U. S. NAVAL OBSERVATORY

Washington, DC 20392-5420

This report covers the period July 2003 through June 2004.

I. PERSONNEL

A. Personnel

In June 2004 Captain David Gillard was relieved by Captain Fredrick Tettelbach as Superintendent of the U.S. Naval Observatory. QMC(SS) Barry Wass, USN, left the Astronomical Applications (AA) Department and retired from the Navy effective 30 September. QMC(SW) Blake Myers, USN, replaced him on 17 November. Steven Dick left USNO to take the position of Chief Historian at NASA effective 3 November. Sean Urban joined the AA Department as Chief of the Nautical Almanac Office effective 13 June.

Ann C. Bascom, Blair C. Fonville, and Eric Newman joined the Time Service (TS) Department. Jim De Young, Nicolette Jardine, Lisa Nelson Moreau, Lara Schmidt, and Ken Senior departed TS. Mihran Miranian retired as head of the Time Transfer Division in April after more than 40 years of service. Mark Lee joined the Earth Orientation (EO) Department in February 2004, replacing Jim Rohde who left to take a position at NOAA.

On 21 May Norbert Zacharias became acting chief of the Cataloging and Requirements Division of the Astrometry Department (AD), replacing S. Urban. Trudy Tilleman was transferred from the AD to the Flagstaff Station (NOFS). Valeri Makarov left the Astrometry Department to take a position at the Michelson Science Center (California Institute of Technology), and Dominic Marcello left to pursue graduate studies. Mel Dyck retired from the Flagstaff Station, NPOI division. Bob Zavala joined the NPOI division and Christian Hummel left for a position at the ESO in Chile.

Marie Jones retired from the Resources Management (RM) Department. Andrew Lott and Daniel Horne joined the RM Department.

B. Summer Students

The USNO summer intern program for high school and college students continued in 2003. Most of the students are supported through the Science and Engineering Apprentice Program (SEAP), sponsored by the Department of Defense (DoD) and administered by George Washington University. During the summer of 2003, the 10 interns and the departments in which they worked were: Joel Bergstein (AA), Brian Brett (TS), Andrew Cenko (AD), Laura Flagg (AD), Tracy Klayton (AD), Eric Liang (Library), Andrei Munteanu (AA), David Price (EO), Paul Ries (EO), and Sabrina Snell (AA). In addition, Steven Movit worked at USNO (in AD) as part of the Naval Research Enterprise Intern Program. The summer intern program coordinators were G. Kaplan (AA) and M. S. Carter (EO). At the end of the reporting period, USNO was preparing to host 12 students during the summer of 2004.

During the summer of 2004, S. Levine (NOFS) hosted A. Krupicka (Colorado Coll.) at USNO Flagstaff, under the auspices of the NSF Research Experience for Undergraduates program.

II. ASTRONOMICAL APPLICATIONS (AA) 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. J. Bangert continued to serve as department head.

A Science Support Division was organized within the department in January, to provide scientific and technical studies and applied research necessary to keep the almanacs and operational software products scientifically current and accurate, and to meet anticipated future requirements. Division staff is M. Efroimsky, J. Hilton, and M. Murison, supervised by G. Kaplan.

A. Almanacs and Other Publications

The Nautical Almanac Office (NAO) is responsible for the printed publications of the department (see http://aa.usno.navy.mil/publications/docs/almanacs.html). The NAO works in close collaboration with Her Majestys Nautical Almanac Office (HMNAO) of the United Kingdom to produce *The Astronomical Almanac*, *The Astronomical Almanac Online*, *The Nautical Almanac*, and *The Air Almanac*. Following the retirement of S. Howard in May 2003, Kaplan, S. Dick, and R. Miller served successive terms as Acting Chief of the NAO. An extensive search was conducted, and S. Urban (formerly of USNO's Astrometry Department) accepted the position on a permanent basis, effective 13 June 2004.

During the reporting period, the almanacs for 2005 and *The Air Almanac* for 2006 were published. Dick, Miller, S. Stewart, and M. Stollberg participated in the production of these annual publications, with additional guidance provided by Kaplan and Bangert. Stewart coordinated the necessary updates to *The Astronomical Almanac Online*. Stollberg modified the code used for Section F (Satellites) following consultation with HMNAO. Additionally, he continued development of an IDL-based application that provides plots of the apparent orbits of selected planetary satellites as a possible future Web service. Efroimsky and Kaplan revised many of the entries in the Glossary (Section M) of the 2005 *Astronomical Almanac*. M. Lukac (retired USNO) assisted in the production of The *Air Almanac*.

At the end of the reporting period, the next editions of the publications were in preparation and on schedule. Extensive changes are being made to the 2006 *Astronomical Almanac*, mostly due to the incorporation of the 1997 and 2000 International Astronomical Union (IAU) resolutions with regard to reference frames, timescales, precession, and nutation. These changes affect virtually every section of the almanac

and required extensive development and integration of new software. Stewart, with guidance from Kaplan, was mainly responsible for maintaining and tracking the incorporation of the new software into the production pipeline. Miller, Stollberg, Stewart, Kaplan, Hilton, Bangert, and Urban assisted HMNAO in editing Section B (Time Scales and Coordinate Systems), the section that will change the most due to the IAU resolutions.

Miller, with some guidance from Kaplan, updated the *Air Almanac* examples to use data from current epochs. Miller produced a revised prototype CD-ROM version of the entire 2005 *Air Almanac*; copies were distributed to selected users for review.

Production problems at the U. S. Government Printing Office (GPO) continued. For example, the 2004 *Astronomical Almanac* was completely sold out by the second week of January 2004. For reasons such as this (and others), the USNO formally requested a waiver of the legal requirement that GPO print the almanacs. In April, Bangert was notified that the request for the waiver would not be granted. However, as a result of the waiver request, GPO agreed to lower the price of the 2005 *Astronomical Almanac* to $40.00 (from $55.00), to implement a marketing plan for the book, and to ensure ready availability of the book by ordering a sufficient supply and using print-on-demand technology.

Howard resigned as co-editor of the *Explanatory Supplement to The Astronomical Almanac*, which is currently being updated and revised. Urban was named her successor. P. K. Seidelmann (U. of Virginia) served as lead editor, with Bangert and Urban completing the editorial team. Hilton, Murison, and Stewart worked on chapters for the book.

The NAO still receives written requests for special astronomical data tables, although data provided through the departments Web site (see below) have greatly decreased the number of such requests. QMC Wass and Y. Hines handled many of these requests.

B. Software Products

The Software Products Division, headed by N. Oliversen, is responsible for the department's software products and Web sites. During the reporting period, the division's efforts were focused on a major upgrade of the MICA (the Multiyear Interactive Computer Almanac) software. MICA is an executable application program that provides high-precision astronomical data in tabular form. MICA 1.5—the current version—is valid for the time interval 1990-2005, and is available in editions for PCs (a DOS application that runs under Windows) and Apple Macintosh 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 the program. The new version will feature a revamped user interface, several important new capabilities, and a greatly expanded time interval (1800-2050). The PC edition will be a true Windows application, and the Macintosh edition will operate under both Mac OS 9 and X. Work this year concentrated on development and incorporation of several astrometric catalogs, a new position type (topocentric local hour angle and declination), the location manager software that handles the observers location(s), the help facility, and the PC installation software. Extensive verification tests of both editions were underway at the end of the reporting period, with formal beta testing having started in May 2004. The MICA 2.0 development team includes W. Tangren, W. Harris, W. Puatua, and Oliversen.

C. Positional and Dynamical Astronomy

1. Solar System Dynamics

Efroimsky continued his work on gauge functions in celestial mechanics. As an application, he has been working on an analytic development of the very long-term evolution of satellite orbits about precessing oblate planets, especially Mars. The object is to develop an independent check of the direct (but very model-dependent) numerical studies of Mars obliquity history. Efroimsky's work is described in two published papers, with one more submitted and two more in preparation.

