THE ASTRONOMICAL APPLICATIONS DEPARTMENT TODAY

John A. Bangert
U.S. Naval Observatory

Introduction

The Astronomical Applications (AA) Department of the U.S. Naval Observatory (USNO) is the parent organization of the U.S. Nautical Almanac Office (NAO) established in 1849. The scope of activities involving almanacs has expanded dramatically over 150 years, in ways in which our early predecessors could never have imagined. This paper will provide an overview of the department, with the primary focus on the its current mission. Today, the AA Department provides practical astronomical data via a broad spectrum of products and services, and has an active research component aimed at supporting and improving these products.

Brief History

Just prior to 1990, the Nautical Almanac Office was one of three scientific departments of the U.S. Naval Observatory. The office employed a staff of approximately 20-25 people engaged in production of the printed almanacs, development of computer almanacs, research, and management of USNO's computer resources. In 1990, the decision was made to reorganize the NAO, splitting it into two new departments: the Astronomical Applications Department and the Orbital Mechanics (OM) Department. The goal of the reorganization was to separate research from production. The new AA Department was tasked to focus on delivery of products and services, with a special emphasis on satisfying U.S. Department of Defense needs. The OM Department was tasked to undertake research and development projects in orbital dynamics, involving both natural and artificial bodies. The AA Department also inherited the computer management responsibilities for USNO. Two things about the new AA Department's organization were particularly noteworthy. First, responsibility for the printed almanacs was given to a "new" Nautical Almanac Office, reduced to the level of a division. Second, responsibility for computer-based products was given to the new Product Development Division. USNO management at that time perceived growing importance of

the computer almanacs, and placed them on par, organizationally, with the printed almanacs.

The face of the AA Department changed for the first time as the result of another USNO reorganization in 1994. The OM Department was disbanded, and its personnel distributed to other USNO departments. The AA Department added two new staff members (actually former NAO staff) as a result of this change. Furthermore, the USNO computer management responsibilities were removed from the AA Department and relocated in a newly established Information Technology (IT) Department. This latter change had an especially positive impact on the AA Department, as computer management for USNO had long taken considerable resources away from the department's core mission work.

A relatively minor organizational change in 1996 completed the current organization of the AA Department by establishing the Dynamical Astronomy Division. The new division, staffed by existing members of the department, was tasked with performing research in dynamical astronomy. Most of this research is applied research, aimed directly at supporting and improving department products.

Mission

The current mission of the AA Department can best be summarized by its (unofficial) mission statement:

> The Astronomical Applications Department of the U.S. Naval Observatory computes, from fundamental astronomical reference data, the position, brightness, and other observable characteristics of celestial bodies, as well as the circumstances of astronomical phenomena. This information is of critical importance to navigation, military operations planning, scientific research, surveying, accident reconstruction, architecture, and everyday activities. The products of the AA Department—publications, software, algorithms, and expertise—are used by the U.S. Navy and the other armed services, civilian government agencies, the scientific research community, and the public. Our products are regarded as benchmark standards throughout the world. The department also carries out a modest research program in celestial mechanics and positional astronomy to enable it to meet future needs.

Current Organization

Today, the AA Department is composed of three divisions. The *Nautical Almanac Office* is responsible for the four annual printed almanacs co-published with H.M. Nautical Almanac Office (HMNAO) of the United Kingdom (UK), and other printed products. The *Product Development Division* is responsible for the computer-based almanacs and for satisfying special astronomical software requirements primarily from the U.S. armed services. The *Dynamical Astronomy Division* carries out a research program to support the current operational mission and to meet the future needs of the department.

It should be noted that the "walls" that separate the divisions are actually rather thin. All divisions now assist in proofreading the pages of the printed almanacs. Staff of the Nautical Almanac Office assists the Product Development Division by testing the software almanacs. Applied research and advice from the Dynamical Astronomy Division has had an influence on virtually all department products.

Products

This section provides capsule descriptions of the main products produced or co-produced by the AA Department.

