THE NAVAL OBSERVATORY- SILENT PARTNER IN SURVEYING AND NAVIGATION

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ABSTRACT

The U.S. Naval Observatory's mission statement, places great emphasis on support of navigation. This paper provides a brief exposure to the history of the U.S. Naval Observatory. It then covers fundamental services provided to marine navigation, geodetic and surveying communities. Insofar as astrometry provides the fundamental inertial reference frame and the means to determine precise time, the U.S. Naval Observatory's "products" are the root source of accuracy in these fields without which positioning accuracy will deteriorate over a period of time.

This paper evaluates present "products" such as almanacs, precise time and stellar positions and goes on to discuss plans for the future to improve accuracy and support. Some of the areas considered are radio interferometry in support of time and polar motion, clock synchronization via satellite, automated almanacs, integration of celestial and radio navigation methods and the use of space vehicles for determination of stellar positions. The conclusion addresses anticipated accuracy requirements and the need for their identification.

Lieutenant Louis M. Goldsborough established, on 6 December 1830, under the aegis of the Naval Board, the Depot of Charts and Instruments. The Depot was intended originally to provide shore storage for naval charts and navigational instruments while the ships were in intercruise layups. Further, it was tasked to purchase and evaluate suitable and accurate navigational instruments. Associated with this tasking was the rating of ships' chronometers. At that time the most perfect "time keeper" was the rotation of the earth as observed by the daily transit of astronomical bodies. Naturally, this led to the development of an astronomical capability. Until 1842, the astronomical functions were carried out in a makeshift manner and it was not until then that the Congress authorized more appropriate quarters with adequate housing for the astronomical instruments. Lt. Matthew Fontaine Maury was appointed Superintendent in 1844 and it was under his leadership that the first astronomical document issued by a proper observatory on this side of the Atlantic was printed in 1846. From this time the international reputation of the Observatory began to rise. In 1854 The Secretary of Navy designated it "The United States Naval Observatory and Hydrographic Office." During this

period Lt. Maury had a time ball installed on the Observatory roof to aid the ships in the river in comparing their chronometers thus opening up its role in time dissemination. Under Maury, however, the hydrographic functions soon became paramount at the expense of astronomical observations. It was not until he left the Naval Observatory in 1861 that order was restored to the astronomical side of the house. The Hydrographic Office was split away in 1866. The Nautical Almanac Office was added in 1893 when the U.S. Naval Observatory was moved to its present location. From that time, the U.S. Naval Observatory has continued to provide astronomical information to navigators, surveyors and geodesists.

The mission of the U.S. Naval Observatory, which was first enunciated by the Secretary of the Navy in 1950, reads as follows:

"Make such observations of celestial bodies, natural and artificial, derive and publish such data as will afford to United States Naval vessels and aircraft as well as to all availing themselves thereof, means for safe navigation, including the provision of accurate time; and while pursuing this primary function, contribute material to the general advancement of navigation and astronomy."

To carry out this mission the Naval Observatory is divided fundamentally into three professional divisions, the Astrometry Division, the Time Service Division and the Nautical Almanac Office. Each of these divisions covers one of the major components of information required by a navigator, i.e., the position of the celestial body, the time, and the tables necessary to reduce the observations.

The Astrometry Division is charged with determining the precise positions and motions of selected stars, the sun, the moon and major and minor planets by observation and the cataloging of these observations. The star catalogues which are produced form the fundamental stellar (inertial) reference frame. Observations are accomplished by use of transit circle telescopes and of astrophotographic telescopes using photographic plates.

The Time Service Division maintains the Master Clock System for the United States. It has done this as a matter of historical precedent which, while challenged in the past, has not been altered. Precise time and time interval (PTTI)

for the Department of Defense (DoD) is defined in DoD Directive 5160.51A of 31 Aug 1971. Under this directive the Naval Observatory is charged with the responsibility for uniformity of PTTI operations. This division determines the standard time(UTC) for the U.S. by using an atomic time scale. It also determines time, defined by the rotation of the earth, by making observations of astronomical bodies as they pass through the zenith. These measurements are compared with the atomic time scale which maintains a more uniform rate. Part of its duties is to monitor the various time-dependent systems such as LORAN-C, Omega, Transit and the Global Positioning System (GPS) and publish differences with respect to Universal Time Coordinated (UTC) kept by the Master Clock System. These differences are available in Time Service Bulletins and through direct computer access by telephone. Because time is equivalent to longitude in navigation and geodesy, the Time Service Division constantly monitors the polar motion and earth rotation parameters. A new method, which will be discussed later, is the use of radio interferometry in monitoring these data.