At the end of the reporting period, Efroimsky had also begun a study of the analytical development of rigid-Earth rotation as affected by lunisolar and planetary torques. Such developments form the basis for the algorithm for nutation currently used in the analysis of high-precision Earth orientation observations. He has found that the currently used theories appear to contain a well-concealed flaw, the correction of which will almost certainly have important practical results.

Hilton was named co-investigator of a NASA grant on asteroids. His specific responsibilities are to (1) study the accuracy of asteroid ephemerides and determine the effect of unmodeled perturbations from other asteroids; and (2) make determinations of the masses of some of the larger asteroids.

Murison continued working with a District of Columbia high school student, A. Munteanu, on the minimum distance between two bodies orbiting a common center in independent Keplerian ellipses. This problem, of great practical value, has turned out to be unexpectedly thorny. For his work on this topic, Munteanu was awarded 9th place nationally in the 2004 Intel Science Talent Search.

Hilton developed an algorithm to replace the lunar librations used in *The Astronomical Almanac*, based on a 1981 Eckhardt theory, with librations derived from the lunar rotation angles in the Jet Propulsion Laboratory (JPL) LE405 lunar ephemeris.

Efroimsky, Hilton, and Murison gave talks on their work at the annual meeting of the American Astronomical Society (AAS) Division on Dynamical Astronomy (DDA), held in Cannes, France, in April.

2. Positional Astronomy

Hilton and Hohenkerk (HMNAO) completed a development of the matrix transformation between the dynamical equator and equinox of J2000.0 and the International Celestial Reference System (ICRS). Their work was published in January.

Kaplan completed an advanced beta release of the next FORTRAN version of the Naval Observatory Vector As-

trometry Subroutines (NOVAS). This version implements the IAU resolutions of 1997 and 2000 on fundamental astronomy. Output from this package was compared with that from independent code, based on different algorithms, used at HMNAO; the results were in excellent agreement. The new NOVAS release was used in the preparation of the USNO sections of the 2006 *Astronomical Almanac*. Kaplan also began writing a USNO Circular describing the recent IAU resolutions and their implementation.

Kaplan continues to collaborate with V. Makarov (JPL) on the possibilities for astrometric detection of unseen companions to apparently single stars, using various kinds of discrepancies in proper motion measurements. A paper on this subject was in advanced draft form at the end of the reporting period.

Bangert, Kaplan, Hilton, Urban, and Dick attended the IAU General Assembly in July 2003 in Sydney, Australia. Bangert and Kaplan gave presentations within Division 1 meetings on the implementation, in USNO products, of the IAU resolutions passed in 1997 and 2000 on fundamental astronomy (specifically regarding astronomical reference systems and Earth rotation models). Hilton gave a presentation on precession theories. Hilton was appointed chair of the new IAU Working Group on Precession and the Ecliptic, and Kaplan was appointed a member of the new IAU Working Group on Nomenclature for Fundamental Astronomy. Both working groups were quite active in the year following the General Assembly. Hilton's working group made significant progress towards recommending a dynamically valid precession theory for general astronomical use. Hilton also continues to serve on the IAU Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites, and is currently assisting in the production of the working group's next report. Urban served as chairman of the Densification of the Optical Reference Frame working group under Commission 8.

Puatua continued working with A. Fey and D. Boboltz (AD), analyzing VLA+Pie Town observations of galactic radio stars to determine their precise positions and proper motions in the ICRS. The approximately 50 radio stars in this data set were chosen because they are visible in both the radio and optical, thus providing a connection between the two frames.

3. Celestial Navigation

Bangert, Kaplan, Urban, and T. Rafferty (AD) continued their collaboration with staff at the Space and Naval Warfare Systems Center — San Diego on development of an automated celestial navigation system (ACNS). Two contractors, one working in the red portion of the spectrum (Microcosm, Inc., funded by the Air Force Research Laboratory) and the other in the near-infrared (Trex Enterprises Corp., funded by the Office of Naval Research), began design and fabrication work for prototype devices to observe stars day and night from a fixed location and obtain a geographic position from the observations. Both contractors' work is being performed as Small Business Innovative Research (SBIR) projects. USNO is providing technical guidance, its STELLA celestial navigation software, and special star catalogs tailored for the ACNS sensors.

D. World Wide Web Site

The AA department's public Web site (http://aa.usno.navy.mil/) continued to grow in popularity. The site handled from 15,000 to over 25,000 user sessions per day during the reporting period. This is an average increase of about 10% compared to the previous year.

Everyone on the scientific staff contributed content and support to the Web sites. Puatua created a new data service to calculate the local circumstances of the 8 June 2004 transit of Venus, utilizing the MICA 2.0 computational engine. Many other Web pages underwent minor updates. Tangren maintained the Web servers. Department staff continued to answer questions related to the departments mission, submitted by e-mail from Web site users. Several questions per day were received, on average, and response time was typically one or two workdays.

E. Other Research and Activities

Hilton completed an analysis of the published magnitudes of Mercury and Venus as a function of phase angle, for use in the magnitude predictions in *The Astronomical Almanac*. At the end of the reporting period, a paper on this topic was in advanced draft.

Both Efroimsky and Murison have been actively involved in the dispersed Fourier Transform Spectrometer (dFTS) project (see Astrometry Department report). Both have taken observations with the instrument, which is mounted on a telescope near Boston, MA but can be remotely operated. The dFTS is yielding high-quality stellar spectra and increasingly precise radial velocities. Efroimsky has been studying the application of the second-order Doppler shift to the very high-precision radial velocity measurements that the dFTS may be able to provide. Murison has been involved in the optical design, and especially in the construction and testing of an adaptive optics front-end.

Murison continues his duties as Secretary of the Division on Dynamical Astronomy (DDA) and was active in helping to organize the annual DDA meeting in Cannes. Hilton serves on the Committee of the DDA.

Hilton organized a special session at the spring 2004 AAS meeting in Denver on the IAU resolutions of 1997 and 2000 on fundamental astronomy. At the end of the reporting period he was organizing a working group within the DDA on this topic.

Bangert continued to serve on the IAUs Standards for Fundamental Astronomy (SOFA) Review Board (http://www.starlink.rl.ac.uk/~sofa/).

III. TIME SERVICE (TS) DEPARTMENT

A. Master Clock Operations

L. Breakiron maintained the Bldg. 52 and 78 mean timescales based on data taken with the Timing Solutions Corp.

(TSC) clock measurement systems. He also continued his research on Kalman filter timescales toward real-time implementation.

D. Johns completed rewriting the timescale programs in the C language. He set up P. Koppangs steering algorithms on four Auxiliary Output Generators. Many additional plots featuring timescale, time transfer, and environmental data were added to the Rom Web site.

B. Global Positioning System (GPS) Operations

Breakiron took over as alternate monitor of GPS operations to F. Vannicola following the departure of L. Nelson Moreau. He wrote an operations duty manual and programmed the data collections from the carrier-phase receivers known as USN1 and AMC1 at the Observatory and the Alternate Master Clock (AMC) site respectively.

H. Chadsey worked with the Naval Surface Warfare Center, Carderock Division, to test various versions of a special-purpose GPS-steered frequency standard. He designed and implemented a test facility for general-purpose frequency, time, and GPS systems testing. This testing is ongoing. Chadsey also worked with J. Brad, D. Matsakis, and E. Powers on the RINEX to CCTF time-code conversion in geodetic GPS receivers.

B. Fonville collected data from Trimble GPS receivers. D. Johns, with the assistance of E. Powers and D. McCarthy (Directorate of Time), implemented two solid Earth tide models at the positions of USNO and the AMC.

Powers contributed to the GPS Capabilities Definition Document and worked with the GPS Joint Program Office on improvements to GPS time steering and to USNO measurements of GPS time bias. He handled interoperability issues between GPS and Japan's QZSS system; contributed to a new GPS navigation message; and worked with the Jet Propulsion Laboratory and KW Microwave, Inc. on a new design for GPS antenna electronics. He conducted experiments involving a GPS simulator and carrier-phase receivers; took part in a GPS III time improvement effort and in writing specifications for a GPS III Digital Satellite Simulator; and participated in the development of a new Navigation and Time System for future Navy ships.

