1825, in *A Compilation of the Messages and Papers of the Presidents*, 1789–1902, ed. James D. Richardson (New York, 1904), p. 56.

Table P.1. *Some important national observatories and their patrons*

	Institution	Founded	Patron
First era	Uraniborg (Tycho Brahe)	1576	Frederick II
	Paris Observatory	1667	Louis XIV
	Royal Greenwich Observatory	1675	Charles II
	Berlin Observatory	1701	Frederick I
	St Petersburg Observatory	1725	Peter the Great
Second era	Royal Observatory, Cape	1820	Great Britain
	U. S. Naval Observatory	1830	U. S. Navy
	Pulkovo Observatory	1839	Nicholas I
	Chilean National Observatory	1852	Chile
	Argentine National Observatory	1870	Argentina
	Potsdam Astrophysical Observatory	1874	German Academy of Science
	Smithsonian Astrophysical Observatory	1891	Smithsonian/United States
	Dominion Observatory	1903	Canada
	Dominion Astrophysical	1918	Canada
Third era	National Radio Astronomy Observatory	1956	NSF/AUI, United States
	Kitt Peak National Observatory	1957	NSF/AURA, United States
	National Radio Astronomy Observatory	1959	CSIRO, Australia
	Cerro-Tololo Inter-American	1963	NSF/AURA/Chile
	European Southern Observatory	1964	Five countries, more later
	Anglo-Australian (Siding Spring)	1967	Great Britain/Australia
	Space Telescope Science Institute	1981	NASA/AURA

Abbreviations:

NSF	National Science Foundation
AUI	Associated Universities, Inc.
AURA	Associated Universities for Research in Astronomy
NASA	National Aeronautics and Space Administration
CSIRO	Commonwealth Scientific, Industrial and Research Organization

suggests three eras in this movement: the first era, in which the prototype Paris, Greenwich, Berlin, and St Petersburg observatories were founded; the second era, characterized by offshoots from previous national observatories, by new observatories of younger nations, and by the rise of astrophysical observatories; and the third, post-World-War-II era, characterized by national or international consortia, large budgets relative to those of previous years, and increasingly sophisticated telescopes, detectors, and spacecraft observing an expanded region of wavelengths. Observatories in the latest era heavily emphasize astrophysics. The founding of the Naval Observatory falls clearly in the second era, and suggests comparison with the Royal Greenwich Observatory, the Cape Observatory in South Africa, and the Pulkovo Observatory in Russia, in terms of origins, programs, and evolution. The comparative history of such similar institutions is an important and unrealized task that we can only touch on in this volume.[2]

[2] A more detailed description of the national observatory movement, and a brief comparison of the U. S. Naval Observatory and Pulkovo Observatory as exemplars of that movement founded within a decade of each other under very different political conditions, may be found in Steven J. Dick, "Pulkovo Observatory and the National Observatory Movement," *Inertial Coordinate System*

How this venerable national observatory theme was first played out in the context of American history is the subject of this book. The United States had its own internal national observatory movement, that is, its series of false starts before the U. S. Navy's Depot of Charts and Instruments evolved into the first national observatory of the United States in the mid-1840s. Four attempts have generally been recognized, including those related to the U. S. Coast Survey, the establishment of a prime meridian of the United States, and the Smithsonian bequest, before the successful attempt of the U. S. Navy.[3] We briefly describe each of these efforts because they were in some ways related, and events surrounding the Smithsonian bequest would have a significant effect on the founding of a permanent Naval Observatory.

When the Survey of the American Coast was authorized in 1807, President Thomas Jefferson and Treasury Secretary Albert Gallatin selected Ferdinand R. Hassler to undertake the work. Among Hassler's plans were two observatories, to serve as fixed points in the Survey for determining base latitude and longitude. One of the observatories, Hassler noted, might be placed in the city of Washington "as observatories are placed in the principal capitals of Europe, as a national object, a scientific ornament, and a means of nourishing an interest for science in general." Hassler even drew up plans for such an observatory, to be located on a hill north of the Capitol.[4] Though President Madison and Secretary of the Treasury Dallas approved Hassler's astronomical plans in 1816, the repeal of part of the Survey act in 1818 brought these astronomical plans, and the work of the Coast Survey itself, to a halt. When the Survey was revived in 1832, the new law specified that nothing in the act should be construed "to authorize the construction or maintenance of a permanent astronomical observatory." This prohibition is often attributed to Congressional dislike of John Quincy Adams, who favored the idea of an observatory, but it was undoubtedly also a cost-cutting move.