The Nautical Almanac Office publishes the familiar Astronomical Almanac, Nautical Almanac and Air Almanac. There are many other publications which are less well-known by the general public, but which address more specific matters such as Astronomical Phenomena, times of sunrise and sunset, Almanac for Surveyors, etc. In addition to producing these publications, the Nautical Almanac Office is tasked with the responsibility for determining the precise motions of the solar system bodies, celestial mechanics (the theory of motions and behavior of the solar system), and prediction of astronomical phenomena.

Another aspect of the Naval Observatory which is not reflected directly by the above three divisions is that of navigation support. Navigation has figured heavily in the historical past of the Naval Observatory, but only recently has there been a drive to establish a division devoted principally to its management. This division, which will soon be established, will provide much-needed, centralized management support for the navigation program in the Navy.

The Naval Observatory acts not only for the Navy, but also for the nation and international astronomy as a whole. Its programs are fundamental to all aspects of astronomy, but often lack the glamor and public appeal enjoyed by those that study black holes and the "Big Bang". Because the programs carried out by the Naval Observatory are of such a long-term nature, they are not undertaken by institutions seeking grants or by academia with its rigid publication requirements. Only the government can make the long-term commitment in money, personnel and time to carry out these fundamental programs. What many of the Naval Observatory's programs lack in glamor, they make up for in importance. Nevertheless, there are many interesting investigations underway. For instance, research is being done to improve the observational accuracy by investigating new obser-

vational methods, the ongoing work in binary star observation to determine stellar masses and parallax determinations to determine stellar distances are of fundamental importance. A particularly interesting search is now underway by Naval Observatory celestial mechanics seeking to find a trans-Neptunian planet (Planet X). The Naval Observatory is a unique institution in that, while it generates products (time, almanacs and catalogues), it must at the same time carry out research to update its methods and instrumentation. This is so because there is no other center of expertise to carry out this research. To support this function, the Naval Observatory has a fully-equipped instrument shop where very delicate instruments such as micrometer mechanisms and telescopes can be fabricated or repaired.

The programs presently undertaken at the Naval Observatory are the very bedrock on which all positioning systems are founded. Too often our navigators have glanced blithely at the flashing red numbers on the face of some super-sophisticated navigation system, unaware of the fundamental role played by astronomy. The fact that tracking stations for satellite systems must be accurately positioned and the local azimuth determined with great precision is forgotten. The same holds true for the many electronic systems. Because the stars do make up the fundamental inertial reference frame, they must continue to be observed. Stellar proper motion and earth precession and nutation will continue to cause their apparent positions in the sky to move.

As can be seen from the above, there are many and varied "products" which come out of the Naval Observatory. This paper will continue by investigating these and their relationship to the navigating and surveying communities.

Fundamental to all positioning systems is the provision of some system which is inherently accurate in and of itself. This is currently the inertial reference frame formed by stars which are within our Galaxy. Such a reference frame is needed for the calibration of inertial and satellite navigation systems, satellite orbit calculations and predictions, precise guidance in space, precise positioning of tracking stations, geodesy and the observational input necessary to improve planetary theories and ephemerides. The Naval Observatory is the only institution in the U.S., or the western world for that matter, which carries out a continuous observation program of the fundamental stars using transit circle telescopes. These instruments have been used for almost two hundred years and are able to work independently of any assumptions about stellar positions. To develop an absolute catalogue, observations of the sun, planets and circumpolar stars help to define the astronomical equator and equinox for the epoch of the program. The stars can then be observed in conjunction with each other and the entire package forms a complete and tidy whole. To come up with a fundamental reference system, however, other catalogues (numbering in the hundreds) must be taken into

account in order to derive the extremely small, but still very important, motion of the stars with respect to each other (proper motion) necessary to bring the different epochs into conformance.