Vannicola managed the Precise Positioning Service (PPS) and Standard Positioning Service (SPS) receivers, associated hardware, and reduction software. Under the control of the Time Transfer Division were four Allen Osborne Associates, Inc. (AOA) TTR-12 PPS receivers, two STel 5401C PPS receivers, two Motorola Oncore SPS receivers, one R100 GPS/GLONASS receiver, and one AOA TTR-6 SPS receiver. Two STel 5401C receivers were shutdown in March and April 2004 and one AOA TTR-6 receiver in December 2003. One AOA TTR-12 PPS receiver and one Motorola Oncore SPS receiver were in operation at the AMC site. The AMC TTR-12 was returned to USNO in September 2003 due to persistent tracking anomalies and replaced with a spare unit from USNO. The original AMC TTR-12 has been operating at USNO without any problems and with no hardware or software modifications.

The GPS Master Control Station (MCS) of the Air Forces 2nd Satellite Operations Squadron (2SOPS) performed successful daily downloads of the USNO GPS PPS timing data for GPS Time synchronization to UTC (USNO). The GPS timescale was maintained to within ± 15 nanoseconds (ns) of UTC (USNO) (its specification is ± 1 microsecond) and the yearly average error of UTC transmitted from GPS was 4.29 ns. Vannicola worked with Johns and GPS MCS contractors to set up testing of USNO data files for future transfers via the Secret Internet Protocol Router Network (SIPRNet) to the GPS MCS.

Vannicola computed the new calibration value (L1 only) for the operational USNO SPS GPS receiver to bring it in line with the operational USNO PPS GPS receiver. The new value was inserted on 2 April 2004 at 0000 UT and the Bureau International des Poids et Mesures (BIPM) was notified. All backup SPS receivers were also adjusted appropriately.

Vannicola implemented a series of alarm monitors for GPS data monitoring, values out of range, SIPRNet connectivity, and L2 interference; monitored the daily GPS MCS 2SOPS downloads of USNO data for GPS Time synchronization; performed the necessary Communications Security (COMSEC) duties required to sustain the USNO GPS PPS timing operations; modified associated software; and replaced the receiver-dependent USNO vs. AMC GPS PPS common-view data files with continuous operational files.

For redundancy and robustness, Vannicola redistributed the GPS PPS operations equipment to balance the primary and backup systems on the two uninterruptible power system sources in Bldg. 78, Rm. 123 and set up GPS PPS data reduction and processes on a second HP-UX computer system (''Hypatia2'') as a hot backup to the primary system (''Hypatia'').

Vannicola monitored the reduction of the NovAtel GPS and WAAS receiver and common-view data and assisted in troubleshooting the failure of the receiver in April 2004. With Powers and Brad, she worked with AOA on the development of their PTTR-12CS Selective Availability/Antispoofing Module (SAASM) receiver.

Vannicola provided support to the National Geospatial-Intelligence Agency in troubleshooting their GPS PPS receivers located at USNO, as well as COMSEC receiver keying. She also provided USNO GPS Timing Operations reports to the Civil GPS Service Information Committee at their September 2003 and March 2004 meetings.

C. Loran-C Operations

USNO signed a Memorandum of Understanding with the U.S. Coast Guard Engineering group at Wildwood, NJ. This venture will put USNO into the Enhanced Loran system as a key reference point. Chadsey continued monitoring Loran timing. He gave a course to Coast Guard personnel on clocks, timing, and reference frames.

D. Wide Area Augmentation System (WAAS) Operations

Chadsey monitored the timing data from the FAA's WAAS.

E. Computer Operations

J. Eler installed, maintained, and repaired all the LAN cabling. Johns set up USNO/AMC SIPRNet e-mail PCs with assistance from T. Hannus and A. Koppas, both of the Information Technology Department. He also evaluated and set up two Web-based e-mail solutions in the event the Exchange Server is no longer available.

W. King developed a comprehensive Web-based interface for monitoring and control of TWSTT operations which is used by the staff to bring new sites on line, adjust calibration and measurement values, plot data, monitor status, and update event logs. She developed two LINUX PCs to take over the SATRE modem data collection and processing to provide high TWSTT availability. She also developed Web-based documentation of the TS instrument LAN and its hosts and all devices, and migrated all the data collection at the AMC from the last 68K machine to the new HP-UX instrument controllers and instrument LAN. She developed a LINUX PC with DVD-RW capabilities now used to archive AOA TTR-12 GPS receiver data.

R. Schmidt upgraded Time Service campus LAN connectivity to 1000-baseTX Ethernet. He installed USNO's first Fabric-login Fibrechannel-switched storage area network, installed HP ServiceGuard high-availability clustering software, and began testing campus fiber-optic connectivity. Schmidt installed the Mysql version 4 relational database for timescale and environmental data mining.

F. Alternate Master Clock (AMC) Operations

Breakiron maintained the operational AMC mean timescale until J. Skinner took it over in January. Breakiron also maintained the mean timescale based on TSC clock data. Skinner continued to provide BIPM with USNO and AMC clock data. Fonville installed and tested a new TWSTT antenna, modem, and cabling.

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

Breakiron monitored the data accuracy and integrity of the TWSTT operational exchanges with 11 other timing laboratories, programming adaptive filters that detected outliers and warned of excursions. He began a study of TWSTT calibration errors.

Fonville modeled a TWSTT carrier-phase system, devised a configuration using dual-loop back, and wrote software to process data from SATRE TWSTT modems operating in carrier-phase mode. He determined the temperature sensitivity of SATRE modems and Ortel fiber-optic controller modules and conducted a noise analysis of an Anacom transceiver.

A. McKinley, A. Smith, and E. Newman handled TWSTT operations; upgraded and calibrated the TWSTT stations in Bahrain, Germany, and Michigan; calibrated the TWSTT stations at the AMC, NIST, Timing Solutions Corporation, and Vandenberg AFB; and changed the frequencies of all the TWSTT sites using the AMC3 satellite. McKinley restored the transatlantic TWSTT link during the satellite change from Intelsat 706 to Intelsat 903; worked with TimeTech GmbH on the software for, and testing of, the new SATRE modems; and repaired the modem at the Midway station. McKinley and Newman maintained, repaired, and upgraded the USNO TWSTT antenna. McKinley and Smith upgraded the TWSTT software at the Michigan and Vandenberg stations. McKinley and P. Wheeler calibrated the Midway station. Smith upgraded the TWSTT equipment in Bldg. 52 and Vandenberg. Newman and G. Luther maintained USNOs TWSTT cabling and calibration equipment.

Powers worked with Johns and McCarthy on improved tropospheric modeling for TWSTT operations.

H. Network Timing Protocol (NTP) Operations

Schmidt, with assistance from Johns, continued to provide nationwide NTP support. The demand for this service continues to expand. Incoming NTP traffic reached a record 5,000 packets/second in Washington, DC, with an additional 700/second at remote NTP sites. Schmidt migrated the current NTP server to version 4.2.0, providing enhanced security and ability to provide cryptographic authentication. Eleven HP A500 servers were integrated with PCI time and frequency processors and Motorola UT+ GPS receivers. These were deployed to USNO NTP host sites at Fairbanks, AK, Palo Alto, CA, Pasadena, CA, Colorado Springs, CO, Gainesville, FL, Maui, HI, Waterville, ME, New York City, NY, Columbus, OH, Houston, TX, and Seattle, WA. Schmidt installed and tested NTP development version 4.1.74, and production versions 4.1.80-rc1, and 4.2.0 on HP-UX 11i platforms.

Schmidt proposed a new SAASM GPS NTP server for the DISA SIPRNet. The USNO NTP SIPRNet was upgraded from 128 kbps to 1.54 Mbps. He provided documentation to Space and Naval Warfare Systems Command supporting retention of NTP time service on the Non-secure Internet Protocol Router Network. He worked with Mitre Corporation on refinements to their National Air Force time synchronization network.