on the Sky, Proceedings of International Astronomical Union Symposium 141, Leningrad, October 17–21, 1989, Jay H. Lieske and Victor K. Abalakin, eds. (Kluwer: Dordrecht, 1990). Also very useful is Kevin Krisciunas, *Astronomical Centers of the World* (Academic Press: New York, 1988). Substantive histories exist for only a few national observatories; see for example the Greenwich Tercentenary volumes *Greenwich Observatory: The Royal Observatory at Greenwich and Herstmonceux, 1675–1975*; volume 1, Eric G. Forbes, *Origins and Early History (1675–1835)*, (Taylor and Francis: London, 1975); volume 2, A. J. Meadows, *Recent History (1836–1975)*, (Taylor and Francis: London, 1975); and volume 3, Derek Howse, *The Buildings and Instruments* (Taylor and Francis: London, 1975). See also C. Wolf, *Histoire de l'Observatoire de Paris de sa fondation à 1793* (Gauthier-Villars: Paris, 1902), and the broader and briefer history in S. Debarbat, S. Grillot, and J. Levy, *L'Observatoire de Paris: Son Histoire (1667–1963)* (Observatoire de Paris: Paris, 1984); A. N. Dadaev, *Pulkovo Observatory: An Essay on its History and Scientific Activity*, trans. by Kevin Krisciunas (Washington, 1978); and Richard A. Jarrell, *The Cold Light of Dawn: A History of Canadian Astronomy* (University of Toronto Press: Toronto, 1988).

3 Charles O. Paullin, "Early Movements for a National Observatory, 1802–42," *Records of the Columbia Historical Society*, **25** (1923), 36–56. See also David F. Musto, "A Survey of the American Observatory Movement, 1800–1850," *Vistas in Astronomy*, **9** (1967), 87–92.

4 Paullin (ref. 3), 38–39. This is the same site where the Depot of Charts and Instruments and its small observatory would be located, 1834–42. For Hassler's observatory plans and its instruments see "Papers on Various Subjects Connected with the Survey of the Coast of the United States," *Transactions of the American Philosophical Society*, **2**, new series (Philadelphia, 1825), 357–370. The quotation is from page 242. See also Florian Cajori, *The Chequered Career of Ferdinand Rudolph Hassler* (Christopher Publishing House: Boston, 1929; facsimile reprint, Arno Press: New York, 1980).

The second attempt for an astronomical observatory was connected to William Lambert's proposal for determining a prime meridian for the country. It was first proposed to Congress in December 1809, and this and similar proposals of Lambert were renewed until 1824. Though some observations were made in 1821, a permanent astronomical observatory was never established. In light of later events, it is interesting to note that the climate of opinion was generally favorable, as evidenced in the remarks of Secretary of State James Madison in July, 1812: "An observatory would be of essential utility. It is only in such an institution, to be founded by the public, that all the necessary implements are likely to be collected together, that systematic observations can be made for any great length of time, and that the public can be made secure of the result of scientific men. In favor of such an institution it is sufficient to remark, that every nation which has established a first meridian within its own limits has established also an observatory. We know that there is one at London, at Paris, Cadiz, and elsewhere."[5]

The third attempt to found a national observatory is associated with the name of John Quincy Adams, whose earliest published efforts in this regard began with his Presidential message of December 6, 1825. A select committee of Congress responded to this proposal with an elaborate report of its own, composed by Major General Alexander Macomb, Chief of Engineers of the Army. No action was taken, and Adams renewed his proposal for an observatory in 1840 in connection with the bequest of James Smithson and the founding of the Smithsonian Institution. This proposal, which was repeated until 1846, is directly associated with the evolution of the Navy's Depot of Charts and Instruments into an observatory, and will be discussed in that context in chapter 1.[6]

If the American government found it difficult to support a national observatory, astronomy in general in the United States did not fare much better prior to 1840. At that time almost nothing qualifying as an observatory existed in the country. However, by 1856 Elias Loomis, in *The Recent Progress of Astronomy, Especially in the United States*, could discuss some 25 observatories, mostly private or attached to educational insti-