The current catalogue, to which all astronomers go is the Fourth Fundamental Catalogue (FK4). This will be supplanted in 1984 by the FK5. The FK5 will have greatly improved accuracies because many newer constants will be used and more stars with more modern observations will be included. These catalogues must be continually updated because of the apparent motion of the bodies relative to each other. Thus, if no observations or cataloguing were done, the FK information would soon deteriorate and become of little practical use to either astronomers or surveyors. Ten years ago the data accuracy was estimated to be about ten to one hundred times better than was required. Now, in some categories, the requirements have drawn even with the data and it is estimated that in the next five or ten years, the remaining categories will be even. This has occurred due to rapid technological advances in science and engineering in general and consequently in the development of weapons systems. In the categories of precise guidance in space, and precise positioning of tracking stations, the requirements have drawn even with the data. In the categories of precise positioning using time-synchronized systems and calibration of satellite navigation systems, it is expected that the requirements will draw even in about 5-10 years. The worrisome aspect of these facts is that it will take almost ten years to accomplish a program of observations and several years to prepare for it.

What is needed is accuracy improvement. The FK4 provides positions of one star per 30 square degrees with an average error of about 0.15 arc sec in the northern hemisphere and with errors greater than 0.30 arc sec in the southern hemisphere (with deviations greater than one arc second in unspecified cases). Reference stars for photographic catalogues have densities of 1 star per square degree and photographic catalogues covering fainter stars have 10-20 stars per square degree. As stated above, the southern hemisphere accuracies are much worse than in the northern hemisphere. The Naval Observatory will begin an observational program in New Zealand commencing next year. This program will tie both hemispheres more closely together and enable a much more complete frame of reference to be developed with pole-to-pole coverage for the first time. Further coverage of the fainter stars will be carried out with a double astrograph. The photographic plates collected will be measured on the two measuring engines at the Naval Observatory. The largest of these, STARSCAN, can measure positions on the plate to an accuracy of 0.5 micron automatically.

Another method of improving accuracy is the study of real-time atmospheric refraction determination through the use of LIDAR (the optical analog of radar) or water vapor radiometers. Optical and infrared interferometry are other promising areas

which are expected to improve accuracies of bright stars by a factor of ten. The Naval Observatory's 6-inch transit circle is the most precise instrument of its kind in the world with an accuracy of ± 0.1 arc sec in an individual stellar position. It reads large angles directly with accuracy greater than that of any other instrument. However, inertial devices such as ring laser gyros are being investigated and show promise of eventually being able to improve on the circle-oriented systems which are unusable in space.

A breakthrough here would allow the development of an astrometric satellite which could be orbited above the disturbing influences of the atmosphere and gravity on the instrument. Such a satellite would enable stellar positions to be determined to up to 0.01-0.001 arc sec accuracy and the proper motion to be extrapolated to about 0.01 arc sec per century. It will allow for the tying together of quasars with brighter optical sources thus further strengthening the inertial aspect of the stellar reference frame. The end result would be the better knowledge of the positions of the stars and planets and increased accuracies for all functions requiring astronomical positions. The Naval Observatory is taking an advisory role in the development of the Space Telescope, though its use for astrometric observations appears to be some years away. Similarly the European efforts to launch the satellite HIPPARCHOS, especially dedicated to the determination of stellar positions, will be watched with interest. To this end, the Naval Observatory will contribute input data for the HIPPARCHOS Project.

The Naval Observatory has begun work on the development of a composite, fundamental catalogue containing 6000 stars from the best of the absolute catalogues and observation programs of the last hundred years. All positions will be computed using first principles with modern refinements. The outcome should provide the most accurate inertial reference frame to date.

The Time Service Division determines astronomical and clock times as well as polar motion. Dissemination of time is not generally accomplished by the Naval Observatory itself, but by other organizations. Transmissions are monitored by the Naval Observatory and corrections are published. Data collected are provided to the Bureau International de l'Heure (BIH) in Paris, France. The BIH is the international standard for time and polar motion. About 23% of the total weight in the determination of earth rotation (UT1-UTC) and about 6% in the polar motion comes from the Naval Observatory. It is one of the greatest single contributors to the BIH. It should be noted that there are 75 observatories contributing polar motion data to the BIH of which 42 are located in Communist countries.

