# U.S. Naval Observatory

*Washington, DC 20392-5420*

This report covers the period July 2001 through June 2002.

## I. PERSONNEL

### A. Civilian Personnel

Marie R. Lukac retired from the Astronomical Applications Department.

Scott G. Crane, Lisa Nelson Moreau, Steven E. Peil, and Alan L. Smith joined the Time Service (TS) Department. Phyllis Cook and Phu Mai departed.

Brian Luzum and head James R. Ray left the Earth Orientation (EO) Department.

Ralph A. Gaume became head of the Astrometry Department (AD) in June 2002. Added to the staff were Trudy Tillman, Stephanie Potter, and Charles Crawford. In the Instrument Shop, Tie Siemers, formerly a contractor, was hired fulltime. Ellis R. Holdenried retired. Also departing were Charles Crawford and Brian Pohl.

William Ketzeback and John Horne left the Flagstaff Station.

Correction to 1999/2000 Observatory Report: Alan D. Fiala (Astronomical Applications Department) retired as chief of the Nautical Almanac Office in June 2000. David R. Florkowski (EO) also retired. Baki Iz left the EO staff.

Corrections to 2000/2001 Observatory Report: Brent Archinal (EO), and Marshall Eubanks (EO) did not retire, but left for employment elsewhere. James O. Martin (EO) did retire. David Johns joined the TS staff. Bryan N. Dorland joined the AD staff and Robert B. Hindsley left. Student Temporary Employees included William Neal Potter (TS) and Danell Sorinmade (Library). Casey Johnson was an aide in TS.

### B. Engineering Apprenticeship Program

The United States Naval Observatory (USNO) summer intern program for high school and college students continued. This program, called the Science and Engineering Apprenticeship Program (SEAP), is sponsored by the Department of Defense (DoD) and managed by George Washington University. For the summer of 2001, under the direction of D. Pascu (AD) and L. Schmidt (TS), the interns and the departments they worked in were Shawnette Adams (Public Affairs), Calvin Ashmore (Library), Andrew Cenko (AD), Arthur Hyder (TS), Dean Kang (AD), Anne Kurtz (TS), Steven Movit (AD), Paul Ries (AD), Diana Seymour (AD), Sabrina Snell (AD), and Lim Vu (EO).

## II. ASTRONOMICAL APPLICATIONS DEPARTMENT

The Department continued to perform its core mission of providing practical astronomical information and data via printed publications, software products, and the World Wide Web. The Department's products are used by the U.S. Navy, other components of the U.S. government, the international scientific community, and the general public. The Department also maintains a research program in positional and dynamical astronomy in order to meet future needs. J. Bangert continued to serve as Department head.

### A. Almanacs and Other Publications

The Nautical Almanac Office (NAO), a division of the Astronomical Applications Department (AA), is responsible for the printed publications of the Department. S. Howard is Chief of the NAO. The NAO collaborates with Her Majesty's Nautical Almanac Office (HMNAO) of the United Kingdom to produce *The Astronomical Almanac*, *The Astronomical Almanac Online*, *The Nautical Almanac*, *The Air Almanac*, and *Astronomical Phenomena*. The two almanac offices meet twice yearly to discuss and agree upon policy, science, and technical changes to the almanacs, especially to *The Astronomical Almanac*.

Each almanac edition contains data for 1 year. These publications are now on a well-established production schedule. *The Astronomical Almanac* is available 1 year prior to the year of the edition, *The Air* and *Nautical Almanacs* are available 9 months prior, and *Astronomical Phenomena* is available 3 years prior. During the reporting period, the almanacs for 2003 and *Astronomical Phenomena* for 2004 were published. At the end of the reporting period, the next editions were in preparation and on schedule. All the publications are sold in the United States by the U.S. Government Printing Office (*http://bookstore.gpo.gov/index.html*). *The Astronomical Almanac Online*, a Web site that complements *The Astronomical Almanac*, went live in January 2002. M. Lukac, R. Miller, S. Stewart, M. Stollberg, and Howard participated in the production of the annual publications.

There are four major efforts ongoing within the NAO: the first to update and enhance the science content of *The Astronomical Almanac*; the second to revise the *Explanatory Supplement to The Astronomical Almanac;* the third to continue adapting the products to meet the needs of the U.S. Navy and the worldwide scientific community; and the fourth to streamline and update production. All are multiyear efforts and involve the entire staff of the NAO.

During this reporting period, there were several improvements to the science and technical algorithms in the almanacs. These improvements will be implemented in future editions of *The Astronomical Almanac*. As part of the continuous review of the underlying science, Stollberg incorporated the latest orbital parameters in all the planetary satellite algorithms used for *The Astronomical Almanac*. Changes in *The Astronomical Almanac* for 2004 include removing the International Astronomical Union (IAU) 1976 list of astronomical constants from the printed book and placing it on the complementary Web site. In place of this list, the printed book will list the constants (and references) used in the computations. Data for the obsolete Besselian day numbers will be removed. The 2004 edition also will contain two new tables: one for bright double stars (produced by Stewart using data provided by B. Mason [AD]), and one for bright gamma ray sources (produced by Stollberg and N. Gehrels, NASA/GSFC). Future plans include improving the methodology used to compute the orbital positions of short-period ($<$ 90 days) satellites. Stollberg is working closely with HMNAO staff on this revision. The new method uses a mixed-function expansion solution for a satellite orbit that produces coefficients suitable for a straightforward production of offsets for every day of the year. This mitigates the technical difficulties of the older methods that cannot adequately handle short-period satellites. The 2005 edition will use the mixed function method for the short-period satellites. Howard presented papers on the status of and future plans for *The Astronomical Almanac* at the January 2002 AAS Meeting and the April 2002 Division on Dynamical Astronomy (DDA) Meeting.

The almanac offices have a plan to implement the relevant resolutions of the XXIVth IAU General Assembly (2000). Bangert presented a paper on this subject at the International Earth Rotation Service (IERS) Paris Workshop in April 2002. Resolution B1.6 encourages the use of the new IAU 2000 precession-nutation theory. This theory was not received in time to incorporate it into the 2004 edition of *The Astronomical Almanac*. Incorporation into future editions will occur when this theory and the accompanying precession theory are available. Resolution B1.8 recommends that the IERS take steps to implement the use of the "non-rotating origin" (NRO) in the Geocentric Celestial Reference System, and that this point be designated as the Celestial Ephemeris Origin on the equator of the Celestial Intermediate Pole. The implications of this resolution on the contents of *The Astronomical Almanac* remain under review by both the NAO and HMNAO. The almanac offices plan a gradual introduction of these concepts, especially of the coordinate systems presented, over a period of several years. Thus, *The Astronomical Almanac* for 2004 will not incorporate these two resolutions.

The information contained in *The Astronomical Almanac* is highly technical and covers a diverse range of topics. To avoid excessive, repetitive detail, the book omits a great deal of background material. The two almanac offices collaborate to provide this background material through the *Explanatory Supplement to The Astronomical Almanac*, published on an irregular basis. The first edition appeared in 1961; the last edition of the book appeared in 1992. Since 1992 there have been many changes to the data and underlying theories; therefore, material in the *Explanatory Supplement to The Astronomical Almanac* is now out of date. P. Seidelmann (U. Virginia), the editor of the last edition, and Howard will coedit the next edition of this book. Staff from both almanac offices, as well as many outside authors will contribute material. The production schedule calls for submission to the publisher at the end of 2003.

The use of celestial navigation from aircraft has been rapidly declining. In July 2002, USNO requested all recipients of *The Air Almanac* to provide their requirements for the book. The results of this survey, when combined with the earlier survey of the U.S. military, will determine the future of the present form of the book.

Miller, Stewart, and Stollberg created a set of standard software routines now used in all production code. Lukac streamlined and documented the already rigorous data verification and proofing process. Miller simplified the graphics production of the eclipse maps and the satellite diagrams.

The NAO still receives written requests for special astronomical data tables, although data provided through the Department's Web site (*http://aa.usno.navy.mil*) have greatly decreased the number of such requests. Lukac, Chief Quartermaster B. Wass, and Y. Holley handled these requests.

### B. Software Products

The Product Development Division, headed by N. Oliversen, is responsible for the Department's software products and the Department's Web site.

STELLA (System to Estimate Latitude and Longitude Astronomically), a celestial navigation software tool developed by USNO specifically for the U.S. military, continues to be widely used throughout the Navy and Coast Guard. The current version of STELLA (Version 2.0) is a Windows/PC application, which can perform calculations over an extended time period (1970-2010). W. Harris made significant progress in the development of a version of STELLA for handheld computers running the Palm OS. Most major design challenges have been solved and a prototype version of this software should be ready for demonstration and testing by fall 2002. There is strong interest in a Palm version of STELLA by several Navy organizations and by the Coast Guard.

MICA (Multi-year Interactive Computer Almanac) is a software tool that provides high-precision astronomical data in tabular form for the time interval 1990-2005. MICA 1.5 is available as a DOS application for Windows/PC computers, and as an application for Mac OS computers. Willmann-Bell, Inc. (*http://www.willbell.com/*) distributes MICA for USNO. Design and development work continued on MICA 2.0, which will be a major upgrade of this software. The new version will feature a revamped user interface and several new capabilities. New capabilities will include more sophisticated rise/set/transit computations, positions of selected minor planets and the Galilean satellites of Jupiter, local circumstances of solar and lunar eclipses and transits of Mercury and Venus, and a search tool for other astronomical phenomena (e.g. Moon phases, conjunctions, oppositions, elongations, etc.). An initial version of the computational engine code was completed and extensive verification tests were in progress at the end of the reporting period. Software is being developed for supporting selected astrometric catalogs within MICA utilizing a commercial database management system. Prototype user interfaces have been created for both the Windows/PC and for the Mac OS versions. Beta testing of MICA 2.0 should begin in fall 2002. The MICA 2.0 development team includes W. Tangren, Harris, W. Hultquist Puatua, and Oliversen.

### C. Positional and Dynamical Astronomy

J. Hilton and Bangert made a practical evaluation of several new precession/nutation theories, including the new IAU precession-nutation theory IAU 2000A by Mathews et al.

(2002, J Geophys Res **107,** B4, 10.1029/ 2001JB000165). This theory is intended to be used as modification of the old IAU precession theory (Lieske et al. 1977, AA **58**, 1) and as a replacement of the old IAU nutation theory (Wahr 1981, GeophysJRAS **64**, 705). Hilton found several inconsistencies in the new theory. There are references to two different definitions of the mean ecliptic, two different precession rates, three different obliquities of the ecliptic, and a set of mean elements ultimately based on DE200 rather than the current DE405. It is not clear how these inconsistencies will affect the final product, but misapplication could affect the position of the pole by as much as 0.″029, or there could be a systematic error in the value of $J_2$ for the Earth of about 0.01%. Given the differences in the basic models in the old and new theories, there appears to be no suitable way to apply the new precession-nutation theory and guarantee there has not been a misapplication. Thus, Hilton, along with J. Williams (Jet Propulsion Laboratory [JPL]) and T. Fukushima (NAO Japan) began work on a new precession theory consistent with the IAU 2000A nutation.

Hilton prepared and gave papers on the relationship between the parameters describing the Celestial Ephemeris Origin and those describing the dynamical equinox. These papers were presented at the IERS Paris Workshop in April 2002, and at the DDA 2002 Meeting. He is currently at work drafting a version for publication in *Astronomy and Astrophysics*.

Hilton and C. Hohenkerk (HMNAO) produced a rotation matrix between the International Celestial Reference Frame (ICRF) and the mean reference frame of J2000.0. A paper will be submitted for publication during the last half of 2002.

M. Murison (AD) and Hilton began work on a new definition for the mean ecliptic. Although the non-rotating origin abandons the ecliptic and equinox, there are still many applications that require an ecliptic. This new definition will replace the ecliptic derived by Newcomb and updated by Lieske et al. (1977). It will have the advantages of not hiding the physics that determines the mean ecliptic, will be valid for a much longer period of time (the current definition is only valid from 1600 to 2100), and will be precise enough for microarcsecond ($\mu$as) astrometry (the current definition is precise to only 100 $\mu$as).

Hilton continued work on the USNO/AE2001 asteroid ephemerides. These ephemerides are of the 78 asteroids not included in USNO/AE1999 (Hilton 1999, AJ**117**, 1077), which have mean magnitudes at opposition brighter than 11 (or 12 if the estimated diameter is $>$ 200 km). Holley is providing data entry of 19th century transit observations of those asteroids in USNO/AE2001.