[5] Paullin (ref. 3), 41. According to Paullin, Lambert was a resident of Virginia and then the City of Washington, and a clerk in the War Department until 1821, when he resigned to make longitude observations, using a temporary observatory. For a history of Washington meridians see Silvio Bedini, *The Jefferson Stone: Demarcation of the First Meridian of the United States* (Professional Surveyors: Frederick, Maryland, 1999), and Matthew H. Edney, "Cartographic Confusion and Nationalism: The Washington Meridian in the Early Nineteenth Century," *Mapline* (Spring/Summer, 1993, 4–8). On American prime meridians in general, see Joseph Hyde Pratt, "American Prime Meridians," *Geographical Review*, **32** (1942), 233–244. On the broader history of prime meridians see *Longitude Zero, 1884–1984*, *Vistas in Astronomy*, **28** (1985), 7–407, and USNOA, SF, "Prime Meridians" folder.

[6] Steven J. Dick, "John Quincy Adams, The Smithsonian Bequest, and the Founding of the U. S. Naval Observatory," *JHA*, **22** (1991), 31–44; Marlana Portolano, "John Quincy Adams's Rhetorical Crusade for Astronomy," *Isis*, **91** (2000), 480–503; and Paullin (reference 3), 44–48. On Adams see also Samuel Flagg Bemis, *John Quincy Adams and the Union* (Academic Press: New York, 1970), especially Chapter 23, "Lighthouses of the Skies, 1825–46." The 23-page Congressional document is "National Observatory," 19th Congress, first session, March 18, 1826, House Report No. 124, copy in USNO, SF, Legislation File.

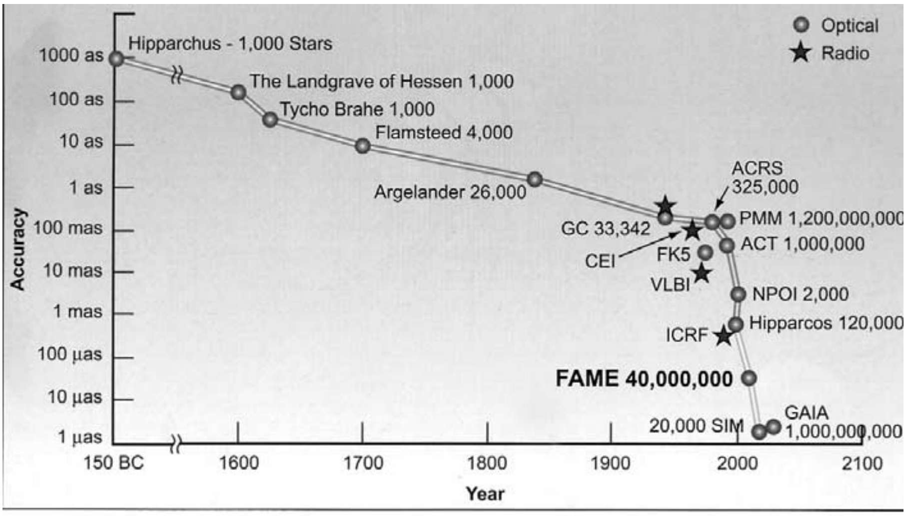

Figure P.1. Astrometric accuracies, showing the "Golden Age of Astrometry" beginning in the 1980s, as accuracies surpassed the milliarcsecond range. Items after ICRF are projected. Source: U. S. Naval Observatory.

tutions.[7] Aside from the observatory at West Point, which was used for teaching and not research, the Navy's observatory was the only government-supported astronomical institution of its era. Moreover, though astronomy experienced even more rapid growth in the United States following the Civil War, for more than a century after its birth the Naval Observatory remained the only government-supported observatory in the country.[8]

The work of the Naval Observatory, like that of other national observatories during much of their history, has been largely devoted to positional astronomy, timekeeping, and celestial mechanics. These have been the principal concerns of astronomers for most of astronomy's history, from the Babylonians and Greeks through the nineteenth century. The likes of Hipparchus and Ptolemy, Brahe, Kepler, and Newton, Laplace and Lagrange embraced this "classical astronomy" as their life work, and their contributions have been examined well.[9] However, what of their nineteenth- and

[7] Elias Loomis, *The Recent Progress of Astronomy, Especially in the United States* (third edition, Harper and Bros.: New York, 1856), pp. 202–292.