I. Systems Engineering

Fonville developed software for the control of a Stanford Time Interval Counter. Smith maintained and repaired all the environmental chambers in Bldgs. 52 and 78.

M. Tran worked with PSI, Inc. to design and develop the outdoor temperature control chambers that are now in use to stabilize the temperature of TWSTT transceivers, the control of which has improved significantly since the chambers were installed on the roof of Bldg. 78. Tran also designed and developed new alarm systems for Bldgs. 78 and 52 that monitor chamber temperatures and critical equipment. The system is able to call, page, and e-mail each individual who is assigned to a specific day and time.

Tran upgraded programs based on Visual C++ for all SATRE modems that control TWSTT automatically, i.e. the up/down converter frequency and data collection. The program allows editing of the schedule times, PN code, up/down frequency, and satellite positions. He also developed a plotting program based on PC labView to perform TWSTT and TSC data analysis and file manipulation.

Tran maintained the TSC hardware and software in Bldgs. 52 and 78. He redesigned the control software based on GUI Visual C++ for greater flexibility, reliability, and user friendliness. He performed periodic Master Clock #2 and #3 calibrations and, with A. Kubik, monitored and maintained the performance of the Digital Acquisition System clock measurement system equipment. He also designed and developed many GPS split amplifiers that have been installed.

J. Clock Development

T. Swanson continued to work with JPL on the mercury ion trap standard. Attempts to remove drift and signal loss are underway. S. Crane, S. Peil, Swanson, and C. Ekstrom continued work on a rubidium fountain. The magnetic shields, optical systems, and control systems are in place. The group presented its work on the fountain and optical frequency doubling at the IEEE Frequency Control Symposium. Koppang and Ekstrom authored a paper on three-cornered-hat analysis of clock stability that will appear in the Transactions on Ultrasonics, Ferroelectrics and Frequency Control (UFFC).

The USNO Astrometry Department Instrument Shop continues manufacturing parts for the atomic fountain clock. Several types of materials were tried for the detection block and its window cells. The titanium and sapphire window combination seemed to work.

K. Miscellaneous

Breakiron served as chairman of the USNO Editorial Review Board and as treasurer and editorial chairman of the Precise Time and Time Interval (PTTI) Systems and Applications Meeting Executive Committee. He edited the previous Observatory Report; edited, published on CD-ROM, and distributed the PTTI Proceedings of the 35th Annual Meeting; and posted the PTTI papers on the USNO Web site.

Vannicola maintained the PTTI Meeting Web pages that included general information as well as the 35th Meetings Advance Program and meeting information in html and pdf formats; coordinated the PTTI 2004 Call for Papers; and continued to serve as a member of the PTTI Executive Committee.

King won the 2004 Gilliss Award for outstanding service to USNO.

IV. EARTH ORIENTATION (EO) DEPARTMENT

The core mission of the department is to determine and predict the time-varying orientation of the Earth's terrestrial reference frame with respect to the celestial reference frame. The department disseminates predictions of polar motion coordinates, Universal Time (UT1), and celestial pole offsets to high-accuracy navigation and real-time or near real-time positioning users. The department's products are used by the U.S. Navy, the DoD, other U.S. government entities, the international scientific community, and the general public. The department serves as the Rapid Service/Prediction Center for the International Earth Rotation and Reference Systems Service (IERS), as an Associate Analysis Center of the International Global Positioning System (GPS) Service (IGS), and as an Operations Center, Correlator, and supporter of observing stations within the International Very Long Baseline Interferometry (VLBI) Service. W. Wooden continued to serve as department head.

A. VLBI Operations

The VLBI Correlator Facility continues as an International VLBI Service (IVS) Correlator Facility. During the reporting period 62 Rapid 24-hour experiments for determining Earth orientation, 202 UT1 intensive sessions, 22 Celestial Reference Frame experiments, 11 Terrestrial Reference Frame experiments, and 4 R&D experiments were processed. The Correlator continues to be the primary rapid-turnaround processing center for Earth orientation monitoring and operates 24 hours per day, 5 days a week with 16 hours of additional processing on weekends. Schedules are prepared for five UT1 Intensives and one 24-hour Earth orientation observing sessions every week. K. Kingham leads the VLBI effort with support from M. Carter and A. Myers.

During the reporting period, the efficiency of processing has increased by almost 50%, mostly due to the conversion of more than half of the processing to the Mark 5 disk-based recording system. Most experiments are now being processed within a month of observation, provided the recording media arrives within a reasonable time. Also in the reporting period, experimental use of e-VLBI began, primarily for data transfer from Japan and data conversion from the K5 to Mark 5 recording systems. This process has now become routine.

Presently, the Correlator has eight playback tape drives and eight Mark 5A units available and is able to efficiently correlate eight-station experiments in a single pass. Due to the increase in throughput due to the Mark 5 system, a few large multi-pass experiments were processed, including a 16-station Terrestrial Reference Frame experiment. Future plans call for the conversion of the Mark 5A units to Mark 5B when they become available, increased use of e-VLBI, and expansion to a full 16-station Correlator.

B. GPS Analysis

The department continued to contribute rapid, ultra-rapid, and tropospheric products for GPS satellites to the IGS. The software used to create these products was GIPSY/OASIS (GOA) II (versions 5 and 6) and GOA IV, which were written by JPL. The addition of a Linux machine running GOA IV has provided a positive contribution to the rapid results. M. Lee leads the GPS effort with support from V. Slabinski, P. Kammeyer, M. Carter, A. Myers, and D. Pascu. Rohde led the GPS effort until his departure from USNO in October 2003. On an interim basis until the end of March, Slabinski was the team leader.

GIPSY/OASIS IV, the latest release of GPS processing software from JPL, was installed on a Linux PC running Redhat Linux 9. This software offers improvements over its previous release, most notably its ability to process up to 80 stations per run. Rapid-orbit solutions were determined from this system for testing and comparison with current solutions from the Unix machines. Results compare well with the per-

formance of GOA II, version 6, running operationally on an HP J6700 (running Unix 11). Occasionally, the results were combined with the operational results from the Unix machines and submitted to the IGS for the rapid combination. In nearly every case, the addition of the GOA IV results has improved the IGS submissions. It is expected that the Linux machine will take on more of an operational role in rapid-orbit processing in the near future.

The USNO rapid orbit processing showed considerable improvement for the reporting period. The average weighted root mean square (wrms) for the GPS rapid satellite orbits was 2.7 cm; the average root mean square (rms) GPS clock solution was 53 picoseconds (ps); the average number of receiver clocks solved for was 112.8; and the on-time submission rate was 98%. The corresponding values for the previous year were 3.2 cm, 68 ps, 100.5 clocks, and 98%. The improvement of our GPS rapid orbit and clock solutions were 16% and 22%, respectively.

The USNO ultra-rapid orbit submissions also had significant improvement. The average wrms for the GPS ultra-rapid orbits was 13.1 cm; the average rms GPS clock solution was 3.53 nanoseconds (ns); and the on-time submission rate was 92%. The corresponding values for the previous year were 18.5 cm, 4.91 ns, and 87%. In addition to improving our on-time ultra-rapid submission rate by 5 percentage points, our GPS ultra-rapid orbit and clock solutions were improved by 29% and 28%, respectively.

In July 2003, the IGS Analysis Coordinator site changed from the Astronomical Institute, University of Berne in Switzerland (part of the Center for Orbit Determination in Europe (CODE)) to GeoForschungs Zentrum in Potsdam, Germany. In March 2004, the backup site for receiving our data changed from Berne to CDDIS (Crustal Dynamics Data Information System) at NASA/Goddard Space Flight Center (GSFC). Rohde, Myers, Slabinski, and Lee made software changes required to meet these and other new requirements.