Hilton, along with J.-L. Margot (Caltech), explored the possibility of using radar ranging from the Arecibo radio telescope to determine the masses of main belt asteroids by ranging to perturbed test asteroids. They looked at all known encounters for the next 5 years. The result of their work showed that only 9 Metis, which is perturbed by Vesta, was both large enough and close enough at the time of encounter to be observed in this way. Unfortunately, at the same time, Metis is in the middle of a 2 1/2 year excursion outside of the declination range of the Arecibo radio telescope.

The chapter on asteroid masses and densities written by Hilton for the forthcoming book, *Asteroids III*, was accepted. The book, intended to be the basic reference for asteroid science, will be published in late 2002.

Puatua, with guidance from G. Kaplan (AD), worked on a program to read Galilean satellite ephemerides and compare those position angles and separations with observed data provided by Mason. This work supports an ongoing USNO project to make speckle interferometric observations of close pairings of the four Galilean satellites of Jupiter.

### D. World Wide Web Site

The Department's Web site (*http://aa.usno.navy.mil/*) continued to grow in popularity. The site handled between 9,000 to over 16,000 user sessions per day during the reporting period. This is an average increase of about 30% compared to the previous year. Everyone on the scientific staff contributed content and support to the site. Tangren maintains the Department's Web server.

The Department staff continued to answer questions related to the Department's mission, submitted by e-mail from Web site users. Several questions per day are received, on average, and response time is typically one or two workdays.

### E. Other Research and Activities

Bangert, along with Commander C. Gregerson (USNO Requirements Officer), Kaplan, and several members of the Space and Naval Warfare Systems Command System Center San Diego (SSC-SD), continued to explore the concept of automated celestial navigation as an accurate navigation backup to the Global Positioning System (GPS). Small Business Innovative Research (SBIR) contracts were awarded through SSC-SD to two companies to begin development of a daytime electronic stellar imaging capability. Bangert and Kaplan wrote a section on automated celestial navigation for a paper entitled ''Alternatives to GPS,'' given at the Oceans 2001 conference in Hawaii in November 2001. Staff at SSC-SD coauthored the paper.

Oliversen continued work on a NASA Astrophysics Data Program project to develop improved extraction software for International Ultraviolet Explorer short-wavelength, high-dispersion data processed with the ''NEWSIPS'' processing system. IDL software was used to study the shape of the short wavelength (SWP) cross-dispersion echelle profiles in the resampled image (SIHI) file. It was determined that the cross-dispersion profile contributes relatively little to the short-wavelength rise in background for hot-star spectra. Echelle-scattered light is the most likely source of this background. The cross-dispersion profiles of several optimally exposed and heavily overexposed emission lines in the short wavelength region of the SWP camera were also measured as a function of position on the camera.

Stewart and G. Byrd (U. Alabama) are studying the recent star formation in the dwarf galaxy IC2574. Stewart's past research of the super star cluster in the galaxy presented the first direct observations of triggered star formation. They plan further analyses that include simulating possible galaxy interactions as the triggering mechanism. The simulations will address the question why super star clusters favor dwarf galaxies. Howard will prepare and run the necessary simulations. Stewart drafted a proposal for the project. Puatua will also assist on this project as all four participants begin the detailed analyses.

Stollberg drafted a proposal to continue his studies of x-ray sources both isolated and in binary systems. He is collaborating with several members of the Compton Gamma Ray Observatory BATSE team to complete his analysis of the Crab Pulsar and mine the BATSE data for other fast pulsars. He installed locally the special data reduction software used by the x-ray community.

Howard was elected to the Executive Committee of the DDA. Hilton continued to serve as chair of the DDA Archives Committee.

Bangert continued to serve on the IAU's Standards for Fundamental Astronomy (SOFA) Review Board. The goal of the SOFA initiative (*http://www.starlink.rl.ac.uk/~sofa/*) is to establish and maintain an accessible and authoritative set of constants, algorithms, and procedures that implement standard models used in fundamental astronomy.

## III. TIME SERVICE DEPARTMENT

### A. Master Clock Operations

In order to provide accurate and precise time, USNO currently maintains an ensemble of 71 cesium-beam frequency standards and 15 cavity-tuned masers in three buildings in Washington, DC and at Schriever Air Force Base in Colorado, and provides clock data to the Bureau International des Poids et Mesures (BIPM). Improved timescale operations involving less aggressive clock characterization, better prediction algorithms, and gentler steering were developed. UTC (USNO) has stayed within 4.6 ns of UTC; the rms of UTC-UTC (USNO) over January-July 2002 was ± 2.6 nanoseconds (ns).

L. Breakiron maintained the Bldg. 52 and 78 and Alternate Master Clock (AMC) mean timescales that are based on data taken with the Timing Solutions Corp. (TSC; formerly Steintec) measurement systems. He copied and adapted all the timescale programs from the ''Simon'' computer to its replacement ''Hathor,'' as well as from AMC's ''Tycho'' to its replacement ''Wings.''

Breakiron published a study of the practicality of replacing the currently operational mean timescale algorithm with one based on a two-state Kalman filter, showing that TSC data from seven hydrogen masers could be utilized to generate a mean timescale even more stable than the one currently used for steering the USNO Master Clocks. He demonstrated a similar result for data for taken from 56 cesium clocks with the Data Acquisition System (DAS).

P. Koppang worked on the operational MC system as well as timescale and control system research, co-authoring six papers on precise time control systems and statistical analysis. He investigated utilizing control theory to optimally combine frequency standards into an ensemble.

### B. Global Positioning System (GPS) Operations

Monitoring of GPS Time has been improved through the installation of calibrated TTR-12 receivers and the use of a raised antenna mount for multipath reduction. Supporting GPS Operations were four STel 5401C Precise Positioning Service (PPS) receivers, four Allen Osborne Associates (AOA) TTR-12 PPS receivers, two AOA TTR-6 Standard Positioning Service (SPS) receivers, one Motorola Oncore SPS receiver, and one R100 GPS/GLONASS receiver. One STel 5401C PPS receiver, one AOA TTR-12 PPS receiver and one Motorola Oncore SPS receiver were in operation at the AMC site. One STel 5401C PPS receiver failed at the AMC.

The STel 5401C PPS receivers were the operational receivers that provided the daily downloads to the GPS Master Control Station (MCS) for GPS Time synchronization to UTC (USNO). The GPS timescale was maintained to within Å 15 ns of UTC (USNO) (specification: Å 1 microsecond) and the yearly average error of UTC transmitted from GPS was Å 5 ns (specification: 28 ns). Clock information was also been contributed to the International GPS Service (IGS).

D. Johns, L. Moreau, E. Powers, L. Schmidt, and F. Vannicola conducted extensive hardware and software testing of the AOA TTR-12 PPS receivers for replacement of the STel 5401C PPS receivers. Absolute calibrations were conducted by Moreau and Powers at the U.S. Naval Research Laboratory (NRL) for the TTR-12 receivers, antennas, and antenna splitters. W. King acquired and installed the required computer and network hardware for data acquisition and transmission.

Moreau repaired and helped Vannicola to maintain operation of the R100 Glonass/GPS receiver. Moreau and Powers calibrated the AOA TTR-12 and Motorola Oncore receivers in preparation for operational status in June. Moreau, Vannicola, and Powers prepared the AOA TTR-12, Ashtech Z-12T, and Motorola Oncore GPS receivers for operational status at USNO and AMC. Moreau installed the new operational SPS and PPS GPS operations equipment at AMC with the help of L. Schmidt, J. Skinner, and W. Bollwerk. Moreau calibrated various other GPS receivers, evaluated GPS equipment for numerous customers, and presenting information at meetings. She also performed GPS carrier-phase research, primarily in cooperation with NIST. She reviewed the specifications for the SAASM AOA receivers and provided daily support for other operational PPS and SPS receivers.

Vannicola and King worked with GPS MCS contractors to set up testing of SIPRnet connections for future data transfers to the GPS MCS.

Vannicola, Moreau, and L. Schmidt discovered an anomaly in the GPS single-frequency ionospheric model computed by the receivers at USNO, the National Institute of Standards and Technology (NIST), and the National Physical Laboratory (NPL) in the UK starting 29 May. The 2nd Satellite Operations Squadron at the GPS MCS was notified, as was BIPM. The problem, which degraded GPS performance by tens of ns, lay in the broadcast parameters used to compute the single-frequency ionospheric model. They were corrected, and normal broadcast parameters resumed 1 June.

Vannicola and Moreau installed and processed time transfer data for visiting GPS SPS receivers from BIPM, NIST, NPL, and Real Instituto y Observatorio de la Armada, Spain.

Vannicola maintained receivers, coordinated the hardware setup of the TTR-12 systems, improving reduction and analysis software with increased error checking and additional common-view scripts, and began migrating the operational GPS software to the new UNIX system ‘‘Hathor.’’

### C. Loran-C Operations

H. Chadsey developed and implemented an upgraded computer system to control the LORAN receivers and collect timing data for processing and reporting to the US Coast Guard. The new system uses inexpensive PCs running LINUX, and communication with the other computers is done through secure-shell login over the Internet, eliminating the need for unreliable modem connections.

### D. Wide Area Augmentation System (WAAS) Operations

Chadsey developed and began evaluation of the FAA Wide Area Augmentation System (WAAS) timing information as a means for time transfer.

### E. Computer Operations

Johns developed time synchronization software for the GPS and Network Timing Protocol (NTP) projects. He wrote device and reference clock drivers that allow NTP to communicate with commercial timing hardware on HP-UX servers, and worked on operational programs for the TTR-12 GPS receivers. He investigated real-time methods of data processing by implementing recursive algorithms in a client-server architecture.

R. Schmidt procured, installed, and implemented an HP N4000 server called ‘‘Hathor’’ and a VA7100 fiber virtual disk array, as well as the associated operating, security, file, and backup systems as the first step in a plan to establish a high-availability, fault-tolerant computing environment. He also replaced the operating system and many applications on the TS Web server ‘‘Tycho.’’ King and R. Schmidt configured the replacement HP 9000 server ‘‘Wings’’ at the AMC, as well as the associated operating, security, file, and backup systems, user accounts, and LAN connections with help from AMC staff and Johns. Omniback backup systems have been expanded to cover 44 computers at USNO and the AMC.

R. Schmidt and Johns configured and tested new NTP servers. NTP traffic coming into USNO Washington now exceeds 800 hits/second and that at the AMC and other USNO NTP sites exceeds an additional 400 hits/second. Four USNO NTP servers were selected by the Executive Office of the President of the United States as its sources of time synchronization. Schmidt installed the operating system and IRIG-b and GPS synchronized generators in HP A180 NTP servers as replacements for failing NTP servers.

R. Schmidt and Johns produced system-level device drivers for the next generation NTP server using Brandywine PCI synchronized generators to replace VME systems presently in use. Regarding SIPRnet, Schmidt continued work on a GPS PPS NTP server, maintained an HP 748i VME development box, and configured VME servers as part of a project to produce a keyed GPS PPS receiver with a rubidium flywheel.

### F. Alternate Master Clock (AMC) Operations

During August 2001, Skinner and L. Schmidt transferred from USNO Washington to the AMC in Colorado Springs, Colorado.

L. Schmidt earned a Ph.D. in mathematical statistics upon completion of her research on fractionally integrated noise processes applied to atomic clock models. She prepared several papers and talks on the subject, including ones at USNO, the Fourth International Time Scale Algorithms Symposium, the Colorado Springs IEEE section, the Mathematics Department of the University of Southern Colorado, and the journal *Metrologia*.

L. Schmidt automated a statistical process control methodology for AMC environmental, clock, and time transfer data. She assumed responsibility for maintaining the AMC timescale and incorporated several statistical techniques including parameter-change determination via optimal least-squares estimators, estimation of clock frequency and drift via fractional differencing for removal of serial correlations, and corrections for the clock-ensemble effect.

Skinner continued to work with Breakiron and P. Koppang on analysis and systems in Washington, DC, as well as on those at the AMC. He also worked with Koppang on possible improvements to the algorithm used to steer the Alternate Master Clock to the Master Clock in Washington, leading to a published paper. Skinner completed his first year of coursework in the Ph.D. program in mathematics at the Colorado School of Mines in Golden, Colorado.

### G. Two-Way Satellite Time Transfer (TWSTT) Operations

TS participated in Two-Way Satellite Time Transfer (TWSTT) for the generation of International Atomic Time. Timing links to NPL and the Physikalisch-Technische Bundesanstalt, Germany, were calibrated.