Printed Almanacs

i. *The Nautical Almanac*

The Nautical Almanac contains the astronomical data required for marine navigation. Most data on the main pages are tabulated at hourly intervals to a precision of 0.1 arcminute. The main pages contain the Greenwich hour angle and declination of the Sun, Moon, and navigational planets; the Greenwich hour angle of Aries; positions of the navigational stars; rise and set times of the Sun and Moon for a range of latitudes; and other data. Each edition also contains a sight reduction table, sight reduction formulas, and various correction tables for sight reduction. *The Nautical Almanac* is required, both by Navy policy and U.S. law. Under the current cooperative agreement, most of the volume is prepared by HMNAO, which also holds a copyright to most of the book. Currently, approximately 13000 copies of *The Nautical Almanac* are printed in the U.S. by the Government Printing Office (GPO), which also handles public sales in the U.S. The book is distributed to the U.S. armed services under the terms of a cooperative agreement between USNO, the National Imagery and Mapping Agency (NIMA) and the Defense Logistics Agency (DLA).

There is also a UK printing of *The Nautical Almanac*. The Stationery Office handles public sales in the UK.

ii. *The Air Almanac*

The Air Almanac contains the astronomical data required for air navigation. Most data on the main pages are tabulated at 10-minute intervals to a precision of 1 arcminute. The main pages contain the Greenwich hour angle and declination of the Sun, Moon, and three navigational planets; the Greenwich hour angle of Aries; rise and set times of the Moon for a range of latitudes; and other data. Each edition also contains sky diagrams for each month; sunrise, sunset, and twilight tables; and positions of the navigational stars. The AA Department prepares most of the book. Currently, approximately 11000 copies of *The Air Almanac* are printed in the U.S. by the GPO, which also handles public sales in the U.S. The book is distributed to the U.S. armed services under the terms of the cooperative agreement between USNO, NIMA, and DLA. Beginning with the edition for 1998, HMNAO introduced a new publication, *The UK Air Almanac*, at the request of the Royal Air Force (RAF). *The UK Air Almanac* provides illumination data, but does not provide the main pages of navigational data or the sky diagrams present in the original *Air Almanac*.

iii. *The Astronomical Almanac*

The Astronomical Almanac contains precise ephemerides of the Sun, Moon, planets, and satellites, data for eclipses, and other astronomical phenomena for a given year. Most data are tabulated at 1-day intervals. The book includes geocentric positions of the Sun, Moon, planets, and bright stars; heliocentric positions of the planets and their orbital elements; universal and sidereal times; daily polynomials for the Moon's position; physical ephemerides of the Sun, Moon, and planets; elongation times and differential coordinates of selected satellites of the planets; rise, set, and transit times of the Sun and Moon; eclipse data and maps; tables of reference data for various celestial objects; useful formulas; and other information. Under the current cooperative agreement, approximately half of the volume is prepared by the AA Department, and the other half by HMNAO. Currently, approximately 6000 copies of *The Astronomical Almanac* are printed by the GPO, which also handles public sales in the U.S. The Stationery Office handles public sales in the UK.

iv. *Astronomical Phenomena*

Astronomical Phenomena is an inexpensive booklet containing a preprint of data from *The Astronomical Almanac*. It contains the calendar; anniversaries and festivals; chronological eras and cycles; equinoxes and solstices; phases of the Moon; visibility and configurations of the planets;

eclipses; equation of time and declination of the Sun; rising and setting of the Sun and Moon; and positions of Polaris. The publication is of particular interest to calendar makers and to the U.S. National Weather Service. Most of this publication is prepared by HMNAO. It is printed by the GPO, which also handles public sales in the U.S.

Software Almanacs

i. *Multi-year Interactive Computer Almanac* (MICA)

MICA[1,2] is an executable application program that provides high-precision astronomical data in tabular form for a wide variety of celestial objects. MICA calculates, in real-time, much of the information tabulated in *The Astronomical Almanac*. However, MICA goes beyond traditional printed almanacs by enabling the user to calculate data for user-specified locations at user-specified times within a long time interval. The first version of MICA, released in 1993, covered the years 1990 through 1999. The current version (1.5), released in 1998, is valid for a sixteen-year interval (1990-2005). Designed primarily for professional applications, MICA is intended for users familiar with the terminology and concepts of positional astronomy. It is available in editions for personal computers with Intel processors and Microsoft operating systems, and for Apple Macintosh systems. The current version of MICA was produced in partnership with Willmann-Bell, Inc. The AA Department produced the software and wrote the user manual. Willmann-Bell published the product and sells it as a hardcover book (user's guide) with a hybrid CD-ROM containing both editions of the software.

ii. *System to Estimate Latitude and Longitude Astronomically* (STELLA)

STELLA[3,4], released in 1995, is an executable application program that automates virtually all of the computations required for celestial navigation. It is the first product produced by USNO that not only computes the astronomical data needed for celestial navigation, but also utilizes these data, along with sextant observations, to determine position at sea.