Astronomical time (UT1) is determined both at Washington and at the Substation in Richmond, Florida. This time is used in a straightforward manner by both celestial navigators and geodesists. It is never more than a second from UTC and

the difference (DUT1) is provided to the user by various means. Coupled with this function is a program which monitors polar motion. Presently the observations allow a prediction of longitude (i.e., time differences) to an accuracy of 2 ms with ten days advance notice and 6.5 ms with 40 days notice. The predictions will be improved by the use of additional instruments using high technology, including the 65-cm photographic zenith tube, radio interferometry and laser techniques.

Polar motion takes on paramount importance when considering military targeting. It affects not only the target location but also the launch azimuth. Stellar tracking devices alleviate some but not all of these problems. Other important user functions are Transit satellite and Global Positioning System tracking.

A new program to determine earth rotation and polar motion was started four years ago, using the connected element radio interferometer at Green Bank, West Virginia. Such a facility, with its 35 km baseline, allows for twenty-four hour, all-weather collection of data based on radio emissions received from quasars. Quasars are among the most distant objects in the universe, as it is now known, and their relative motion is for all intents and purposes equal to zero. It is expected that near real time output of polar motion and UT1-UTC values will be achieved. Positional accuracies of these quasars are presently reaching 0.01 arc sec and the radio positional reference frame has an internal precision better than 0.02 arc sec. Most importantly, this system is independent of foreign sources. Planned improvements in this area will be the addition of a leg normal to the present baseline. In conjunction with this work, an investigation is underway to evaluate the effects of water vapor on the delay of the radio signal. These effects appear to make the largest error contributions to the observational data.

The matter of Clock Time is considerably more complex. The Master Clock of the U.S. consists in reality of two separate and independent systems. Each uses a computer to sample an ensemble of between 20 to 24 cesium beam frequency standards. Then, using a computer algorithm, a time scale is determined with a system internal precision of about one nanosecond per day.

Precise clock time is the heart of modern electronic radio navigation systems. Not only do they depend on precise time but they are the primary disseminators of it. The Naval Observatory monitors all systems which are dependent upon, or disseminate, precise time and provides users with corrections to bring them in conformance with the Master Clock. Such information is available through a variety of Time Service Bulletins or by directly accessing the computer which is tied to the Master Clock System. This computer link was brought on line recently and it is accessed frequently by users at sea over INMARSAT. A recent study done for the Naval Observatory has revealed accuracy requirements for precise time as stringent as 1 ns for certain applications in

electronic (satellite) navigation and communications. Frequency precision is required for ship platforms from 1×10^{-10} to 1×10^{-12} .

Precise time dissemination is done either by portable clock or over the Defense Satellite Communications System (DSCS). The latter provides accuracy of 0.2-0.3 microseconds. The Naval Observatory operates a network of Precise Time Reference Stations world-wide which both monitor and disseminate precise time, as required. These stations, when located with DSCS SATCOM terminals, are able to maintain these accuracies and are fully automatic, making contact daily with the computer located in the Naval Observatory.

A major problem for the Naval Observatory is the dissemination of this time in the best way possible. The tried and true method in the past has been to send out portable atomic clocks. However, the increasing accuracy requirements have necessitated a search for better methods. The Naval Observatory has been investigating the use of laser time transfer. This would allow two stations in widely-separated locations to bounce laser beams off a satellite. Through the use of an event-timer, a measurement of the difference in arrival time of the laser pulses from those stations and the time difference can be derived. It is expected that a time transfer of better than 1 ns could be achieved. This will be tried soon in conjunction with the European LASSO satellite.

Many people have been quick to embrace GPS as the answer to navigators' and marine surveyors' prayers. This may, however, not be as straightforward as many think when it comes to the requirements for seeking extreme precision. There is no capability to utilize the high quality clocks in the GPS, and the evaluation of those clocks could well become a problem. Because of possible orbital errors, there will be no guarantee that satellite positions will be accurately known. The error budget of 30-50 ns in the GPS clock will result in an error in the estimated distance involved by about 10 meters. Such of an error could be greatly reduced by simultaneously tracking a GPS satellite from two stations, using a laser at each and utilizing the information to update the clocks.