### H. Systems Engineering

The Systems Engineering Division maintained the Master Clock hardware, installed new batteries for the Uninterruptible Power System (UPS), and moved most essential data flow operations to LINUX-based control computers. Calibrated PPS and carrier-phase GPS receivers were installed at USNO Washington and at the AMC, while support was given to GPS III technical working groups. TWSTT operations were expanded to new customers, and equipment was ordered to provide essential redundancy for quality control.

King configured or upgraded and maintained a whole array of computer equipment, including new workstations and PCs used as instrument controllers and data collectors. She acquired and installed new computer and network hardware, and wrote or acquired and installed new software, necessary for LAN-based instrument control. She also set up and maintained many computer processes, including clock, environment, weather, GPS, and LORAN data collection and storage.

King and M. Tran designed and developed paging and e-mailing alarm systems that monitor chamber temperatures, the Voice Time Announcer, the UPS, Quorum Decision Unit clocks, and Leitch comparators in Bldgs. 52 and 78. Tran redesigned TSC hardware and Visual C++ software configurations in both buildings for greater reliability and flexibility and easier use. Each building has two identical systems with the same Master Clock (MC) inputs based on different references. Tran performed the periodic calibrations between MCs #2 and #3, monitored all the time measurement system equipment, and identified and corrected any problems.

Tran completed three more fast-rise-time 1 PPS amplifier modules with the individual channel time delays calibrated. He also completed designing, testing, and assembly of multiple splitter amplifiers for GPS calibration projects.

Tran completed window programs based on Visual C++ for all three Satre TWSTT modems that provide fully automatic control based on user interfacing schedule files, yet allow the user to edit times PN code, up/down converter frequency, and satellite position. He worked with PSI, Inc. to develop specifications and design methods for outdoor chambers that will be used to stabilize the temperature of two-way transceivers.

### I. Clock Development

Through the efforts of C. Ekstrom and T. Swanson, a still experimental cesium-based atomic fountain has reached frequency stabilities of $1 \cdot 10^{-15}$ at 1 day and demonstrated the steering of a hydrogen maser and removal of the maser's drift to below $2 \cdot 10^{-16}$ /day. Construction of a rubidium-based fountain has begun. Delivery of a mercury-based trapped-ion clock (LITE) from JPL was accepted in July 2002.

Research by Ekstrom and P. Koppang into the characterization of the stability of a clock ensemble produced an analytic expression for the confidence intervals of the ‘‘three-cornered-hat’’ estimator.

### J. GPS Carrier-Phase Research

TS participated in a joint IGS/BIPM pilot project to develop carrier-phase GPS time transfer. It was shown that continuous filtering can remove the day-boundary discontinuities evident in independent daily GPS carrier-phase time-transfer solutions, and that modifications to Turbo-Rogue/Benchmark GPS receivers can make them time-stable in the presence of power outages and system resets. A distributed timescale was developed for the IGS that is under evaluation to become an official product.

### K. Miscellaneous

USNO, BIPM, and the Istituto Elettrotecnico Nazionale, Italy, sponsored the Fourth International Timescale Symposium held 18-19 March 2002 in Sèvres, France.

Breakiron served as chairman of the USNO Editorial Review Board and served as treasurer and editorial chairman of the Precise Time and Time Interval (PTTI) Meeting Executive Board, in the latter capacity editing the Proceedings of the 33rd PTTI Meeting and this Observatory Report.

Koppang also served as general chairman of the 2001 PTTI Systems and Applications Meeting.

Vannicola maintained the Precise Time and Time Interval (PTTI) Meeting Web pages that included abstracts, Meeting and general information, and the advance program in html and pdf formats; coordinated the PTTI 2002 Call for Papers; and continued to serve as a member of the PTTI Executive Committee.

Vannicola hosted the Institute of Navigation's Washington Section's May meeting at USNO, and organized the $97^{th}$ Range Commanders Council Telecommunication and Timing Group meeting held at USNO 21-23 August.

## IV. EARTH ORIENTATION DEPARTMENT

### A. VLBI Operations

The VLBI correlator continues to operate 24 hours/day for 5 days/week with an additional two shifts on weekends, for a total of 136 hours/week. In 2001 the correlator was expanded to an 8-station correlator and was responsible for processing weekly 24-hour National Earth Orientation Service (NEOS) Earth orientation observations and daily UT1 Intensives. Twelve additional geodetic and astrometric 24-hour experiments were also processed.

As experience with the Mark 4 correlator led to improved processing efficiency, in 2002 the correlator increased the number of experiments processed and also removed the backlog left from the Mark IIIA correlator. The correlator facility became an International VLBI Service Correlation Center and is now responsible for 64 International VLBI Service (IVS) 24-hour Earth orientation experiments, 208 UT1 Intensives, and 12 celestial reference frame experiments each year. Additional special processing is also accommodated.

### B. GPS

The Earth Orientation (EO) Department continued to contribute rapid, ultra-rapid and tropospheric products to the International GPS Service (IGS). The software used to create these products was GIPSY-OASIS II version 5, which was written by JPL. Contributions of tropospheric products to the IGS Troposphere Working Group's pilot project began on 24 September 2001. Modifications to existing procedures have improved the quality of the rapid and ultra-rapid products. On 2 December 2001, the IGS realization of the ITRF2000 was adopted. On 8 August 2001, the augmentation of rapid solution clock files using precise-point positioning was begun. The most effective improvements to the rapid and estimated ultra-rapid procedures occurred on 1 January 2002, when comparisons of USNO rapid orbits to IGS combined ultra-rapid orbits were used to assign weights to the satellite observations. In addition, combinations of two USNO products using slightly different approaches began to be used to form the final products for submission.

The average weighted root mean square (wrms) for the rapid satellite orbits for the 6 months prior to 1 January 2002 was 7.2 cm, which was reduced to 4.0 cm for the 6 months thereafter. The same quantities for the ultra-rapid satellite orbits are 46.2 and 19.8 cm. The reliability of the rapid products was good, with 96% of the submission deadlines being met. For the ultra-rapid products, 88% of the twice-daily submission deadlines were met.

### C. Analysis and Predictions

Several substantial changes were made which affect the performance of IERS Bulletin A (Rapid Service/Predictions of Earth Orientation). In December 2000, it was determined that the contributions of the National Centers for Environmental Prediction (NCEP) model estimates of atmospheric angular momentum (AAM) excitation of length of day (LOD) were actually degrading the near-term UT1-UTC predictions. Therefore, the contributions of AAM were removed from the Bulletin A solution and the usefulness of the NCEP model to the prediction of UT1-UTC was reevaluated. This reevaluation indicated the presence of quasi-periodic variability in the AAM-derived LOD that was not present in the UT1-UTC time series. It was determined that this variability could be reduced and that the resulting AAM-derived LOD time series could improve the near-term UT1-UTC predictions (Johnson et al., 2002, J. Geodynamics, in review). Therefore, beginning 14 August 2001, the AAM-derived LOD time series was reintroduced into the combination of datasets used in the solution of Bulletin A.

Also, beginning with the 1 May 2001 issue of IERS Bulletin A, we changed the systematic corrections and weights of the contributing series and removed the USNO VLBI reductions from the combination procedure. For recent data, the rms differences with respect to the final solution of the IERS in polar motion are $< 50$ $\mu$as and in UT1-UTC are $<$ 5 $\mu$s.

Starting 22 May, the number of past data points used to estimate polar motion predictions was changed from 1,100 days to 400 days. In testing the two prediction lengths since 1995, the new algorithm produced significantly better results for all prediction intervals. While the shorter time span makes separating the Chandler and annual oscillations more difficult, the advantage is that time-varying characteristics of the oscillations change less year to year than they do over the course of 4 years. This change has caused a larger-than-normal change in the polar motion prediction coefficients and in the long-term polar motion predictions.

Beginning 9 October 2001, the IGS Final Earth Orientation Parameter (EOP) file is being used. The new file is a concatenation of several originally inhomogeneous segments, all of which have been transformed to be consistent with the ITRF97 realization. The effect of this change on IERS Bulletin A polar motion values is generally $< \sim 0.1$ milliarcsecond (mas). For the period since MJD 51601.5 (27 Feb 2000), when the SINEX combination officially replaced the previous orbit combination series, the mean and rms difference for Bulletin A polar motion (PM) are nearly zero and 0.036 mas, respectively, for each component. However, the differences are not entirely random. For the most recent period, the previous difference of about 0.1 mas between IERS Bulletins A and B for PM-y has been reduced almost to zero.

The data available from the IERS Rapid Service/ Predictions Center consists mainly of the data used in the IERS Bulletin. This includes: x, y, UT1-UTC, d$\psi$, and d$\epsilon$ from NEOS VLBI, from IAA VLBI, from the IERS Rapid Service/Predictions Center, and from the IERS Earth Orientation Center; x, y, UT1-UTC, and d$\psi$ from GSFC VLBI; UT1-UTC from NEOS 1-day Intensives; UT1-UTC from SpbU and GSFC 1-day Intensives; x, y, and UT1-UTC from GSFC 1-day Intensives and from CSR LAGEOS 3-day SLR; x and y from Delft U. of Technology 3-day SLR, from Inst. Applied Astronomy 1-day SLR, and from the Russian Mission Control Center 1-day SLR; UT0-UTC from U. of Texas LLR; x, y, and LOD from the IGS; UT from USNO GPS and from NRC Canada (EMR) GPS; and predictions of x, y, and UT1-UTC from the IERS Rapid Service/Predictions Center.

In addition to this published information, other data sets are available. These include: UT0-UTC from JPL LLR; UT0-UTC from CERGA LLR; UT0-UTC from JPL VLBI; latitude and UT0-UTC from Washington PZTs 1,3,and 7; latitude and UT0-UTC from Richmond PZTs 2 and 6; x and y from CSR LAGEOS 5-day SLR; x and y from Delft 5-day SLR; and x, y, UT1-UTC, d$\psi$, and d$\epsilon$ from IRIS VLBI.

The data described above are available from the Subbureau in a number of forms. One may request a semiweekly machine-readable version of the IERS Bulletin A containing the current 90 days worth of predictions via e-mail from *ser7@maia.usno.navy.mil* or *http:// maia.usno.navy.mil/*. Internet users can also direct an anonymous FTP to <*maia.usno.navy.mil*> and change to the ser7 directory, where they can access the IERS Bulletin A or more complete databases. WWW access is available at *http:// maia.usno.navy.mil/*.

## V. ASTROMETRY DEPARTMENT

### A. Washington Double Star Program

Observations of 4,740 objects were obtained using the speckle system attached to the USNO 26-inch refractor. Observers included D. Hall, W. Hartkopf, G. Hennessy, B. Mason, D. Pascu, S. Urban, and G. Wycoff. While the primary observing program at Washington continues to emphasize rapidly moving and ‘‘neglected’’ double stars, additional datasets include: bright pairs, potential rectilinear motion systems, calibration pairs, systems with orbits, and those having uncertain motion. Data obtained from this project during 2000 have been published by Mason and Hartkopf (AJ **122**, 1586). Observations from 2001 have been analyzed by Mason and Hartkopf and are currently in press. The speckle system and 26-inch refractor were also used in collaboration with Kaplan and Puatua (AA) to observe six mutual events of the Galilean satellites. Reduction of these data continues.

In July, 2001 the speckle camera was used on the 4-m telescopes of KPNO and CTIO. Observations of 1,343 stars were made. The observing program consisted of nearby G-dwarf stars, continuing the work started in 1996 to investigate the multiplicity characteristics of solar-type stars of different ages (Mason et al., 1998, AJ **116**, 2975). Initial reduction is complete and final reduction is in progress. Reduction and analysis of ~1,300 observations obrtained with the 100-inch Mt. Wilson telescope continued by Hartkopf.