STELLA performs six major tasks for the navigator: almanac, position update, rise/set/transit/twilight, gyro/compass error, sight planning, and sight reduction. It is based on several new mathematical approaches to celestial navigation. These include new developments for the sailing formulas, a rigorous method of computing a celestial body's position in the sky, a new algorithm for rise and set predictions for a moving platform, and new, flexible ways of combining observations to form a fix. As a result, STELLA carries out celestial navigation from a unique and computa-

tionally correct approach. STELLA's computations are performed to one-arcsecond precision—about 30 meters on the surface of the Earth—far exceeding the accuracy attainable by hand-held sextants. Even with hand-held sextants, the improved precision of STELLA's calculations and the options it provides the navigator are likely to result in better fixes.

STELLA was developed by the AA Department in response to a specific U.S. Navy requirement. The U.S. Coast Guard also adopted it in 1996 for use aboard all of its ocean-going vessels. STELLA is available only to the U.S. armed services for official use, but the new, underlying methods used in the software have been placed in the public domain through a series of three papers[5,6,7] that were published in the American journal, *Navigation*.

Other Software Products

i. *Naval Observatory Vector Astrometry Subroutines* (NOVAS)

NOVAS[8] is an integrated package of source-code modules that can compute a wide variety of common astrometric quantities and transformations. The package can provide, in one or two module calls, the instantaneous coordinates (apparent, topocentric, or astrometric place) of any star or planet. At a lower level, NOVAS also provides general astrometric utility transformations, such as those for precession, nutation, aberration, parallax, and the gravitational deflection of light. The computations are very precise. They are based on a vector and matrix formulation that is rigorous and consistent with recent International Astronomical Union (IAU) resolutions[9]. The NOVAS package is relatively easy to use and can be incorporated into data reduction programs, telescope control systems, and simulations. In fact, NOVAS is used by the AA Department staff to generate the data for many of the tables in *The Astronomical Almanac*. The NOVAS modules are available in both Fortran and C. They are available for download from the AA Department Web site.

ii. *Solar-Lunar Almanac Core* (SLAC)

The Solar-Lunar Almanac Core (SLAC) is a set of integrated software modules that provides information concerning the Sun and Moon, useful for operations planning, mission scheduling, and other practical applications. SLAC is not an executable application program. Rather, it is a self-contained source code "engine" designed for incorporation into larger software systems. SLAC provides equatorial and horizon coordinates of the Sun and Moon; times of rise, set, transit, and twilight; fraction of the Moon illuminated; and an approximate calculation of the amount of natural light reaching the surface of the Earth (the illuminance). SLAC was

produced in response to a specific U.S. Navy requirement and is available only to the U.S. armed services for official use.

The AA Department World Wide Web Site

In the summer of 1996, the AA Department initiated a major upgrade of its site on the World Wide Web (WWW). A significant amount of discussion and planning went into the design of the new site. It was decided from the outset that the site would distinguish itself by its content, not by extensive use of multimedia or sophisticated graphical design. Thus, department staff set out to provide as much frequently requested material as possible, and to make that material easy to access by the general public. The goal was to reduce the amount of staff time spent responding to the many routine phone, letter, and e-mail requests that the department receives daily for astronomical data and other information. Every division within the department contributes to the site.

The AA Department uses its WWW site to describe its products, services, and research results, and to direct customers to sources that distribute the products. The site also provides answers to frequently asked questions. The "crown jewel" of the site is the Data Services area. Here, users can compute, via interactive software, astronomical data tailored for particular dates and locations of their interest. The Data Services area allows users to compute, among other things, complete Sun and Moon data for a single day, yearly tables of rise, set, twilight, and Moon illumination, local circumstances of lunar eclipses, and horizon coordinates of the Sun and Moon. Even a limited Web-based version of MICA ("WebMICA") is provided. Most of the software underlying these services was reused from other AA Department products, such as MICA, STELLA, or SLAC.

The site has been a success. The AA Web server currently handles approximately 3000 user sessions, or more than 19000 hits, per day. The address of the AA Department home page is *http://aa.usno.navy.mil/AA*.

Research

This section provides capsule descriptions of key research projects that have or will have an impact on the operational products of the AA Department. Staff members are also engaged in other projects in areas as diverse as the dynamics of trans-Neptunian objects (TNOs), measuring changes in the solar diameter[10], optical misalignment analysis[11], improvement of Global Positioning System (GPS) satellite orbits, and star formation in dwarf galaxies[12].