Slabinski continued working on improvements to the CODE model for the solar radiation force (SRF) on GPS spacecraft for use in his ultra-rapid predictions. He introduced a revised mathematical expression for the Block II spacecraft during eclipse seasons and determined model parameters for the recently launched Block IIR spacecraft, once out-gassing from their surfaces had subsided. He also continued work on a physical model for GPS SRF computations. Summer intern S. Ditmore assisted in the modeling effort.

Kammeyer continued his investigations on modeling the rates of motion of GPS angular momentum vectors, rates used in producing the UT1-like product UTGPS. Since the gravitational accelerations of GPS satellites are well known, Kammeyer is analyzing the remaining part of the motion of each angular-momentum vector, caused by radiation pressure. The importance of Kammeyer's investigations results from the contribution of UTGPS to the Bulletin A product of the department and from the systematic, although not understood, nature of the effect of radiation pressure.

C. Earth Orientation Parameter (EOP) Combination and Prediction

The department serves as the Rapid Service/Prediction Center for the IERS with the effort being accomplished under the EOP combination and prediction program. This program is responsible for producing both the daily and weekly IERS Bulletin A and the USNO Mark III EOPs. Currently, the Mark III solution is a subset of the weekly Bulletin A solution. T. Johnson leads the effort with support from Carter and Myers.

During 2003 a number of changes occurred that affected the accuracy of the IERS Bulletin A. In January, the IAU 2000 resolutions were introduced into the departments products. The finals2000A.data and the finals2000A.daily solution files were created to comply with these resolutions. These new files contain the nutation in terms of dX/dY computed using the IAU2000A Nutation Theory. In late summer finals2000A.all was added to our list of products. The finals2000A.all file is the finals.all file converted to the IAU2000A Nutation Theory in the dX/dY paradigm.

In early 2003 two additional VLBI 24-hour time series were added to the combination solution. These new series are the USNO R1/R4 VLBI solution and the IVS Combination EOPS VLBI solution. The addition of these series to the solution has improved the robustness of the nutation parameters.

To improve the accuracy of the department's daily Bulletin A EOP solution, scripts were developed to automate the updating processes for both the VLBI 24-hour and VLBI Intensive datasets. This allows for the VLBI data to be updated in the daily solution as soon as new updates become available.

In June and July new VLBI global solutions required the estimation of new rates and biases for the combination software. The rates and biases for all of the satellite laser ranging (SLR) data sets were also reestimated. These updates resulted in improvements to the x and y components of polar motion (PM-x and PM-y) time series. Unfortunately, there was a problem with a VLBI intensive UT1-UTC bias correction. This error was detected and corrected in early August.

In August the weekly script was modified. New routines were added to automate the retrieval of the SLR data from the mail server. This modification reduced the processing time for the weekly Bulletin A EOP solution.

Later in the year, an investigation was made to determine whether the newer R1 VLBI 24-hour sessions were actually better than the less expensive older R4 VLBI 24-hour sessions. The results indicated that the R1 observations of PM-x are slightly better than the R4 observations. However, this improvement appears to be the result of the R1 experiments having a better station network, with a long north-south baseline close to the prime meridian, and not due to the more expensive use of wider bandwidths. Therefore, the R4s may also be improved through modifications to the stations used in the R4 network.

In March 2004 this R1/R4 VLBI study was extended to R1 and R4 experiments number 102 and also to the R&D experiments from 2003. The results of this study were presented at the April European Geosciences Union (EGU)

General Assembly meeting in Nice, France. They indicated that except for PM-x, the R1 experiments were not any better than the R4 experiments and it appears that the network geometry is the cause of the improvement in the R1 PM-x and not the increased bandwidth. There was also evidence that the TIGO Station was introducing a drift into the PM-x values as well as trends into the PM-y and UT1-UTC values. This is most likely the result of using improper station motions and not correcting this stations motion for the recent two large earthquakes.

In April the interannual spectra of three atmospheric and three oceanic models were studied. The results indicated that the National Center for Environmental Prediction (NCEP) reanalysis, the GSFC Earth Observing System version 1 (GEOS-1) experimental, and the European Centre for Medium Range Weather Forecasting (ECMWF) operational atmospheric models all had different annual to interannual variability. Furthermore, these differences appeared to result in different wind stresses that, when used to drive an ocean model, influence the spectra of the ocean models. Therefore, any research pertaining to the estimation of an angular momentum budget should use the atmospheric model that was used to drive the ocean model. Another result from this study was that the Parallel Ocean Climate Model run 4B (POCM 4B) model is not as good as the more recent Massachusetts Institute of Technology (MIT) and the Estimating the Circulation and Climate of the Ocean (ECCO) ocean models at estimating oceanic variability with periods of a year and longer. The results of this study were presented as an invited paper at the European Center for Geodynamics and Seismology (ECGS) and IERS Chandler Wobble Workshop in Luxembourg in April 2004.

On 14 April new global solutions for GSFC's 24-hour and intensive VLBI were introduced into the EOP combination. This required the estimation of new biases and rates for these time series. The new GSFC intensive data set includes both the Kokee-Wettzell and Tsukuba-Wettzell baselines. The additional data increased the file length, which created an array allocation problem within one of the processing routines. This routine was modified and converted to FORTRAN 90 and now uses dynamic array allocation. Some additional minor precision and initialization errors were also corrected.

As a result of this incident, an effort to update current operational code to standard FORTRAN 90 was initiated. This will result in operational software that takes better advantage of modern computer hardware as well as increase its portability onto different computer platforms. Since May, six programs within the EOP combination and prediction system have been updated and a few previously unknown problems were discovered and corrected.

In May new global solutions for USNO's 24-hour VLBI solution were introduced into the EOP combination. New biases and rates for these time series had to be estimated. In addition due to the USNO, GSFC, and Institute of Applied Astronomy, St. Petersburg (IAA) Analysis Centers' inclusion of VLBI experiments that were not designed for EO parameters such as the T2 experiments in their VLBI time series, the VLBI processing routine was modified to remove these experiments. The upper limits on the formal sigma errors used in the automated editing of VLBI data were also reduced to edit out additional experiments such as the VLBI EURO experiments.

The department's effort in support of the IERS Combination Pilot Project (CPP) began in late May after notification of the acceptance of our proposal in April. The purpose of the CPP study is to gain a better understanding of the strengths and weaknesses of different EOP techniques with the ultimate goal being the production of improved weekly EOP solutions. The CPP will examine and evaluate individual EOP techniques as well as the combination of these techniques into a weekly EOP solution to achieve its goal. The different techniques being studied in this program are VLBI, GPS, SLR, and DORIS. Currently, only the GPS and DORIS weekly solutions are available. At this time, much of the department's CPP work is focused on the creation of scripts for downloading files and for converting data to and from the SINEX format.

In early June the actual reduction in UT1-UTC prediction errors resulting from the introduction of an atmospheric angular momentum derived UT1-like quantity (UTAAM) into the EOP combination was more rigorously determined. This estimate was computed by comparing the C04 UT1-UTC time series to both the operational UT1-UTC that uses both geodetic and UTAAM and the formerly used operational geodetic-only daily UT1-UTC for the same 12- month period starting March 2003. The results indicate that the introduction of UTAAM reduces prediction error by $\sim$57% at 10 days into the future. This comparison clearly showed that for predictions 5 to 60 days into the future the addition of UTAAM into the combination process significantly reduces the UT1-UTC predictions errors.

Currently, the department is investigating ways to improve the estimation of biases between the different Analysis Center datasets and the C04 series. It is also investigating the use of additional prediction methods and geophysical fluid models in improving the EOP predictions.

As the IERS Rapid Service/Prediction Center, the department continues to make EOP data available in a variety of forms. Specifically, a weekly machine-readable version of Bulletin A containing the current predictions for 365 days into the future via electronic mail is available as well as standard and daily data files available by anonymous ftp.