The Tycho Double Star Catalogue (Fabricius et al., 2002, A&A **384**, 180) appeared in the literature. This catalog contains information on 103,259 components of multiple stars, including the discovery of 13,251 doubles, mostly with separations between 0.3 and 1.0 arcsec. This catalog was used to identify and remove numerous duplicate systems in the Washington Double Star (WDS) Catalog, prior to which two entries were in the database. In a further effort to improve the clarity of the WDS, 930 systems with duplicate discovery designations have been reassigned so that there is no repetition. The coordinate precision of the WDS has been improved by 3.5 orders of magnitude for ~80% of the WDS (i.e., 78,655 systems). The remaining systems are under investigation. In an attempt to ferret out optical doubles, proper motions of secondary companions have been added when available. This has been done for 37% of the WDS (i.e., 36,042 systems) to date. Measures by Walt Sanders and Nils Wieth-Knudsen, previously only available in manuscript from the USNO Library, have been added to the WDS Web site to make their availability more universal. In collaboration with Howard (AA) and Stewart (AA), *The Astronomical Almanac* has been modified to include parameters of easily seen double stars. These will first appear in the 2004 edition. A total of 148 orbits were calculated which appear in IAU Commission 26 Circulars 144-145; Seymour et al., 2002, AJ **123**, 1023; and Fekel et al, 2002, AJ **123**, 1723. Preliminary investigations of the complex multiple system Finsen 332 by Mason and Hartkopf were presented at the spring 2002 DDA Meeting. Analysis of this system continues.

The USNO Double Star CD 2001 was made and over 1000 copies have been distributed. This CD contains four catalogs: the WDS summary catalog, the Delta-M catalog, the 5th Orbit catalog, and the Interferometric catalog. Publications describing the CD and each of the catalogs appeared in the literature (Mason et al., 2001, AJ **122**, 3466; Hartkopf et al., 2001, AJ **122**, 3472; Hartkopf et al., 2001, AJ **122**, 3480; and Worley et al., 2001, AJ **122**, 3482). Over the reporting period the WDS increased by 4%, the Delta- M catalog by 227%, the Orbit catalog by 12%, and the Interferometric catalog by 21%. The USNO filled over 5,400 data and observing list requests. Hartkopf continued as Vice President of Commission 26 (Double and Multiple Stars), and work continues on the Washington Multiplicity Catalog in preparation for Special Session #3 at the IAU General Assembly #25.

Continuing collaborations for the double star program include D. Barlow (U. Victoria), D. Berger (GSU/CHARA), H. Bond (StSci), T. ten Brummelaar (GSU/CHARA), C. Fabricius (Copenhagen), F. Fekel (TSU), G. Gatewood (U. Pittsburgh), D. Gies (GSU/CHARA), E. Griffin (Oxford), R. Griffin (Cambridge), T. Henry (GSU/CHARA), E. Horch (RIT), H. McAlister (GSU/CHARA), A. Moffat (U. Montreal), E. Nelan (StSci), L. Penny (C. of Charleston), L. Roberts (Rocketdyne), C. Scarfe (U. Victoria), D. Soderblom (STScI), A. Tokovinin (CTIO), N. Turner (GSU/CHARA), S. Unwin (JPL/SIM), and D. Wallace (GSU/CHARA). In addition to these, personnel working on the WDS project and catalogs also included D. Seymour (Harvard), D. Kang (Rutgers), and L. Flagg (Wilson HS).

### B. Full-sky Astrometric Mapping Explorer (FAME)

The Full-sky Astrometric Mapping Explorer (FAME; *http://www.usno.navy.mil/FAME*) is a space astrometric mission to measure the positions, parallaxes, and proper motions of 40 million stars between 5th and 15th magnitude to an accuracy of 50 microarcseconds (9th magnitude). A collaboration between USNO, NRL, Lockheed Martin Advanced Technology Center, and Harvard Smithsonian Center for Astrophysics (CfA), the FAME program was selected by NASA in October 1999 as one of two missions to begin development within the NASA Medium-Class Explorer (MIDEX) program. AD members of the FAME team include T. Codella, B. Dorland, R. Gaume, A. Hajian, Hennessy, Kaplan, J. Lee (Universities Space Research Association [USRA]), V. Makarov (USRA), M. Murison, R. Olling (USRA), Urban, and N. Zacharias. The FAME mission began this reporting period toward the end of development Phase B, the preliminary design phase, which began in September 2000. FAME Phase B development culminated in a program Preliminary Design Review (PDR) held October 30-31 2001. In addition, a Confirmation Assessment Review and Confirmation Readiness Review were held shortly after the PDR. Due primarily to technical problems obtaining detectors and the resulting schedule uncertainty leading to increased costs, in January 2002 NASA announced that it was not confirming the FAME mission for Phase C development and withdrew future funding support. Shortly before the NASA announcement, an alternate supplier of detectors was identified.

The science that would result from the FAME observations remains compelling, which is why efforts to continue development of the project have continued in 2002. Fabrication of preliminary detectors by the alternate supplier has been extremely successful, and testing continues. In addition, significant progress has been made in the definition of optics and structural requirements to meet mission astrometric accuracy goals. At the end of the reporting period, consideration was being given to various ways of restarting the mission.

### C. Fourier Transform Spectrometer (FTS)

The basic instrumental FTS development accomplished in FY00 and FY01 was extended in FY02. During FY01, the FTS consisted of a dual output interferometer using a reflection grating as a cross-disperser with a resolving power of R = 400. In FY 2002, the FTS was upgraded with a transmission grating cross-disperser with an R = 2600. The corresponding sensitivity increase in the resulting spectra goes as R.

With the help of experienced observers such as T. Rafferty, Murison, Olling, and others, spectra of several astronomical objects were obtained, including the Sun (with a bare 50-micron fiber), Procyon (6-in telescope), Sirius (6-in telescope), and Arcturus (6-in and 11-in telescopes). The spectrum of Arcturus is an excellent match to model spectra published by R. Kurucz (SAO). Also, there is good spectral agreement among the various spectra obtained for the same object. The quality of the Arcturus spectra was high enough so that precise velocity extraction was possible. Histograms of thousands of lines in each spectrum show a Gaussian distribution about the mean velocity. In addition, two different methods of estimating the errors are in agreement, suggesting that our results are robust. Though limited, the current set of data indicates that the FTS can produce photon-limited Doppler velocities in the many tens of m/s level.

In anticipation of the next phase of the project, which involves probing photon-limited Doppler precisions of a few m/s with a larger aperture, the FTS has been configured onto a small, transportable breadboard. Several proposals have also been submitted for small projects involving FTS development and research. A patent application for this technology has been prepared and is proceeding through the system. Multiple scientific publications describing the instrumental configuration have been prepared, but have yet to be submitted pending patent approval.

### D. Space Interferometry Mission (SIM)

The July 2001 speckle observations mentioned in Section A included observations of apparently single stars for possible consideration as SIM Grid stars. Mason's collaboration on a SIM Key project (PI: T. Henry, GSU/CHARA) as co-investigator continued.

A. Fey, D. Boboltz, Gaume, N. Zacharias and K. Johnston continued their roles on the SIM Science team and participated by phone in several SIM Science Team meetings during the course of the year. Boboltz attended the February meeting held in Boston and Zacharias attended the August meeting in Hawaii.

A pilot program was started to investigate the temporal stability of optical centroid positions of a sample of ICRF sources, using the 1.5-meter K. A. Strand telescope at Flagstaff, Arizona. The purpose is to investigate the stability of the ICRF sources at the mas level. Observations will be made over a period of years. The plan is to image the selected fields frequently in the R bandpass, with the source in the center of the field of view. Some V band images per field give colors for all relevant objects to derive differential color refraction corrections.

Radio work on quasar stability is being done in collaboration with A. Wehrle's (JPL) SIM Science Team. A proposal submitted last year to the NRAO to conduct phase-referenced observations of a number of close quasar pairs was accepted.

Optical observations for the radio-optical link continue with a long-term proposal at KPNO and simultaneous CCD imaging with the USNO astrograph (in the same, narrow, red bandpass) to link counterparts to the optical Hipparcos frame. About 400 sources have been observed since 1998, following the USNO CCD Astrographic Catalog (UCAC) survey, and individual, absolute, optical positions in the 10 to 30 mas range are expected for most sources. The outcome of this investigation will affect the SIM target selection of reference frame sources.

Observations of 19 radio stars were conducted with the VLA in A configuration in conjunction with the Pie Town VLBA antenna. For the 15 stars in our program previously observed with the VLA, we found proper motions with an average error of Å 1.6 mas/yr. This accuracy approaches that of Hipparcos for the same 15 stars, and for a few of the stars in our program, the radio proper motions are better than the corresponding Hipparcos values. In addition to these VLA+PT observations, we have also observed the same set of stars with the MERLIN array.

A program of Southern Hemisphere radio astrometric/ imaging experiments continues. A number of experiments have been observed with the Australian Long Baseline Array. The Northern Hemisphere ICRF is continuously being observed by us and other agencies, so the bulk of our effort is going to the Southern Hemisphere sources.

### E. Fundamental Reference Frames – Radio

In support of the ICRF, the VLBA astrometric/geodetic experiments RDV28, RDV29, RDV30, RDV31, RDV32, and RDV33 were observed. Imaging of the experiment RDV31 was completed and imaging was started and significant progress made toward imaging RDV12 and RDV14. All current images (2,900 images at S/X bands of 447 sources) from the USNO Radio Reference Frame Image Database were added to the NASA/IPAC Extragalactic Database. A VLBA proposal was prepared and submitted to NRAO to continue the RDV series of VLBA observations of ICRF sources into the year 2003. Several astrometric experiments in support of the ICRF were scheduled, observed, and processed through the CALC/SOLVE software, including CRF-11, CRF-12, CRF-13 and CRF-14. One more experiment, CRF-15, was scheduled and observed and is currently awaiting correlation.

The CALC/SOLVE suite of software, the catalog system, and the database of geodetic/astrometric observations continue to reside on the Fundamental Reference Frame Division HP computer workstation known as ‘‘Geb.’’ The software is patched as required and the database of observations is updated with new data as they arrive from the various correlators or other VLBI analysis centers.

Hall, Boboltz, and Fey continue to analyze both IVS-R4 (formerly NEOS), IVS-R1, and Celestial Reference Frame (CRF) RF experiments through the CALC/SOLVE software. The resulting daily solutions of the IVS-R4 and CRF experiments are now the official versions submitted to the IVS.

Boboltz and Fey continue to work on the production of global VLBI solutions for the purpose of estimating EOPs and the CRF. The global EOP solutions USNO_2001d and USNO_2002a were completed and submitted to the IVS. The most recent solution (in this case USNO_2002a) is updated twice weekly and resubmitted to the IVS as the IVS-R1 and IVS-R4 experiments are analyzed. The global CRF solution CRF2001a was also completed. Results from these solutions can be obtained from the AD Web page (*http://rorf.usno.navy.mil/solutions/*).

Fey and Boboltz carried out an analysis of the effects of including VLBA RDV data in global VLBI solutions on astrometric position estimation and EOP estimation. This included doing various solutions using different combinations of data (e.g. MkIII only, VLBA only, MkIII+ VLBA, etc.). Results are posted on the AD Web page (*http://rorf.usno.navy.mil/vlba_rdv/*) and suggest that the data products derived from the VLBA data are consistent with those from the MkIII data.

Fey and Gaume traveled to the Paris Observatory to meet with its personnel to review the implementation of the IERS International Celestial Reference System (ICRS) Product Center (PC). The USNO and Paris Observatory are jointly responsible for the PC, which is responsible for the products of the IERS with respect to the ICRS.

Boboltz and Fey began participation in a joint NASA, USNO, and NRAO project to extend the ICRF to higher radio frequencies. The goal of the project is to provide accurate radio astrometric positions for a suitable set of sources for use at Ka-band (34 GHz) by NASA's Deep Space Network (DSN) spacecraft tracking array. Due to increasing interference at the radio frequencies currently used for the ICRF and the DSN for spacecraft tracking (2.3/8.4 GHz), the DSN must move to the next radio frequency allocation at Ka-band. The initial work involves obtaining radio frequency images and determining astrometric positions at K-band (22 GHz) and Q-band (43 GHz) using the VLBA. These ''bracketing'' frequencies must be used because the VLBA does not currently have Ka-band capability. The observations at K- and Q-band will be interpolated to Ka-band. This project supports NASA's Mars 2005 Mission. USNO will use results of this project to determine whether higher radio frequencies could be used to define future realizations of the ICRF.

Fey initiated work on a global VLBI astrometric solution for the construction of ICRF Ext. 2, the second extension of the ICRF.

### F. USNO CCD Astrograph Catalog (UCAC)

In September 2001, after completing 74.5% of the sky (63,479 fields), the USNO CCD astrograph was packed up at CTIO, Chile and shipped to USNO Flagstaff Station (NOFS), Arizona. The disassembled telescope arrived at NOFS on 22 October. N. Zacharias, Rafferty, G. Wieder, Holdenried, M. Zacharias (USRA), and NOFS personnel M. Divittorio, A. Rhodes, S. Sell, and B. Canzian aided in putting all the systems back in place. Regular survey observing started on 31 October. At the end of June 2002, 82% of the sky was completed, matching the expected schedule of about 50% throughput as compared to the CTIO site. Rafferty handled most of the instrumental problems with support from Divittorio, while Hennessy and Canzian solved intermittent computer problems.