Solar System Dynamics

i. *Newcomb*

Newcomb is the name of a new software system for generating high-accuracy, fundamental ephemerides of major solar system bodies, now under development in the AA Department. Prior to 1984, the printed almanacs utilized fundamental ephemerides that were produced "in house" at USNO. One of the goals of the Newcomb project is to regain that status. Furthermore, Newcomb will provide a valuable independent check on other high-accuracy ephemeris-generating programs, very few of which exist worldwide. It will also provide a valuable tool for performing basic research in solar system dynamics. Newcomb is being developed from first principles, both from an algorithmic and a programming perspective. The software is being written in the C++ language using modern object-oriented design techniques. This, in itself, should result in a system that is far easier to debug, extend, and maintain.

The software will be composed of three main modules. The *observations module* will process astrometric observations of various types, taken from various platforms including spacecraft. The *integration module* will be responsible for numerically integrating a sophisticated model of the dynamics of the solar system. This module is largely complete and exists as a stand-alone system called "Newton," which has already been used for investigations of the dynamics of asteroids and TNOs. Finally, the *parameter estimation module* will solve in a least-squares sense for the most probable set of model parameter values that minimizes the "observation minus computed" (O–C) residuals.

Current plans call for Newcomb to become operational during 2001[13].

ii. *Asteroid Ephemerides and Masses*

Beginning in year 2000, a new set of minor planet (asteroid) ephemerides is required for *The Astronomical Almanac*. For this reason, an extensive set of observations, some going back into the 19th century, have been analyzed to provide new ephemerides and masses of some of the largest asteroids. Additionally, all asteroids that have measurable gravitational effects on their neighbors are being studied for possible mass determinations; the feasibility of such determinations depends on the strength of the dynamical interactions and the availability of good historical observations. The Smithsonian Astrophysical Observatory's Planetary Ephemeris Program (PEP)[14] is being used to generate the new ephemerides and make the mass determinations.

Improved masses have already been determined for four asteroids[15,16,17]. New high-precision ephemerides for 15 asteroids have been completed[18], and will be made available to the astronomical community during 1999.

Other Projects

i. *New Approaches to Celestial Navigation*

As previously mentioned, new algorithms for celestial navigation were developed for use in STELLA. Given suitably accurate observing systems, these algorithms would provide sight reduction and positional fixes at the one arcsecond (30 meter) level of precision. Exploratory work to identify such a "suitably accurate observing system" is now underway[19]. The study is focusing on a hybrid system utilizing an automated star tracker (AST) operating in the far-red or near-infrared closely coupled to an inertial navigation system (INS). During periods of clear or partially clear weather, AST observations referenced to the local vertical and fed to the new navigation algorithms could provide high-accuracy positions of the vessel, day and night. These positions could also be used to continuously reinitialize the INS. The INS, in turn, could then provide vessel positions during times of high sky obscuration. Such a system could form an independent backup for a GPS-based navigation system.

ii. *Algorithms for High Precision Astrometry*

As astrometric requirements and measurement capabilities move from the milliarcsecond level to the microarcsecond level, it is necessary to assess the accuracy of current algorithms and improve them if need be. The astrometric algorithms, such as those implemented in NOVAS, are needed not only for the almanacs, but for other USNO programs as well. One recent study[20] compared two very different types of astrometric reduction—the approach based on angles, used for optical observations, and the approach based on interferometric delay, used for Very Long Baseline Interferometry (VLBI) observations. Despite their differences, both approaches should yield essentially identical results. A procedure by which VLBI algorithms can be used for optical observations was developed and implemented in software. This scheme allowed a large number of numerical tests to be performed, providing practical information on the differences between the angle-based and delay-based algorithms. The results of this study indicated that the differences between the two sets of algorithms in current use were less than one microarcsecond. This level of precision will be important for a new generation of astrometric satellites.