[8] With the exception of the Smithsonian Astrophysical Observatory, which has always been considered as "quasi-governmental" because of its dual funding sources, not until the founding of Kitt Peak National Observatory and the National Radio Astronomy Observatory in the mid-1950s did this situation change. On the Smithsonian Astrophysical Observatory see Bessie Zaban Jones, *Lighthouse of the Skies: The Smithsonian Astrophysical Observatory: Background and History, 1846–1955* (Smithsonian Institution: Washington, 1965), and the "Smithsonian Astrophysical Observatory Centennial" issue of the *JHA*, **21** (February, 1990). On the later American national observatories see Frank Edmondson, *AURA and its U. S. National Observatories* (New York: Cambridge University Press, 1997).

[9] See, for example, Robert Grant, *History of Physical Astronomy* (London, 1852), A. Pannekoek, *A History of Astronomy* (George Allen and Unwin: London, 1961), and a host of more recent studies.

twentieth-century successors? Figure P.1 places those centuries in the context of earlier astrometric accuracies, which are expressed in terms of "arcseconds," 1/3,600th of a degree (the full Moon subtends about one half degree, or 1,800 arcseconds). Increasing technological sophistication brought observational capabilities for position determination from 60 arcseconds (or one arcminute) for Tycho Brahe in 1600, to a few tenths of an arcsecond at the time the Naval Observatory was founded, more than 100 times better.[10] The improvement over the next century and a half to 1980 was only by about a factor of ten, despite the use of devices like the traveling-wire micrometer, ingenious methods for reading the graduated circle, and improvements to refraction theory. Most of our history deals with this period of slow improvement. During the last two decades of the century, however, new technologies routinely achieved milliarcsecond accuracies (an improvement by a factor of a million over the ancient Greeks), and technologies for microarcsecond accuracies were being developed. As Figure P.1 certainly indicates, developments over the last two decades have led to a "golden age of astrometry."

These developments over 170 years give rise to important historical questions: What problems did new levels of accuracy enable astronomers to tackle and resolve? Conversely, what have been the drivers behind their quest for greater accuracy? How have practical problems of navigation and more purely scientific problems such as stellar motion and galactic structure intermingled? As one of the few American institutions to carry on this work, and the only one over such an extended period, the Naval Observatory is a natural choice for an analysis of this kind.

The improvements in the capabilities of positional astronomy affected strongly another task of the Naval Observatory – the accurate determination of time. This necessarily follows because for centuries astronomy held a monopoly on time determination, since no more accurate periodic phenomenon was known to exist than the rotation of the Earth on its axis, measured with respect to a celestial body. However, in the 1920s and 1930s, quartz-crystal clocks, and then in the 1950s atomic clocks, showed the irregularities in the Earth's rotation. The man-made clock now outdid Nature itself, but only by exploiting another part of Nature, the natural properties of the atom. "Atomic time" now joined the "Earth time" that had reigned for centuries, and made physicists rather than astronomers the keepers of the most accurate time. Taking a broad view, Figure P.2 shows that the accuracy of clocks improved by a factor of a billion over three centuries, which is even more impressive than the improvements in positional astronomy.[11] This was possible because of the development of

[10] The technology behind improvements in astrometric accuracy before the founding of the Naval Observatory is described in Allan Chapman, *Dividing the Circle: Development and Critical Measurement of Celestial Angles*, 1500–1850 (E. Horwood: New York; 1990); "The Accuracy of Angular Measuring Instruments used in Astronomy between 1500 and 1850," *JHA*, **14** (1983), 133–137. See also David W. Hughes, "Astronomical Angular Accuracy," *Nature*, 307 (January 5, 1984), 15–16.

[11] From Derek Howse, *Greenwich Time and the Discovery of the Longitude* (Oxford University Press: Oxford, 1980), and the new edition *Greenwich Time and the Longitude* (Philip Wilson: London, 1998); and Eric Forbes, *The Birth of Scientific Navigation: The Solving in the 18th Century of the Problem of Finding Longitude at Sea*, National Maritime Museum monograph 10 (1974), p. 181.