Hall completed extraction of 1,000 sample frames for upcoming software developments, checked incoming data tapes, and updated the archive. N. Zacharias and M. Zacharias trained the observers, T. Tillman, C. Crawford, and S. Potter. M. Zacharias performed the daily quality control and extracted data for minor planet occultation predictions. N. Zacharias analyzed flip observations on calibration fields, resulting in improved systematic error corrections (mainly the Charge Transfer Efficiency effect). N. Zacharias and M. Zacharias constructed position-only catalogs, including all survey observations up to 11 April 2002 containing 52.8 million stars, as part of the upcoming UCAC2 data release.

D. Monet (NOFS) provided yellow sky catalogs based on the V plates of the Southern Proper Motions (SPM) and Northern Proper Motions (NPM) projects (completely scanned on the NOFS Precision Measuring Machine [PMM]). I. Platais (USRA) provided an independent analysis of the SPM measures (both B and V plates) with special evaluation of grating and exposure sets. Further details are found in Section I. To prepare for UCAC proper motions of the brighter stars, Wycoff matched the Tycho-2 Catalogue and the UCAC2 positions. Over 97% of the Tycho-2 stars were matched unambiguously. This includes the Tycho-2 stars both with and without proper motions in that catalog.

Preliminary UCAC data were provided to the Sloan Digital Sky Survey project (SDSS; J. Pier, NOFS), the 2MASS IR-survey, A. Monet (NOFS) for a JPL comet mission project, M. Ratner (CfA) for the Gravity Probe B project, and various smaller requests. The UCAC project was presented at the January AAS and April DDA Meetings.

### G. Planets/Satellites

IR observations of outer planet satellites, made by Pascu, Rohde (EO), F. Vrba (NOFS), A. Henden, and F. Vachier (IMCCE, Paris) with the 61-inch Strand Astrometric Reflector in Flagstaff, were reduced by Pascu and summer intern P. Ries. The IR observations were made with the Astrocam (Aladdin-type) camera. Reduced observations of Miranda (UV), Adrastea (JXV), Metis (JXIV), Amalthea (JV), and Thebe (JXIV) were sent to JPL in support of ephemeris development.

Speckle interferometer observations of close approaches of the Galilean satellites were made with the 26-inch refractor by Pascu, Kaplan, and Mason, in preparation for observing the 2002/2003 mutual phenomena astrometrically.

Pascu formed a community panel to produce a white paper on solar system astrometry for the use of the NRC-sponsored Solar System Exploration Survey Committee, tasked to produce a ''Decadal Report'' on solar system exploration for 2003-2013. The white papers of the 22 such community panels have been collected and edited by M. Sykes (U. Arizona) and published. The members of the Solar System Astrometry community panel were Pascu, T. Johnson (EO), Rohde (EO), R. Stone (NOFS), and N. Zacharias of USNO; J. Giorgini, R. Jacobson, and E. Standish of JPL; B. Marsden of the Minor Planet Center; and L. Ball of Emerald Lane Observatory.

### H. Washington Proper Motions

A second reduction of the Astrographic Catalogue measures was completed by Urban, Wycoff, T. Corbin (retired), Makarov, and E. Hoeg and C. Fabricius (Copenhagen U. Observatory). CDs containing this catalog, called AC 2000.2, were manufactured and distributed to over 600 colleagues. A paper was presented at the winter 2002 AAS Meeting (Urban et al., BAAS **33**, 4, 1494). These data have been utilized in the computation of proper motions for Tycho-2 and UCAC1, and will be used for the bright end of the UCAC2, currently in production.

For computation of fainter stars, data from the NPM and SPM programs, measured by D. Monet on the PMM, will be used. Monet reduced data from the yellow plates for both hemispheres and calls the catalog ‘‘Yellow Sky 3.0 (YS3.0).’’ Platais reduced only the SPM plates, but used both the yellow and blue plate measures (called SPM_U05). Since these are not independent data sets, an evaluation of which data to keep for determining proper motions was made by Wycoff and Urban. Results were discussed with all parties. The general results are that the SPM_U05 has smaller systematic errors than YS3.0, but the YS3 random errors are significantly lower than SPM_U05’s. This holds true for data segregated in a variety of ways (RA, Dec, galactic latitude, magnitude, etc.) except for the brightest (brighter than about 11.0) stars, where the random errors between the two data sets look similar. The plan is to remove the systematics from the YS data and use the resulting positions for UCAC proper motion computations of the fainter stars.

The SPM reductions, completed last year by Platais in collaboration with T. Girard and W. van Altena (Yale,) contain 28 million stars. These data were measured by D. Monet on the PMM. This reduction, termed SPM_U05, does not go down to the plate limit of about 18.5, but instead ends at about 16.5, due to the input list used. Wycoff modified this input list using the USNO A2.0 catalog. Platais and Wycoff reran the reductions to extract an additional 70 million objects; this set is called SPM_U06.

In the evaluation phase of the data, Wycoff concluded that these two versions contain different positions, even though the differences in those versions were supposedly that the SPM_U06 had more stars. That is, stars in common were supposed to have identical positions; however, several million did not, and the differences were quite large in many cases. Platais, who is currently working in Belgium, was unable to quickly determine the cause and did not have the available resources to investigate the matter as of this writing. The SPM_U05 data, when compared with other sets such as Tycho-2, 2MASS, and UCAC, appear to have about 50% lower systematic errors than the SPM_U06.

### I. DoD Requirements

Urban and Cdr. S. Diaz (USNO Requirements Officer) briefed the Space Technology Alliance on current status of astrometric issues and potential shortcomings. Urban attended the 2002 Space Control Meeting held at MIT/Lincoln Laboratory.

### J. StarScan Measuring Machine/AGK2 Plates

The StarScan measuring machine was extensively modified for automated plate measurements. L. Winter (USRA) was in charge of the hardware, electronics, and image processing software, and Holdenried was in charge of software-to-hardware interface and the computer operating system. The goal has been to automate the entire measuring process with the exception of the actual loading of the plates. This was successful by the end of 2001. Additional hardware support was given by Rafferty, J. Pohlman, and Wieder.

Measurements on the AGK2 plates, on loan from the Hamburg Observatory, began in December. A ‘‘test zone’’ band of 10 degrees from - 5° to +5° was originally envisioned to investigate problems in the operating system or measuring accuracy. These data were to be combined with UCAC positions for inclusion in the UCAC2 catalog to get proper motions at the 1 mas/yr level, comparable to Hipparcos. As the work on other aspects of the UCAC2 was delayed, this test zone was expanded and is currently from -5° to +40° . In total, 1,216 plates have been measured. Urban, Wycoff, Mason, Hartkopf, Pascu, Hall, and Hennessy have all contributed to the plate loading and data storage.

N. Zacharias developed software for the reduction pipeline. Transformation of ‘‘direct’’ and ‘‘reverse’’ measures of plates show good repeatability (0.5-micron projected error for a single observation); however, large-scale (machine table) and small-scale (footprint mapping) patterns in the residuals show the need for an improved calibration of the machine. It is anticipated that final calibration will get the machine precision to the 0.3-micron level, translating to 30 mas on the AGK2 plates; however, due to other effects the expected accuracy of a catalog position is about 70 mas.

### K. Instrumentation

The Instrument Shop, under the leadership of Pohlman and including the instrument makers Wieder, J. Bowles, D. Smith, and Siemers, continued work on projects for AD, as well as for some other departments.

The majority of the work continued to be on the Navy Prototype Optical Interferometer. This work included 36 of a total 72 Long Delay Line (LDL) mirror pop-ups, the completion and shipment 34 elevator cans, multiple mirror mounts for the beam combiner table, Klinger mirror mounts, and six 20-inch diameter vacuum seal plugs. The Shop also manufactured new periscope cans and modified most of the parts, previously made in the Shop and by other contractors, for the final periscope system for the Long Delay Line.

The Shop, along with Rafferty and A. Kubik (TS), repaired the RA drive on the 26-inch refractor. Broken wiring was found and replaced. The Shop also repaired the refractor’s RA clutch.

Work continued on the upgrade of the 24-inch reflector in Washington. Rafferty modified the electronics of the mount. The optics were moved, cleaned, replaced, and realigned by members of the Shop and Rafferty. The Shop modified the finder scope eyepiece and CCD guider assembly for the telescope, as well as digitizing the focus. At the end of the reporting period, Rafferty was taking the test CCD frames.

The Shop met with J. Geary (SAO) in Massachusetts to discuss the manufacture of CCD mounts for the FAME project. The shop completed four test Invar CCD table mounts and shipped them to SAO.

The Shop and Rafferty disassembled, moved, and assembled the Six-inch transit circle into the lobby of Building 1 for display.

The Shop started manufacturing a new version of the Cesium Fountain Clock for TS. They also repaired several machines in the Shop that had failed, and purchased and installed a hardware/software upgrade to the Coordinate

Measuring Machine. The Shop made several parts for the FTS this year, including the guider for the 11-inch and 18-inch telescopes. They also manufactured 20 plateholders for use on the StarScan measuring machine.

### L. Miscellaneous

Boboltz continues to pursue a program of independent research with ties to the SIM Key Science Project ''Astrophysics of Reference Frame Tie Objects,'' involving spectral-line radio observations of SiO maser emission in the circumstellar envelopes of asymptotic giant branch (AGB) stars. Approximately 50-100 of these stars will be observed by SIM for the purpose of investigating the transition of spherical AGB stars to asymmetric planetary nebulae. VLA observations of 21 SiO maser sources were recorded, data calibrated, and imaged. Maps of these sources (many of which had never been previously mapped) show the spatial and velocity structure of the SiO masers in the circumstellar atmospheres of these objects. A paper reporting the results is in preparation, and this work has already generated an accepted VLTI/VLBA joint proposal for follow-up observations on two of the stars. Now that the VLA has been shown to be a valuable tool for making low-resolution maps of these objects, additional VLA A-configuration time (spring 2003) will be requested to continue the survey. Boboltz also continues to serve on the NRAO Users Committee.

Fey continues to work on several astrophysically interesting and relevant projects. Collaborations continue with J. Lazio (NRL) and G. Piner (Whitier C.). Fey has been the primary author or co-author on several accepted proposals for VLA and VLBA observing time with a variety of collaborators at institutions both inside and outside the US. Fey was author or co-author on numerous manuscripts prepared for publication in refereed astronomical journals or proceedings, including ''AGN Variability from the USNO Radio Reference Frame Image Database'' and ''Multi-frequency Very Long Baseline Array Observations of the Compact Double B2 2050+36: Constraints on Interstellar Scattering Revisited.'' Fey continues to serve on the IAU Working Group on the Maintenance of the ICRS and is a member of the IVS Analysis Working Group on the ICRF.

Between July 2001 and June 2002 Prof. Marcelo Assafin (Brazil) worked at USNO Washington with N. Zacharias on the radio-optical reference frame link. Data from four CTIO runs and overlapping 1.6-meter LNA observations were reduced using reference stars from UCAC data. A negligibly small overall (optical-radio) offset in RA was found for the 172 sources, while a 15 mas offset in declination needs to be investigated further.

The USNO observing program continued with four runs at the 0.9 m Kitt Peak telescope using the MOSAIC camera, in parallel with astrograph observations, using the same bandpass with dedicated red filters (N. Zacharias, M. Zacharias, and Rafferty). N. Zacharias performed raw data reductions on most 0.9 m frames.

N. Zacharias proposed a new ground-based astrometric project for 10 mas positions of faint (15-20 mag) and bright (3-6 mag) stars based on a 1-m-class design of U. Laux and C. de Vegt (Germany), in combination with a new 10k single chip CCD camera. N. Zacharias explored options for funding in collaboration with Assafin. After the joint NOFS/AD program meeting Johnston suggested going ahead with the CCD and camera acquisition if USNO FY03 funding allows it.

T. Strikwerda (APL/JHU) contacted Rafferty and Urban regarding stars for use in a star tracker for a mission to Pluto's satellite. The main problem stems from high parallax and high proper motion stars, and the positional changes that will result on such a long duration mission and at the distance of Pluto. Urban completed the statistics; roughly 12% of the viable stars that would likely be used in a near-Earth mission would create problems for a long duration mission to Pluto

Twelve colloquia, coordinated by Pascu, were presented by national and international experts primarily in the areas of astrometry, dynamics, earth orientation, and time.