Summary and Conclusion

The Astronomical Applications Department of the U.S. Naval Observatory provides a variety of important and widely used astronomical data products and services. These products, produced or co-produced by the AA Department, carry the USNO seal throughout the world. *The Nautical Almanac* and STELLA are on board virtually every U.S. Navy ship, and are used on a daily basis. Furthermore, *The Nautical Almanac* is a near universal standard for civilian navigators. *The Astronomical Almanac* and MICA provide high precision astronomical data worldwide to intermediate and advanced users in a broad spectrum of technical disciplines. Air navigators still rely on *The Air Almanac* despite decreased use of celestial navigation from aircraft. Thousands of people from countries throughout the world visit the AA Department Web site each day, obtaining practical astronomical data for planning their activities. Finally, research conducted by AA Department staff has resulted in substantial, distinct improvements to the content of the products. This research has also contributed to the general, archival body of scientific knowledge. The work of the AA Department is still as relevant today as the mission of the Nautical Almanac Office was 150 years ago.

Acknowledgements

The author would like to thank the following members of the AA Department staff—Alan Fiala, James Hilton, George Kaplan, Marc Murison, and Susan Stewart—whose product and project descriptions, both published and unpublished, contributed to the content of this paper.

NOTES

1. J. A. Bangert and G. H. Kaplan, "MICA: A High-Precision Almanac for Small Computers," *Bulletin of the American Astronomical Society*, **24** (1992), 740.

2. U.S. Naval Observatory, *Multiyear Interactive Computer Almanac 1990-2005* (Richmond, Virginia: Willmann-Bell, 1998).

3. P. M. Janiczek, "STELLA: Toward Automated Celestial Navigation," *Surface Warfare*, **21**, No. 2 (1996), 34-37.

4. J. A. Bangert, "Set Your Sights on STELLA: New Celestial Navigation Software from USNO," *Chips*, **XIV**, No. 5 (1996), 5-7.

5. G. H. Kaplan, "Practical Sailing Formulas for Rhumb-Line Tracks on an Oblate Earth," *Navigation*, **42**, No. 2 (1995), 313-326.

6. G. H. Kaplan, "Determining the Position and Motion of a Vessel from Celestial Observations," *Navigation*, **42**, No. 4 (1995), 631-648.

7. G. H. Kaplan, "A Navigation Solution Involving Changes to Course and Speed," *Navigation*, **43**, No. 4 (1996), 469-482.

8. G.H. Kaplan, "NOVAS," *Bulletin of the American Astronomical Society*, **22**, No. 2 (1990), 930-931.

9. G. H Kaplan, J. A Hughes., P. K. Seidelmann, and C. A. Smith, "Mean and Apparent Place Computations in the New IAU System. III. Apparent, Topocentric, and Astrometric Places of Planets and Stars", *Astronomical Journal*, **97** (1989), 1197-1210.

10.A. D. Fiala, D. W. Dunham, S. Sofia, "Variation of the Solar Diameter from Solar Eclipse Observations, 1715-1991," *Solar Physics*, **152** (1994), 97-104. (Proceedings of IAU Colloquium 143, *The Sun as a Variable Star*, Boulder, Colorado, June 20-25, 1993.)

11. M. A. Murison, "Analytical Study of Optical Wavefront Aberrations Using Maple," *MapleTech*, **4**, No. 2 (1997), 52-62.

12. S. G. Stewart, M. N. Fanelli, G. G. Byrd, J. K. Hill, D. J. Westpfahl, K.-P.Cheng, R. W. O'Connell, M. S. Roberts, S. G. Neff, A. M. Smith, and T. P. Stecher, "Star Formation Triggering Mechanisms in Dwarf Gal-

axies: The Far- Ultraviolet, Hα, and HI Morphology of Holmberg II," *Astrophysical Journal*, submitted.

13. Additional and more detailed information concerning the Newcomb project can be found in the Research section of the AA Department World Wide Web site (*http://aa.usno.navy.mil/AA*).

14. M. E. Ash, "Generation of Planetary Ephemerides on an Electronic Computer," Lincoln Laboratory Technical Report 391, (1965).

15. J. L. Hilton, P. K. Seidelmann, J. Middour, "Prospects for Determining Asteroid Masses," *Astronomical Journal*, **112** (1996), 2319-2329.

16. J. L. Hilton, "The Mass of the Asteroid 15 Eunomia from Observations of 1313 Berna and 1284 Latvia," *Astronomical Journal*, **114** (1997), 402-408.

17. J. L. Hilton, "U.S. Naval Observatory Ephemerides of the Largest Asteroids," *Astronomical Journal*, **nn** (1999), ppp-ppp.

18. Ibid.

19. G. H. Kaplan, "New Technology for Celestial Navigation," these Proceedings.

20. G. H. Kaplan, "High Precision Algorithms for Astrometry: A Comparison of Two Approaches," *Astronomical Journal*, **115** (1998), 361-372.