Very Long Baseline Interferometry (VLBI) may provide another method for time transfer. This involves a radio interferometer consisting of two telescopes located at positions far distant (transcontinental and transatlantic) from each other which, through the simultaneous observation of quasars, would be able to determine very accurately the differences between the Maser clocks at each station. The Naval Observatory sees this as an excellent opportunity for time transfer with possible accuracies to within 1 ns. VLBI also has potential for the measurement of polar motion and UT1. A VLBI chain is presently being established by the National Geodetic Survey and is being watched carefully in order to evaluate its use in solving some of the above time transfer problems and the determination of polar motion. The Naval

Observatory is cooperating in this effort by allowing the installation of one of the antennas at its Richmond, Florida Substation.

The cesium beam frequency standards, which together form the Master Clock have extremely high long-term stability. However, random fluctuations cause errors in the real-time read-out of 5-10 ns. Although these errors can be corrected through mathematical analysis days after the read-out, requirements for real-time read-out to 1 ns precision or better have forced the Naval Observatory to begin a program of upgrading the Master Clock. The addition of Hydrogen Masers and Superconducting Cavity Oscillators, combined with a vastly improved data acquisition system, will allow real-time sub-nanosecond read-out and also maintain a stability of 1 ns in ten days. This, in turn, will provide the calibration stability to allow remote platform clocks to keep to within required tolerances for periods in excess of one year.

The Nautical Almanac Office at the Naval Observatory produces the almanacs mentioned above. Additionally, it does many of the special computations necessary to predict astronomical phenomena and solar system ephemerides. A great deal of support is given by the Nautical Almanac Office to NASA for its outer planet space probes.

In order to accurately predict the positions of the sun, moon, planets and natural satellites, the Nautical Almanac Office must apply, in depth, the theories of celestial mechanics. This is one of the driving forces behind the study now underway at the Naval Observatory to predict the existence of, and to later find, a trans-Neptunian planet. This planet is believed to exist because theory has not been able to predict the position of the outer planets without acknowledging the probable existence of an undiscovered perturbing body.

Present requirements for navigational almanacs are ± 3 arc sec, while those for astronomers are ± 0.001 arc sec. Much of the information in the almanacs is now available in the Almanac for Computers which is designed for hand-held calculator users. This publication allows for maximum flexibility for the user and gives a foretaste of what might be available to navigators and geodesists in the future.

This leads into a discussion on the establishment of the Naval Observatory's new Navigation Division, which will be established later this year with the arrival of a naval commander. He will be the first of a growing team whose responsibility it will be to work closely with the Oceanographer of the Navy in the coordination and management of the Navy's conventional navigation program. By conventional navigation, it is intended to mean non-radiolocation methods, though there will be a coordinating function to ensure that the navigation suites aboard all platforms are integrated with other systems. One of the programs to be undertaken is the development of a Future Integrated Navigation System (FINS) which will

coordinate all navigation functions on a given platform with the intention of integrating them into one system. A logical progression in instrumentation might very well include a digital sextant which could read directly into a computer. The computer would take inputs from all other navigation systems aboard the platform and give a best position based on the weights of the various equipment and system accuracies.

There is already a contract let with the Naval Air Development Center to investigate requirements for conventional navigation expertise. Another contract has been let to investigate the development of a low-light digital sextant. The navigation community can expect to see a lot more action from the Naval Observatory than it has in the past.

The problem of meeting the requirements of the many and varied users of U.S. Naval Observatory "products" is a difficult one. It becomes one of fundamentally anticipating the accuracies required by the users who have equipment and instrumentation which is still under development. Because of the lead time necessary to carry out astronomical observations, a great deal of foresight is necessary, especially from the astronomers. Few users are willing to commit funds on as-yet-unspecified accuracy requirements. Thus the U.S. Naval Observatory continues, as mentioned above, to press for and undertake research in PITI, astrometry and celestial mechanics. The more lead time that users can give, the better the chance that the requirements will be met. The U.S. Naval Observatory will continue to seek requirements from the users and will strive to maintain the highest possible accuracies. This can only be done with the help of every user.