Urban continued as Chairman of the Densification of the Optical/Infrared Working Group of the IAU. He was named Chief of the Cataloging and Requirements Division November 2001, as which he had been acting for a year. Urban volunteered as USNO's representative to the Astronomical Data Facilities Scientific Steering Committee.

## VI. NAVAL OBSERVATORY FLAGSTAFF STATION (NOFS)

### A. Astrometry

#### *1. Parallaxes and Proper Motions*

C. Dahn continued to oversee the CCD trigonometric stellar parallax efforts. The 61-inch Strand Astrometric Reflector was employed for this project on a total of 154 nights during this report year. Two different CCD cameras continued to be employed on a routine basis: one (referred to as Tek2k) utilizing a ''bare'' Tektronix 2048x2048 CCD for targeting stars fainter than R$\sim$12; and a second (designated ND9), also utilizing a Tektronix 2048x2048 CCD, but with a 3 mm diameter neutral density attenuation spot mounted directly in front of the chip, providing 9.0 mag of magnitude compensation, and permitting stars as bright as R$\sim$4 to be targeted.

During the past year the Tek2k program has continued to concentrate on obtaining parallaxes for a selection of brown dwarfs with L and T spectral types. These objects were primarily discovered by the 2MASS and SDSS collaborations. Some preliminary values, along with CCD and near-IR photometry, were presented in a paper that has subsequently appeared in *The Astronomical Journal* (Dahn et al. 2002). The results define the colors, luminosities, and temperatures of the main sequence for three bolometric magnitudes through the full range of L spectral types. No correlation was found between the peculiar near-IR colors of L dwarfs and other measured parameters, including the detection of lithium, H-alpha emission, projected rotation velocity, and tangential velocity. CCD parallax astrometry has proven to be difficult for the late L- and T-dwarfs due to their faintness. As a result, future astrometric observations of such very red targets will be made primarily with ASTROCAM (the Observatory's near-IR camera). Tek2k parallax determinations have now been completed for 152 stars and another dozen or so will be completed within the next few months. A publication presenting the results for these stars will be prepared in the next report period.

The ND9 program, which began routine observations in December 1995, was concluded at the end of the May 2002 run. This program successfully demonstrated that a CCD camera employing a neutral density occulting spot could be used for high precision astrometry. The 72 targets observed were primarily sdF-G stars, solar analogs, periodic variables, field Horizontal Branch stars, and Mira variables, all with apparent brightnesses in the range $5.2<V<9.5$. The formal precisions achieved — typically Å0.6 to Å0.7 mas in relative parallax — are somewhat poorer than the results achieved with the Tek2k camera, which are more typically Å0.5 mas in relative parallax for well-exposed fields. This is in part due to (1) the numerous charge traps in the engineering-grade CCD employed in the ND9 camera, and (2) the loss of field for reference stars due to an unusable region resulting from light reflected off the occulting spot returning to the CCD off of the flat secondary mirror. Preliminary comparison with HIPPARCOS parallaxes for 63 objects in common shows excellent agreement in all but a few instances. The ND9 astrometry has revealed possible perturbations, apparently previously unrecognized, for two stars: HD11131 (G0V) and HD15096 (sdG), for which further results will be published later.

With the ND9 camera now decommissioned, active discussion is currently in progress to decide the priorities for most effectively utilizing the astrometric capabilities of the 61-inch telescope. Final decisions will involve, among other considerations, balancing its use at CCD wavelengths versus near-IR wavelengths. The previously anticipated commissioning of a new CCD camera (ND5), which would provide 5.0 magnitudes of compensation and permit astrometric (including parallax) observations of targets with apparent magnitudes in the 9.0 to 13.0 range, is presently on hold. Such a camera would be particularly effective for stars fainter than those routinely targeted by HIPPARCOS, but brighter than those targeted to date by CCD programs without magnitude compensation. Potential targets might include a selection of nearby M-dwarfs to look for astrometric perturbations from faint companions in the brown-dwarf and giant-planet mass range. Alternative uses of 61-inch time under consideration include adaptive optics work and testing new technology CCDs (e.g., orthogonal charge transfer devices) for astrometric applications.

The infrared group led by Vrba and including H. Guetter, Henden, and C. Luginbuhl continued efforts in an infrared parallax and proper motion program of L- and T-dwarfs discovered by SDSS or 2MASS. Twenty-two L-dwarfs, 18 T-dwarfs, and one late M-dwarf are on the initial program, which began taking data in September 2000. Data are obtained at the 61-inch telescope in the J- or H-band with the ASTROCAM imager, which uses an ALADDIN 1024 x 1024 InSb detector, providing an approximate 6.2 x 6.2 arcmin field of view. To date, a typical program star has about 1.3 years of time baseline, with 60 frames obtained over 20 nights. Preliminary parallaxes and proper motions are now being calculated, based on these early data. For several stars that are in common with the USNO optical CCD parallax program, parallax and proper motion results agree to within their errors.

Henden completed modifications to the ASTROCAM software and data processing pipeline in support of the IR parallax program. The real-time astrometry software, written by D. Monet, was updated to handle the format of ASTROCAM images, and provide centroids of program stars and their reference frames. Ancillary IRAF scripts were written to review ASTROCAM data.

Henden also acquired deep K -band images of the field of the Soft Gamma-ray Repeater SGR1900+14, and performed an astrometric reduction using the UCAC reference catalog. This calibration will be used by K. Hurley (UC Berkeley) to help match Chandra, IR and radio data of the same field.

### *2. 8-inch Flagstaff Astrometric Scanning Transit Telescope (FASTT)*

The 8-inch Flagstaff Astrometric Scanning Transit Telescope (FASTT) continued to make CCD observations this past year under the direction of R. Stone. All aspects of the telescope's operation are automated (e.g., target selection, data acquisition, and reductions), and all data are reduced to the ICRS using differential reductions with reference stars taken from the Tycho-2 catalog of star positions. Accuracies of Å 60 mas in each coordinate are routinely achieved for a single observation. A series of observations can produce accuracies better than Å 30 mas. Observations of sources with well-known positions, such as bright Tycho-2 stars and ICRS reference sources, show that FASTT has a systematic error under Å 20 mas in each coordinate. The telescope continues to operate well in automatic mode. Only a few nights were lost because of instrumental problems, and manpower needs are now under one-half person per year, mostly for the dissemination of FASTT data and writing publications.

### *3. Solar System Astrometry*

In the past year, the FASTT made 39,173 observations of asteroids, and 1,210 of the outer planets Uranus, Neptune, Pluto, and 17 satellites of these planets. The planetary observations are part of an ongoing project to improve their ephemerides and to support various existing and proposed spacecraft missions to the outer planets. Paper V of FASTT planetary observations was recently published in *The Astronomical Journal*. The observations of asteroids are being used to refine their orbits, to determine some of their masses dynamically, and to predict occultations. On a quarterly basis, FASTT data are sent to the Minor Planet Center. Stone and Hilton (AA) are collaborating on the second project, which started in 1997.

Concerning occultations, considerable success was achieved last year based largely on FASTT astrometry. FASTT positions were used to derive accurate paths for the Tr231 Triton and 8 September 2001 Titania events, as well as for the P126 and P131.1 events for Pluto. All four occultations required expeditions to various parts of the world, and each was successfully observed. In particular, the P131.1 event crossed over Hawaii and was observed in different passbands, which should enable the profile and composition of Pluto's atmosphere to be determined. Also, the FASTT continues to provide data to various occultation groups around the world. Largely because of these data, the number of observed occultation has increased about tenfold in the past 4 years. Most of the credit should be given to the accuracy of the Tycho-2 catalog, which provides the reference stars used in FASTT reductions. The FASTT continues to observe 5535 Annefrank, which is a target for the Stardust Mission.

The observing contract with JPL was extended for another year. Asteroids, comets, and planetary satellites were among the targets observed, either in support of space missions or for ephemeris improvement. The most notable of this year's projects was the effort to provide accurate astrometry of Comet Borrelly as the Deep Space 1 spacecraft made a close approach. Both the 61- and 40-inch telescopes were used, and observations were reduced using a special subset of the UCAC catalog. A final, unscheduled course correction was uploaded to the spacecraft immediately prior to the encounter, based primarily on USNO data. Images obtained during the encounter are the most detailed ever of a comet nucleus, and post-encounter analysis showed that the navigational error due to the ground-based data was Å 50 km — the most accurate attained to date. A report on the Borrelly encounter was given at the AAS/DPS 2001 Meeting by S. Chesley et al. (NASA/JPL), with A. Monet and Stone as co-authors.

Additional observing campaigns were conducted to improve the ephemeris of Comet Schwassmann-Wachmann 3 (target of the ill-fated CONTOUR mission), several of the faint outer Jovian moons, and 2002 FD6, an asteroid passing close enough to Earth to be a target of radar ranging.

A. Monet continues her collaboration with E. Bowell (Lowell Observatory). This past year, they submitted a grant proposal to NASA to extend the LONEOS project by using data from the NOFS 1.3-m telescope to search for faint near-Earth asteroids (NEAs) and trans-Neptunian objects (TNOs). The proposal was accepted by NASA. Commencement of the work awaits completion of the 1.3-m mosaic CCD camera.

The IR group continued their collaboration with D. Pascu (AD), Rohde (EO), and P. Vashier (Paris Observatory) in obtaining near-infrared astrometric observations of the inner moons of Jupiter, Saturn, Uranus, and Neptune with ASTROCAM.

### 4. Sloan Digital Sky Survey (SDSS)

J. Munn and J. Pier continued supporting the SDSS astrometric pipeline. During this year, additional sky coverage of many hundreds of square degrees has been obtained and the astrometric pipeline reductions continue to produce results that far exceed survey minimum requirements. Reductions are carried out employing two different astrometric catalogs: the UCAC is used where it is available and the Tycho-2 is used where the UCAC is not available. Reductions against UCAC generally result in systematics of 20-30 mas and rms residuals of 40-50 mas. Reductions against Tycho-2 have similar systematics and rms residuals of 80-85 mas.

In October 2001, Pier was appointed for a 3-year term as chair of the SDSS Advisory Council, an oversight group responsible for the budget and management of the SDSS Project. Munn continued supporting the SDSS Operational Database.

The number of carbon stars discovered in the SDSS is now about 200. USNO is measuring their proper motions by combining their SDSS positions with POSS positions from USNO-A and USNO-B Catalogs. Monte Carlo population models are used to analyze the sample. From the distributions of proper motions and radial velocities, it appears that most of these faint, color-selected stars are dwarf C stars, evenly split between disk and halo populations.

A study of white dwarf stars observed by SDSS is being led by H. Harris. Photometric, spectroscopic, and proper motion data from SDSS and from followup spectra are being used to identify and classify a complete sample of WDs and hot sdO/sdB stars. Many unusual WDs have been discovered. A catalog of WDs contained in Data Release 1 (planned for January 2003) is being prepared. The proper motions from SDSS and USNO-A and -B Catalogs are also proving to be important data to discriminate between WDs and BL Lac objects with weak or no spectral features.

### 5. Precision Measuring Machine (PMM)

D. Monet spent much of the year working on the PMM. Highlights, including establishing a target date of September 2002 for the public release of USNO-B1.0; revising the algorithm needed to search for objects with high proper motion ($>$ 0.5 arcsec/year); coding and compilation of internal releases of the USNO-B Catalog; and forgoing a hard-copy distribution of USNO-B1.0 to instead work with various data centers to provide community access to the catalog. At a projected size of 80 GBytes, a public distribution on CD-ROM or DVD is not cost-effective.

B. Canzian has completed the computation of all star-galaxy classifications on all relevant plate material (POSS-I SO and SE, POSS-II SJ and SF, ESO-R, SRC-J, and AAO-R) for the USNO-B1.0 catalog. These classification data have been incorporated into the USNO-B1.0 Catalog by D. Monet and S. Levine for release to the public and the Air Force. Canzian and Munn worked together to compare SDSS catalog classifications with the USNO-B1.0 classifications.

Levine continues to maintain the PMM Image and Catalog server, which makes available the PMM scans of the $\sim$13,000 Schmidt photographic sky survey plates. These images cover the whole sky and were taken at multiple epochs and in several colors (*http://www.nofs.navy.mil/data/FchPix*). Work is underway to substantially upgrade the server, and to integrate the USNO-B catalog into the database.