D. Miscellaneous

In February 2004 S. Lambert from the Paris Observatory began a one-year visiting scientist position at USNO to extend his previous work in the modeling of nutation and to gain a better understanding of the measurements that produce ''observed'' nutation. Specifically, he is focusing on free core nutation modeling and examining the basic assumptions, other models, and procedures embedded in the VLBI observations that may affect the fundamental measurement of nutation. In particular, numerical checks were run for the implementation of the IAU 2000 resolutions in the VLBI analysis software CALC/SOLVE. Research on the effects of Earth's rotation rate variations and zonal deformations on precession-nutation, which noted some errors in the Mathews, Herring, Buffett 2000 tables, was published.

As part of a larger study to understand the angular momentum budget of the Earth and its effect on Earth orientation parameters, summer intern D. Price worked with Johnson to examine the effect of groundwater variations, as determined from well data and NCEP precipitation, on the gravitational coefficient J_2. Variations in J_2, an order of magnitude smaller than what is seen in SLR data, were observed and the trends were similar. This research was presented at the fall American Geophysical Union (AGU) meeting.

During the past year department personnel were heavily involved in international conferences, workshops, and directing boards related to Earth orientation activities. Johnson participated in the CNES Hydrology from Space Workshop in Toulouse, France; the NASA GRACE Hydrology Workshop in Irvine, CA; the NASA Surface Water Working Group meeting in Irvine; the IERS Chandler Wobble Workshop; the European Geosciences Union (EGU) General Assembly in Nice; and the fall AGU meeting. Kingham attended all IVS Directing Board meetings, served on the IVS Observing Program Committee, and participated in the third IVS General Meeting and the fifth IVS Analysis Workshop in Ottawa, Canada. Wooden participated in the IAU General Assembly meeting, the Journees 2003 meeting in St. Petersburg, Russia; the IVS General Meeting and Analysis Workshop; the 10th anniversary IGS Symposium and Workshop in Bern, Switzerland; all IERS Directing Board meetings; the fall AGU meeting; and the EGU General Assembly. Kammeyer gave a paper on his investigations on orbit modeling for producing the UT1-like quantity, UTGPS, at the spring AGU meeting in Toronto, Canada. Lee and Carter participated in the IGS Symposium and Workshop. The Rapid Service/Prediction Center Annual Report for 2003 was submitted to the IERS for publication in the IERS Annual Report. The Joint USNO-Paris Observatory Explanatory Supplement for IERS Bulletins A and B was updated for 2004. The department played an active role both in supporting (hosting three students) and in coordinating the Science and Engineering Apprentice Program. Also, Johnson assisted in giving public tours of the Observatory.

Johnson won the 2004 Newcomb Award for outstanding scientific research related to the understanding of the geophysical phenomena underlying the variations in Earth orientation.

V. ASTROMETRY (AD) DEPARTMENT

A. Washington Double Star Program

Observations of 2,693 objects were obtained using the speckle system attached to the USNO 26-inch refractor. Observers include W. Hartkopf, B. Mason, T. Rafferty, Urban, and G. Wycoff. The program primarily consisted of neglected doubles. Observations from 2003 have been analyzed and submitted for publication. Analysis of 2004 data is ongoing. In addition, the 61-inch telescope at the Flagstaff Station of the USNO was used two weeks in experiments to test the applicability of this instrument for speckle interferometric observations. A total of 922 observations were obtained by Hartkopf, Mason, and Rafferty. Collection and reduction of data continues.

Work continues regarding the double star catalogs maintained by the USNO (Washington Double Star Catalog, 6th Orbit Catalog, 4th Interferometric Catalog, and 2nd Magnitude Difference Catalog). Data, both current and historical, was added to all catalogs (e.g., the WDS increased by over 43,000 observations, or 7%). The USNO filled 507 data and observing list requests over the reporting period. In addition to the addition of data, corrections were made to published data, precise coordinates were added for approximately half of the systems without them, and cross-references were expanded and improved.

Hartkopf completed his duties as Vice President of Commission 26 (Double and Multiple Stars) and was installed as President of the Commission for the 2003-6 triennial cycle. Mason and Hartkopf co-chaired and gave talks at Special Session 3 (SPS3) on multiple star nomenclature at the IAU-GA. A Type C Resolution endorsing the Washington Multiplicity Catalog (WMC) work was passed by relevant commissions and a Working Group was formed by Commission 26 to continue work on an all-sky WMC to be prepared and presented at the Prague GA for a Type B Resolution. Proceedings of SPS3 were edited by Mason and Hartkopf. Hartkopf met with T. Oswalt (FIT) and H. McAlister (GSU/CHARA) and consulted with D. Dravins (IAU Div. President) and P. Ianna (NSF) regarding a double-star meeting anticipated for 2005.

Continuing collaborations for the double-star program include D. Berger (GSU/CHARA), T. ten Brummelaar (GSU/CHARA), D. Gies (GSU/CHARA), E. Griffin (U. Victoria, Canada), R. Griffin (Cambridge, UK), T. Henry (GSU/CHARA), H. McAlister (GSU/CHARA), E. Nelan (StSci), D. Pourbaix (U. Brussels), L. Roberts (Rocketdyne), D. Soderblom (STScI), N. Turner (GSU/CHARA), D. Wallace (NASA), and A. Wehrle (JPL).

B. Astrometric Space Missions

OBSS: Astrometry Department (AD) personnel (B. Dorland and R. Olling) led the development of the successful Origin's Billion Star Survey (OBSS) mission study proposal, prepared in response to the NASA Origin's Roadmap announcement of opportunity. OBSS will provide a complete census of giant extrasolar planets for all types of stars in the galaxy and the demographics of stars within 10 kpc of the Sun. It will measure a billion stellar positions, parallaxes, proper motions, luminosities, binarity determinations, photometry, spectrometry, and photometric variability. OBSS will provide observations of stars 7^{th} to 20^{th} visual magnitude with an astrometric precision of 10 microarcseconds at 14^{th} magnitude. OBSS was one of nine missions, selected out of a total of 28 proposals, for further study.

At the end of the eight-month study period, an OBSS mission study report will be submitted to NASA. Based on the study reports, two of the eight proposals will be selected for inclusion as Origin's Roadmap missions. AD personnel will lead the OBSS instrument study group, and have signifi-

cant roles in the OBSS Science Team, the spacecraft study group, the missions operations and data analysis study group, and the error budget study group.

Data Reduction Pipeline: Development of a prototype space astrometry mission data reduction pipeline, led by G. Hennessy, continued. Improvements implemented this year included: attitude representation using both Taylor and Chebyshev polynomials, calculation of the O-Cs, and development of partials to allow for corrections to various instrument parameters, such as the focal length, basic angle, or chip positions. In addition, the pipeline was converted from an interpreted system based on IDL to a compiled version based on 64-bit C and Fortran. The system runs approximately 300 times faster than the interpreted version. Community packages such as NOVAS, CFITSIO, SLALIB, PGPLOT, and SLATEC were used to lower development time. Hooks were added so the pipeline can work either with FITS binary tables, or a SQL database mySQL.

SIM: AD is working closely with JPL to support NASAs Space Interferometry Mission (SIM). AD has become involved in developing SIMs grid star data reduction pipeline. During this period of performance, G. Hennessy pursued basic research into grid star data and data requirements. Olling prepared a proposal to SIM for re-observation of many of the Hipparcos stars. This proposal, if accepted, would provide significantly increased proper motion values. It would also greatly extend the lifetime of the position measurements, many of which are significantly degraded since the Hipparcos observations due to proper motion uncertainties.

A. Fey, Boboltz, R. Gaume, N. Zacharias and K. Johnston continued their role on the SIM Science team as members of the Key Science Project Astrophysics of Reference Frame Tie Objects and participated by phone in several SIM Science Team meetings during the course of the year. Fey and Johnston attended the 10th SIM Science Team Meeting held in Pasadena, CA where Fey presented a status report on our Key Science project of work done during FY03. N. Zacharias (together with Hennessy and Johnston) attended a meeting at IPAC, Pasadena to identify areas for a collaboration of USNO in the SIM project beyond the Key Science projects. N. Zacharias participated in the weekend SIM Science Team meeting at IPAC, which was devoted entirely to grid star issues. Monthly (internal) Science Team meetings were initiated.