### 6. Navy Prototype Optical Interferometer (NPOI)

During the period of the report, members of the USNO staff that worked on the NPOI were J. Benson, D. Dodd, H. Dyck, N. Elias, J. Horne, C. Hummel, D. Hutter, and W. Ketzeback. Hutter was the project manager of the NPOI for USNO. Early in the reporting year Ketzeback and Horne left the project for employment elsewhere.

Eighteen additional personnel worked on the project. From NRL were J. Armstrong, C. Gilbreath, R. Hindsley, J.

Howard, D. Mozurkewich, E. Oh, R. Young and T. Pauls. Mozurkewich served as the NRL project manager. From Lowell Observatory were K. Isbrecht, B. O'Neil, J. Shannon, W. Wack, and N. White. White acted as the Lowell project manager. Also on the project were J. Clark, L. Ha, and J. Walton from USRA and S. Nichols from Schriever Air Force Base. Naval Reservist Capt. C. Barry has also worked with the group.

One of the two primary goals for the NPOI was the demonstration of simultaneous, six-telescope beam combination. The first interferometric combination of more than four optical telescopes was done in late September 2001. As a result of these observations, a number of new problems were discovered with the fringe-tracking system that were eventually resolved. We achieved the six-telescope goal on 8 January 2002, with fully-phased operation. Although many-telescope combination is routine at radio wavelengths, this is the first time in the history of optical interferometry that such a large number of telescopes have been operated coherently to observe astronomical sources. More recently, NPOI's six-station array observed the triple star Eta Vir and detected all three components as ''visual'' companions for the first time. The close pair was previously known as a spectroscopic binary with a period of about 72 days, whereas the wide pair has been extensively observed by speckle interferometry and the orbital period was determined to be about 13 years. Some motion in the close pair can already be observed. A press release describing the achievement was distributed on 7 March 2002. The release was picked up by a number of news organizations, including the BBC as well as the Cosmiverse and Optics.org Web sites. NPR aired a piece about the interferometer in June.

The other principal goal for the NPOI is to achieve a few-mas accuracy level of astrometry for a catalog of hundreds of the brightest stars. Previously, our astrometry yielded a formal error of about 20 mas for a single observation using full-night solutions. Benson, Elias, Hummel, Hutter, and Mozurkewich have continued to pursue the application of atmospheric corrections to the baseline metrology corrections and, recently, Benson has been able to show that we can reach the 1-2 mas level for 90-second integrations on single stars. Before beginning an astrometric survey catalog, it must be shown that these same corrections yield 1-2 mas formal single-observation errors for a full night of data on many stars.

Observing programs in imaging and astrometry were carried out during the year, with O'Neil and Wack serving as the telescope operators. In particular, we began an observing program on early-type emission-line stars using narrow-band Balmer-line filters and continued our regular program of binary star observations. During the year, we made scientific observations on 72 nights and obtained about 3,700 interferometric observations (i.e., scans). Not as many science observations were obtained this year as last because of the engineering effort expended in the co-phased, six-telescope demonstration project. The number of observations and nights used for engineering purposes are not counted in the previous totals.

A paper entitled ''Direct Multi-Wavelength Limb-Darkening Measurements of Three Late-Type Giants with the Navy Optical Prototype Interferometer'' by M. Wittkowski (ESO), Hummel, Johnston, Mozurkewich, A. R. Hajian, and White was published in *Astronomy and Astrophysics.*

Two papers were submitted to *The Astronomical Journal*: ''The Effect of TiO Absorption on the Angular Diameters of Cool Stars'' by Dyck and Nordgren (U. the Redlands) and ''An Observational Test of the Spherical Model Atmospheres for the M-class Giants: The Case of delta 2 Lyrae'' by J. Sudol (NOAO), Benson, Dyck, and M. Scholz (Heidelberg U.).

Hutter continued work on a manuscript intended for *Applied Optics* that will describe the details of the NPOI baseline metrology system. Elias continued work on the second in a series of papers describing polarimetry with an optical interferometer. Hummel continued work on a variety of double-star projects. He also attended the inter-ferometry working group of the IAU.

Construction continued on the unfinished parts of the interferometer array. In the north astrometric telescope, much progress was made on the metrology system. With help from Benson, Horne, Nichols, and Shannon on control electronics and software, Hutter and Dyck installed the cat's-eye retroreflector and determined its position in the telescope siderostat. Dodd completed a set of cables for the metrology detector systems that Hutter installed. Dyck and the NOFS instrument shop developed a set of customized motorized micrometers to control key beam-steering mirrors. Hutter and Dyck installed the motors and demonstrated that the mirror mounts could be controlled remotely either by use of a simple hand paddle or by a computer under the control of a LabVIEW program specifically written for the task. Dyck designed and constructed a bridge-rectifier motor driver circuit for use with this system. Hutter and Clark worked on the installation of optical anchor components in this telescope metrology chamber. They, along with Ketzeback and Walton, also designed, fabricated, and installed a visitor-viewing window in the metrology chamber.

Following the development of an alignment fixture by Clark, internal optics in the elevator units can be aligned in a clean, quiet environment. A number of elevator assemblies were populated with components, wired, aligned, and installed on the north and west arms of the interferometer. The inner part of the north arm now has a complete complement of elevators, except for station N00. Walton installed optics in the mirror pop-up units for the long delay line stations. Horne evaluated the motors used with these units, including life-cycle tests, at the low temperatures expected during winter. Dyck finished making current tests on the motors to be used to move the mirrors in the delay lines and elevator assemblies. Dodd, Shannon, and White collected information on the siderostat electronic control units to allow the upgrade of the earliest, incompatible units to the state of the most recent versions. Construction of the remaining new units can also be started. Horne, Ketzeback, and Mozurkewich worked on the tests of stability of the integrated long delay line system. Horne worked on the design of the prototype autoalignment control electronics. Finished circuit designs and documentation were sent to Gilbreath to be sent out for fabrication by NRL. Horne also developed basic control software for the first autoalignment experiments.

Considerable effort was expended on hardware and software needed for the six-telescope combination. Dodd worked on assembly of the new version of the fringe engine hardware. Benson demonstrated the first 4-, 5-, and 6-beam combination in July using a white-light source in the lab. He also made several upgrades to the fast delay line and identified and fixed serious jitter and linearity problems with the delay-line optical carts. Isbrecht provided technical support for the conversion to the new fringe engine.

Hummel and Elias continued work on the conversion of existing software for use in processing the data from the six-telescope array configuration. Hummel also wrote simulation code for six-way fringe frames and tested bias corrections for closure phases and triple amplitudes in the presence of Poisson noise. He implemented sub-array reduction capability for the OYSTER software package and worked on optimal observing strategies for the array. Hummel also continued to provide the first stage of data reduction for the NPOI observations. Elias corrected signal dropout errors in the metrology data during the nights when astrometric observations were made. Hummel and Elias both worked on various aspects of the ultimate accuracy to the metrology system hardware, including the effects of polarization on the optical train and offset starlight feed positions on the siderostats.

Shannon installed fiber-optic connections from the array center to the beam-combining laboratory.

### *7. Full-Sky Astrometric Mapping Explorer (FAME)*

Significant effort went into the FAME satellite project during this report period. D. Monet wrote a PSF generator, fitter, and analyzer so that various changes to the mission baseline could be evaluated. This simulator is not part of the spacecraft simulator, but is rather devoted to understanding the astrometric properties of the focal plane and CCDs. Various rescoped FAME missions were analyzed.

F. Harris spent considerable time on support for FAME CCD testing. He aided Lockheed Martin in operation of the test camera he supplied. He advised SITe on the construction of their test camera, prior to the cancellation of their contract to supply FAME CCDs. He received back from Lockheed Martin all CCDs, cameras, and electronics that had been on loan in support of the FAME effort. He worked with J. Geary (SAO) in developing low-noise high-speed preamplifiers for FAME CCD test cameras.

## B. Photometry

### *1. Individual Objects*

Guetter continued to analyze the JHK colors and magnitudes for the USNO standards stars, which were obtained with IRCAM during the observing period 1994 to 2000. A paper, coauthored with Vrba, Henden, and Luginbuhl giving the results for new JHK standard stars between JHK 10 to 14th mag, is nearing completion.

Henden continued his work with dedicated AAVSO amateurs with CCD cameras. High-precision light curves of several eclipsing binaries were made and published. The AAVSO International GRB Network, under the guidance of Henden, has about 100 members and has observed several GRB afterglows over the past year.

Henden discovered a light-echo surrounding the peculiar nova V838 Mon. He has continued to monitor this object from the ground at UBVRIJHKL wavelengths, and together with U. Munari (Asiago U.) has written several papers on the nova. Henden has also participated in two HST proposals to study the star.

The dwarf novae WZ Sge had its third recorded outburst in the past hundred years during the summer of 2001. Henden monitored the star in U-band, and collaborated with J. Patterson (Columbia U.) on a large paper for the outburst, and in addition is working with S. Howell (Planetary Science Institute) on a multicolor paper for this object.

Henden, S. Howell, and J. Mattei (AAVSO) are setting up a long-term monitoring program for a selected set of Polars (magnetic CVs). Ground-based data will be used in conjunction with X-ray and IR space-based observations of these stars to provide an understanding of the accretion process.

Henden has supplied M. Ratner (CfA, Harvard U.) with UBVRI photometric information for the stars near M Peg, the target for the GP-B satellite.

Henden participated in the campaign on V410 Tau, a T Tauri variable that was followed from ROSAT as well as from the ground. A preliminary paper was given at the Sunspots and Starspots workshop in Potsdam, Germany.

Henden and P. Szkody (U. Washington) are studying new cataclysmic variables discovered in the SDSS survey. Henden is acquiring time-series photometry on the objects, while Szkody and collaborators are obtaining spectra from APO.

The Amateur Sky Survey (TASS) Mark IV camera has been used by Henden to produce a photometric all-sky survey of the sky as a complement to the UCAC catalog. This survey should be completed in the next year.

Vrba joined an international effort, led by W. Herbst and C. Hamilton (Wesleyan U.) to obtain photometry of KH15d, an unusual variable young star located in NGC 2264. In all, 53 nights of I-band monitoring at the 1.3-m telescope, 23 nights of BVRI-band photometry at the 40-inch telescope, and 9 nights of JHK-band photometry at the 61-inch telescope were carried out by Vrba. The approximately 1700 1.0 to 5.0 minute frames obtained at the 1.3-m telescope helped to establish the best lightcurve yet of this object. The object undergoes a 3.5-magnitude eclipse every 48 days that lasts approximately 18 days, but without significant color changes. This is interpreted as seeing a proto-planetary disk edge-on, with likely two areas of obscuration orbiting the central star with a period of 96 days. Results of this work were presented at the Symposium in Honor of Fred Gillette, ‘‘Debris Disks and the Formation of Planets’’ held in Tucson, Arizona, at the Extrasolar Planets Conference, in Washington, DC, where a press conference was held, and at the Albuquerque AAS Meeting.

Vrba, Henden, and Canzian observed the position of GRB 011212 in the I-band with the 1.3-m telescope on two nights and wrote a GCN describing the I-band flux limits at approximately 1.0 and 2.0 days after the burst. Vrba also observed the position of GRB 020124 in the I-band with the 1.3-m telescope, but the observations did not set any meaningful flux limits.

The infrared group, in collaboration with J. Greiner (Astronomical Institute, Potsdam), continued their long-term program of observing GRS 1915 in the K-band with the 61-inch telescope.

Vrba continued collaborations with V. Straizys, A. Kazlauskas (Vilnius Obs.), and R. Boyle (Vatican Obs.) to obtain Vilnius photometry of reddened stars in the Pelican Nebula, Collinder 428, and several other star formation regions using the Tek 2048x2048 CCD at the USNO 40-inch telescope.

Stone and J. Hobart continue their investigation of asteroids that show large variations in their light curves. High-resolution light curves have been obtained so far for the asteroids 1419 Danzig, 1620 Geographos, 1545 Thernoe, 1446 Sillanpaa, and 1248 Jugurtha. All show similar light curves with large amplitudes in magnitude. These asteroids are probably rotating bars, and observations of other asteroids are planned.

Hobart recorded the occultation of star HIP 1512 by minor planet 74 Galatea and reported the results to the International Occultation Timing Association. To support timings of a recent occultation by minor planet 638 Moira, Hobart and Stone obtained and reduced a light curve and determined the rotational period of the asteroid. From his home south of Flagstaff, Hobart observed a 3-second occultation of TYC 6193-00470 by minor planet 147 Protogeneia. This observation placed Hobart near the southern limit of the occultation and confirmed the excellent asteroid astrometry determined by Stone using the 8-inch FASTT.