Work continued in support of SIM on a program of spectral-line radio observations of the 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. In support of this research, Boboltz has been the primary author on several accepted proposals for VLA and VLBA observing time with a variety of collaborators at institutions both inside and outside the U.S. Observations conducted over the past year in relation to this research include VLBA experiments BB176 (observed in March and July 2004) and BB185 (observed in July 2004). The BB185 observations were conducted quasi-simultaneously with VLTI observations of the same two stars. Data from an earlier VLA experiment (AB1088) were recently reduced as part of a continuing program to map the SiO maser emission from 50-100 AGB stars using the VLA. An additional 15 stars were imaged bringing the total number of mapped SiO maser sources to 36.

In support of SIM a program of Southern Hemisphere astrometric/imaging experiments continued. A number of experiments have been observed with the Australian Long Baseline Array (LBA). Images for a total of 69 sources at X-band have been produced to date and published in the Astronomical Journal (AJ). Imaging observations will allow for modeling of the systematic effects introduced by intrinsic structure in astrometric solutions. A paper on one of the more interesting sources (PKS1934-638) was also published in the AJ. Dr. Roopesh Ojha visited the USNO to analyze and image LBA data taken on Southern Hemisphere ICRF sources. Several experiments were calibrated and images were made for another approximately 60 sources.

N. Zacharias and V. Makarov met with M. Millman (JPL), discussing the SIM grid star algorithm and parallels to the block adjustment procedure. N. Zacharias commented on several versions of the SIM Science Requirements Document, participated in telecons and SIM meetings, and worked on the SIM Input Catalog (structure, format) with A. Boden, IPAC.

N. Zacharias led a program for testing the optical astrometric stability of ICRF sources as part of the preparatory science of our SIM key project. The data are obtained with the 1.55-m telescope by NOFS scientists. N. Zacharias reduced all data for the sources 0241+622 and 0552+398 obtained up to the end of 2003 and presented first results at the January AAS meeting. N. Zacharias pointed out that the UCAC astrograph is currently the only option to continue with the reference frame tie observations of any deep CCD imaging (NOAO and NOFS) to the Hipparcos system, which is part of our SIM preparatory science work.

N. Zacharias wrote a memo about the minimum number of observations per star required for a SIM program to observe a large fraction of Hipparcos stars to improve the stellar reference frame utilizing the original Hipparcos epoch data.

N. Zacharias made a first cut in selecting bright, optical QSOs for the SIM extragalactic reference frame link targets.

Preliminary results from the speckle G dwarf survey were presented at the winter AAS meeting (2003, BAAS, 203, 4203). A final report is in preparation. Work continued screening candidates for SIM Guide Stars and TPF target stars. Mason (Co-Investigator) participated in meetings related to project MASSIF (SIM Key project; PI, T. Henry, GSU/CHARA) and began work in preparation for large telescope speckle interferometry related to this.

TPF: Olling supported NASA's Terrestrial Planet Finder (TPF) mission by revising and optimizing the TPF target list.

HST: Dorland and A. Hajian were awarded Hubble Space Telescope (HST) orbits during HST observing cycle 12. These observations were successfully executed during November, 2003. Reduction of much of the data was completed and analysis will continue during the next year.

CCD Research: Dorland conducted ongoing research into development of high-speed, low-noise, radiation-hard CCDs for use in future space astrometry missions. During the period of performance, AD tested both Semiconductor Technology Associates (STA) FAM STA700 and Wide Field Camera 3 (WFC3) CCD43 e2v technologies CCDs. The CCDs were exposed to a fluence of 5 x 10^9 protons per cm^2 to simulate three years on orbit. They were then tested for noise, dark current and Charge Transfer Inefficiency (CTI) as a function of temperature. In addition, the effectiveness of CTI suppression methods (line charge injection, fat zero) was assessed. The results were presented at the June 2004 SPIE conference on Astronomical Telescopes and Instrumentation.

The test results were also used to validate USNO's Radiation Effects Simulation Code, a model that predicts the effects of on-orbit radiation damage on astrometric measurement precision. A paper was presented on this model at the August 2003 SPIE meeting.

In addition to testing current devices, Dorland led the specification and procurement activities for two new, improved designs. New CCDs were procured from both STA and e2v technologies with improved noise and radiation hardness. The new devices will be tested over the next year.

dFTS: The Dispersed Fourier Transform Spectrometer (dFTS) project, led by Hajian, is developing a new sort of high-resolution optical spectrometer that combines the traditional Fourier Transform technique with a dispersive grating in order to boost the effective throughput of the system by factors of hundreds to thousands. An internal laser metrology system measures interferometric path length differences with an accuracy of better than 0.1 angstroms, providing a wavelength calibration for the derived spectra that is superior to those attainable with traditional high-resolution dispersive spectrographs. Our instrument is thus ideally suited for precision radial velocity measurements of stars and detection of any radial velocity wobble due to low-mass planetary companions.

In fall 2003, after several months of test observations at the USNO 24-inch telescope, the portable dFTS prototype instrument was moved to the Clay Observatory in Brookline, MA, to take advantage of the excellent seeing and tracking performance of their 25-inch telescope. Observations from this site have yielded stellar radial velocities with accuracies as good as 35 m/s, within a factor of two of the velocity limit expected from photon statistics. Many of these observations were made via remote control over the Internet, with the ''observer'' located in Washington, DC. Over the summer of 2004, we have been implementing a series of upgrades to the instrument to improve the photon efficiency, temperature stability, and remote operations capabilities of the dFTS. When these modifications are complete, we plan to resume regular observations of stars with known low-mass companions. We are also currently designing a subsequent version of the instrument, with improved portability and performance, with which we will be able to make guest observations at large telescopes worldwide.

C. Fundamental Reference Frames

Radio: D. Hall, Boboltz, and Fey continue to analyze both IVS-R4 (former NEOS) and IVS-R1 experiments through the CALC/SOLVE software. These included 51 weekly IVS-R4 experiments (R4076-R4126) and 54 weekly IVS-R1 experiments (R1074-R1127). The resulting analyzed databases of the IVS-R4 experiments are the official versions submitted to the IVS. New this year is the analysis of the daily (weekdays) IVS 1.5-hr VLBI Intensive experiments. These experiments are designed for rapid determination of UT1.

Boboltz and Fey continue to work on the production of global VLBI solutions for the purpose of estimating Earth Orientation Parameters and the Celestial Reference Frame. The global EOP solutions 2003b and 2004a were completed and submitted to the IVS. The most recent solution (in this case 2004a) is updated twice weekly and re-submitted to the IVS as the IVS-R1 and IVS-R4 experiments are analyzed. Results of the EOP solution are also now included directly in IERS Bulletin A produced by the USNO Earth Orientation Department. The global CRF solutions CRF2003b and CRF2004a were also completed. New this year is the production of a solution using the IVS Intensive experiments. The first global UT1 solution i2004a was completed and will soon be incorporated into Bulletin A. Results from these solutions can be obtained from the Astrometry Department Web page (http://rorf.usno.navy.mil/solutions/).

Numerous 24-hr astrometric experiments in support of the ICRF were scheduled, observed, and processed through the CALC/SOLVE software, including CRF-21, CRF-22, CRF-23, CRF-24, CRF-25, CRDS-10, CRF-26, CRDS-11, CRF-27, and CRF-28. Additional experiments scheduled and observed specifically for the purpose of increasing the sky density of sources in the Southern Hemisphere included CRF-DS6, CRF-DS7, CRF-DS8, CRF-DS9, CRF-S1, CRF-S2. The resulting daily solutions of the CRF experiments are the official versions submitted to the IVS.

Hall, Boboltz, and Fey attended the IVS 2004 General Meeting held in Ottawa, Canada from 9-11 February, 2004. A total of five presentations were made and are included in the General Meeting Proceedings.