### *2. Star Clusters*

Stone and Guetter continue their astrometric and photometric studies of the old Galactic clusters NGC 7044 and IC 1311. Membership probabilities have been derived using both photographic and CCD data. Clear separation between cluster and field stars was achieved, and UBVRI CCD frames of the clusters have been taken with the NOFS 40-inch telescope in order to study the properties of each cluster.

### *3. Extragalactic Objects*

Canzian worked on several research projects to study selected extragalactic objects. One project uses imaging data from the 40-inch telescope to uncover previously unknown spiral structure in SO disk galaxies that are misclassified as ellipticals. One such galaxy, IC3328, was discovered serendipitously with an 8-meter-class telescope; Canzian was able to duplicate the detection using the 40-inch. Telltale faint spiral structure in the SO disk can be found at the level of a few percent perturbation in brightness. About 60 such galaxies with dubious elliptical classification are being observed for this project.

Canzian is also using the ASTROCAM on the 61-inch telescope to image spiral galaxies in Ks-band. In addition to the grand-design spiral galaxy NGC4321, systems with multiple spiral arms are being studied to learn about differences between blue-light morphology and near-IR morphology.

Vrba, Henden, Canzian, and Luginbuhl continued analysis of data obtained both at USNO and by various observers worldwide on the luminous blue variable in NGC3432, discovered in 2000. They are collaborating with M. Wagner (Ohio State U.) on a paper about this object.

A new hypernova candidate, SN2002ap, was discovered in the galaxy M74. Henden has been monitoring this supernova in UBVRI.

Several gamma-ray-burst counterparts were studied by Henden, Vrba, Luginbuhl, Guetter, Levine and Canzian. The first HETE-2 afterglow (GRB010921) was observed by Henden, resulting in two collaborative papers. Many of the other GRB photometric observations have been included in many-author papers. Photometric sequences of all new fields with optical transients were made by Henden and presented in the GCN circulars.

J. Fischer and C. Dudley (NRL) continued a long-term supernova search program at near-infrared wavelengths using the ASTROCAM imager at the 61-inch telescope.

## C. Instrumentation

Canzian and DiVittorio have been formulating prospective large future projects for the Flagstaff Station. Through consultations with staff members Dahn, Henden, Levine, D. Monet, Pier, and Vrba, they are working on feasibility studies and mission related applications for a large-aperture telescope and a wide field near-IR camera. Other projects under consideration include an adaptive optics system for the 61-inch telescope and a 3.5-m class telescope to replace the 61-inch in the existing dome.

With DiVittorio, Dyck, Hutter, and F. Harris, Canzian submitted a proposal as PI to the National Reconnaissance Office under the Director's Innovation Initiative to build an adaptive optics system for the 61-inch telescope.

DiVittorio built and commissioned a wavefront-sensing camera for use on telescope alignment and mirror support engineering at NOFS.

DiVittorio, Sell, and A. Rhodes completed a rebuild of the NOFS vacuum coating system.

The 1.3-m telescope, built by DFM Engineering, has been operated with a SITe 2Kx4K CCD detector giving a 20x40 arcmin field, while a six-CCD mosaic camera is being completed. Hardware and software is being developed and tested to provide fully automated operation. Tests have been done observing known satellites and searching for space debris in geosynchronous orbit.

F. Harris abandoned the first design for electronics for the 1.3-m array camera. The second design was manufactured and significant progress made in completing the electronics to operate the six CCDs of the array camera. Hobart greatly assisted in construction and software support tasks, and Dodd also assisted the construction effort. F. Harris constructed a data simulator to generate labeled test data for debugging the array camera control software, and started the array camera's computer interface.

Stone continues to develop software for the NOFS 1.3-m telescope. The focal plane of the instrument contains nonlinear terms that can be modeled with a cubic term. However, other small systematic effects are present that can be reduced further with a better model. A look-up table of focal plane corrections has been calibrated and used to reduce 1.3-m data, giving better accuracy than the simple cubic model. Stone is investigating whether spline interpolations can be used to produce further gains, albeit many reference stars would be needed. The UCAC catalog might provide enough stars for this approach to work. Moreover, Stone used FASTT data collected over the past 4 years to characterize the NOFS site in terms of weather and seeing conditions, finding that a CCD astrometric survey down to declination -30 degrees with twofold coverage could probably be completed in 4-5 years with the 1.3-m telescope.

The partnership of USNO, NOAO, and NASA/Ames to build 2048 x 2048 InSb infrared arrays at Raytheon Infrared Operations continues. This array, called ‘‘Orion,’’ is 2-side buttable, with 25-micron pitch pixels. It uses a motherboard packaging concept that allows for close buttability for 2 x 2 mosaic applications. To date, two prototype arrays and the first science grade attempt have been made. The early devices look cosmetically very good, with no evidence of cracking or debonding and with more than 99% operability. The largest problem encountered so far is a few PEDs (photon emitting defects), which can be dealt with by techniques derived in the earlier ALADDIN program. Several more science grade devices are planned to be fabricated during the coming year.

H. Epps (Custom Optical Designs) was contracted to carry out a preliminary optical design study for a potential USNO-Lowell Observatory large aperture telescope. The design results showed that a lens corrector system to meet the USNO/Lowell wide-field imaging goals is feasible.

F. Harris collaborated with Urban (AD) and N. Zacharias (AD) on the proposal to NRO for development of a monolithic 10Kx10K CCD detector.

F. Harris completed his collaboration with the QUEST team, with the publication of a paper describing the QUEST 16-CCD array camera. This concludes collaborations started while F. Harris was still a USRA contractor.

F. Harris designed a fiber-optic-based system to distribute precision standard frequencies from the GPS precise-time receiver to the various detector data-acquisition systems around FS. Hobart constructed the distribution system, and changed jumper options within the GPS receiver to supply the needed frequencies.

Henden continued his software development for ASTROCAM. The fully automated processing pipeline, written using IRAF scripts, was put into production. New operating modes for L-band imaging, as well as several window sizes for region-of-interest imaging, have been implemented. Henden is studying the low-level DSP code to add new operating modes for readout of the InSb array.

**D. Theoretical Studies**

Levine is working on a project to determine the distribution of mass in a possible halo for the LMC using number counts derived from the USNO-A2.0 catalog. The initial results of this work show that the center of the possible LMC halo is misaligned with respect to the center of the bar, and almost coincides with the centroid of the planetary nebula population. The putative halo also shows little if any of the tidal distortion that might be expected, given the LMC proximity to our Galaxy.

Levine is working on building self-consistent models for temporally periodic potentials. This is an extension of the basic idea pioneered by Schwarzschild (1979), and the aim is to help us to understand better asymmetric galaxies. Initial work was presented in a talk entitled ‘‘Lopsided Galaxies and Periodic Potentials’’ given at the 33$^{rd}$ Division on Dynamical Astronomy Meeting in April 2002.

Levine worked with D. Hunter (Lowell Observatory) and L. Sparke (U. Wisconsin) to understand the kinematics and dynamics of dwarf irregular galaxies. A model based around a disk made up of tilted rings, with a twisted line of nodes that is inclined with respect to our line of sight, was investigated and the radial velocity maps were compared with those actually observed in NGC4449.

Levine began working with J. Bury (U. Oregon) on a project to study gravitational microlensing of extended disk-like objects. This work is being done under the auspices of the Research Experiences for Undergraduates program of NSF, which is being hosted by Northern Arizona U.

**E. Other Scientific Studies**

Henden gave a workshop on Precision Photometry at the fall 2001 meeting of AAVSO. He also gave an invited paper at the PARI GRB workshop on procedures for observing GRB afterglows.

Pier and Levine have been involved with the National Virtual Observatory (NVO) effort. Part of the aim is to make sure that the USNO data products (e.g., USNO-B catalog and PMM image data) are compatible with the emerging NVO framework.

Vrba continued working with H. Fliegel and L. Warner (The Aerospace Corp.) on photometric monitoring of GPS satellites. The resultant B-, V-, R-, and I-band lightcurves as a function of Sun-observer-GPS phase angle are fit to models of reflected light specularity in order to understand surface degradation. Observations of numerous Block II and IIA satellites show that the satellites’ surface reflectivities decrease at a rate of about 10% per year. Similar observations are now concentrating on the newer Block IIR spacecraft. Additional observations in the J-, H-, and K-bands are being made to determine differences in reflected spectral energy distributions between the Block IIR and the earlier Block II and IIA vehicles.

Stone completed a study of differential color refraction (DCR) that can be a major source of error in astrometric applications. The DCR was computed in the BVRI passbands using data taken with the NOFS 40-inch reflector. In all cases, the DCR was well determined and agreed well with theoretical predictions. A paper describing the results has been accepted by PASP.

During the report year, the Time Service Data Acquisition System (DAS) measured the time of emission of LORAN stations in the western US with only one significant interruption, which was due to a long duration power outage.

### F. Miscellaneous

Luginbuhl continues his extensive involvement in local, regional, and national light pollution and observatory encroachment issues. In the past year he has assisted several Arizona entities in drafting new or revised lighting codes, including the town of Prescott Valley, and Coconino and Yavapai Counties. He gave invited presentations on lighting, lighting codes, and encroachment topics at the following venues: Southern Utah U. (Cedar City) Convocation Series; Village (Oak Creek) Business Association; Yavapai County Planning and Zoning Commission; Arizona Space Commission; Arizona League of Cities and Towns; Camp Verde city council; Utah Section of the Illuminating Engineering Society; Prescott Astronomy Club; Flagstaff Crime Free Multi-housing Manager's Workshop; the $11^{th}$ Annual Conference of the Rocky Mountain Land Use Institute; and IDA 2002 Meeting.

In related lighting and sky-brightness research efforts, Luginbuhl initiated a project in collaboration with D. Davis (Planetary Sciences Institute), G. Lockwood (Lowell Observatory), and K. Pick (Northern Arizona U.) to characterize the relation between a variety of land uses (such as commercial, industrial, and residential) and lighting use.

Luginbuhl also continues in his capacity as a Technical Advisor to the Arizona Department of Transportation. Research by an independent laboratory has commenced on two topics relevant to the use of low-pressure sodium lighting for roadways. At this early stage both projects are in fact seeking only to document the current state of knowledge in the area and assess the value of future new research. The first topic concerns the effects of lamp source spectral distribution (from high-pressure sodium, low-pressure sodium, and metal halide lamps) on visibility and roadway accident statistics; the second assesses the effects of the three lamp types on roadway lighting system designs and overall costs.

With collaborators C. Moore (National Park Service, Pinnacles National Monument) and D. Duriscoe (NPS, Sequoia-Kings Canyon National Park), Luginbuhl used the new NPS all-sky photometric camera to collect sky brightness data on NPS units in the Flagstaff area (Walnut Canyon and Wupatki, New Mexico) and with collaborator Lockwood at the Lowell Observatory Mars Hill site. At the Mars Hill site simultaneous Stromgren b,y, and Johnson V data were taken at the Lowell 21-inch telescope, to allow independent verification of the NPS CCD-based system by a classical single-channel PE system. In fall 2002 further data will be taken, with an emphasis on the NOFS site to both document its sky conditions and determine short and medium-term (hours to days) variations in sky brightness.

To support the 24-inch Cassegrain telescope USNO donated to the Booneville, Mississippi, school district, DiVittorio, Hobart, and Sell installed the telescope in August and instructed the school district staff in its operation. In January, Hobart revisited Booneville to align and collimate the telescope, correct several minor malfunctions, instruct the school staff in telescope operation, provide guidance about integrating the telescope into the overall school curriculum, and represent the Flagstaff Station at the formal dedication.

## VII. GENERAL

About 1,500 people visited the USNO in Washington during the report period as part of the Monday night tours, coordinated by Public Affairs Specialist G. Chester. The tours were suspended after the terrorist events of September 11, and were resumed on a reduced scale in April. Numerous special tours were given for government officials, schools and other special groups, including participants in the AAS Meeting in January. Dick and Chester began work on a new USNO video for the general public. Dick served as Education and Public Outreach Lead for the FAME satellite until the project was terminated in January.

Dick saw his history of the USNO, *Sky and Ocean Joined: The U. S. Naval Observatory, 1830-2000*, through the press. Dick completed work on the Time Museum. With help from Rafferty and the Instrument Shop, the historic 6-inch transit circle was removed from Bldg. 7 and placed on display in the lobby of Bldg. 1.

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