The manuscript entitled ''The Second Extension of the International Celestial Reference Frame. ICRF-Ext.2,'' by Fey, *et al*. was published in the 2004 June issue of the AJ.

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. Boboltz installed and tested a newer version of the software, which runs in parallel with the operational version, for use in generation of SINEX files. This new version will become the operational version in FY2005.

In support of the International Celestial Reference Frame, the VLBA astrometric/geodetic experiments RDV40, RDV41, RDV42, RDV43, and RDV44 were observed. A VLBA proposal was prepared and submitted to NRAO to

continue the RDV series of VLBA observations of ICRF sources into the year 2005.

Boboltz and Fey continued participation in a joint USNO, NASA, NRAO, and Bordeaux Observatory 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. The work involves obtaining radio frequency images and determining astrometric positions at K-band (22 GHz) and Q-band (43 GHz) using the VLBA. The USNO Radio Reference Frame Image Database currently contains 783 images of 231 sources at K- and Q-band. USNO is using the results of this project to determine whether higher radio frequencies could be used to define future realizations of the ICRF.

Optical: M. and N. Zacharias presented a poster paper at the IAU JD16 meeting about the USNO extragalactic link program. M. Zacharias began with the reductions of the KPNO 2.1m data on ICRF optical counterparts, including software development to utilize UCAC reference stars.

N. Zacharias and Rafferty worked together with NOFS in testing and astrometrically evaluating the 1.3-m telescope, which lead to the tilt adjustment performed in September 2003. Test observations by the 1.3-m of selected QSO fields suffered from image elongation due to not guiding. As an alternative, N. Zacharias proposed for observing time at NOAO.

N. Zacharias observed for 10 nights at the 0.9-m KPNO in April (560 frames of 110 ICRF source fields) and 5 nights at the 0.9-m CTIO in May (new ICRF extension sources, 330 frames, 64 fields). At the same epoch the astrograph observed the same fields to allow for a tie to the primary optical system (Hipparcos/Tycho-2).

D. USNO CCD Astrograph Catalog

The remaining 6,552 survey fields (7.7% of the sky) were completed by 18 May with additional special fields and calibration observations ongoing. A total of 29,776 frames were taken with the astrograph during the reporting period, including calibration, reference frame link and special fields. Most of the observing was done by T. Tilleman and D. Marcello with 1 week each covered by Rafferty and N. Zacharias. N. Zacharias oversaw the operations and reductions. M. Zacharias performed the daily quality control, corrected files, upgraded visualization software, and produced statistical plots.

Hall continued checking of raw data frames (from tapes) and put pixel data onto the 2TB RAID array. Tillman and Marcello continued copying 8-mm tape data onto DVDs and Tilleman processed most of the darks and sky flats. Canzian and Hennessy solved computer problems.

Copies of UCAC2 on CDs arrived in time for the public release at the IAU GA by Urban and N. Zacharias. About 50 copies were distributed at the IAU and M. Zacharias sent 755 copies to requesters during the reporting period. At the IAU JD16, N. Zacharias gave an invited talk about 2MASS-UCAC astrometry. UCAC2 was found superior over CMC, M2000 and FASTT data at discussions with D. W. Evans (Cambridge, UK) and L. Helmer (Copenhagen U., Denmark).

N. Zacharias wrote a paper for the AJ about the UCAC2, with sections written by Urban and D. Monet (NOFS); it appeared in the May 2004 issue. Wycoff checked UCAC2 binary and ASCII files and proofread documentation.

Urban, N. Zacharias, and Wycoff constructed, tested and released the Bright Star Supplement (BSS) to the UCAC2, 383,915 stars from Hipparcos and Tycho-2 which are not in UCAC2. M. and N. Zacharias constructed the r13, a position-only catalog based on astrograph observations beyond the UCAC2 release. The data were made available to the Carlsberg Transit Circle program, and the Sloan project, and were used for the 1.3m astrometric evaluation. M. Zacharias extracted UCAC data for various requests, mainly for minor planet occultation predictions. N. Zacharias reduced 0.9-m CTIO data with UCAC reference stars and sent results to J. Bernstein (U. of Michigan) for his KBO/HST program.

E. Washington Proper Motions

Measurements of all AGK2 plates on StarScan, including re-measures for various reasons are complete (Urban, N. Zacharias, Wycoff, Rafferty, Mason, and Hartkopf). N. Zacharias began with the reductions of the complete set of accepted measures. ''Direct'' minus ''reverse'' measures show a precision of better than 0.6 micrometer per stellar image.

Wycoff matched rNLTT high proper motion stars for UCAC2 and performed checks on UCAC2 proper motions and resolved multiple entries in YS3. N. Zacharias compared ERLcat and UCAC2 data to derive external proper motion errors. Systematic differences in the 1 to 4 mas/yr range were found. Wycoff and N. Zacharias corrected the Web version of the ERLcat.

On two trips (November and March) M. and N. Zacharias packed 2002 plates at Hamburg Bergedorf (Germany). These are USNO Black Birch (BB) and Hamburg Zone Astrograph (ZA) plates taken mostly on reference frame link fields and covering over 30% of the entire sky down to 14th magnitude.

Wycoff assumed full responsibility for plate measuring and data backup on the 18 May, due to Urban's transfer to the AA department. By end of June, 230 BB and 312 ZA plates were measured on StarScan. Together, AD and NOFS initiated the Naval Observatory Astrometric Merged Database (NOMAD) project. D. Monet constructed the merged file based on USNO-B, UCAC2, 2MASS, Hipparcos and Tycho-2 data, with input from Urban and N. Zacharias. The testing team also included Wycoff. The first release of NOMAD only picks the ''best'' entry for each star. NOMAD is not a compiled catalog; systematic differences between catalogs have not been handled yet.

Wycoff developed a cross-reference between the Durchmusterung numbers in the Hipparcos Main Catalogue and the WCC catalog numbers.

F. USNO Robotic Astrometric Telescope

In August 2003, EOST provided to USNO the result on their URAT optics and mechanical studies, including tolerance analysis. The telescope is technically feasible. By February EOST could identify suppliers for all components and USNO received a fixed-cost quote on the complete instru-

ment. Further design studies with U. Laux (Tautenberg Obs., Germany), EOST, and an outside review by H. Epps (Lick Obs.) to lower cost and risk were prepared by N. Zacharias and Urban, and approved by Gaume in March.

Starting in Sepember 2003, N. Zacharias explored options for a large, monolithic detector and a SBIR proposal was prepared by Urban and N. Zacharias. The topic was approved by ONR on 6 May and N. Zacharias answered technical questions from proposers.

Laux continued to consult USNO in matters of optical design. N. Zacharias evaluated an alternative optics design from EOST and concluded that it is a factor of 3.5 to 100 inferior to the Laux design for some key astrometric parameters.

G. Instrumentation

The Instrument Shop, under the leadership of J. Pohlman and including instrument makers G. Wieder, D. Smith, and T. Siemers, continued work on projects for the Astrometry Department, as well as for some of the other USNO departments. As the chief of the Instrument Development Division, Rafferty shared some of the administrative duties for the division with Pohlman, an arrangement that allowed Rafferty to spend the significant of his working time on instrumentation.

NPOI: The Instrument Shop completed the last three siderostats for the Navy Prototype Optical Interferometer (NPOI) and was preparing to ship them to Flagstaff at the end of the reporting period. They also completed work on 60 of a total 72 Long Delay Line (LDL) mirror pop-ups; inspected, calibrated, and shipped them to Flagstaff.

Atomic Fountain Clock: The Instrument Shop continues manufacturing parts for the atomic fountain clock (see Time Service section).

UCAC Astrograph: Rafferty performed maintenance and troubleshooting problems for the UCAC astrograph located at NOFS. During each visit to NOFS, Rafferty would make upgrades to the instrumentation based on input from the observers or things he felt needed to be done. The Instrument Shop in Washington as well as Divittorio, Rhodes, Sell, and Tilleman in Flagstaff supported this work. The full-sky coverage of the UCAC project was completed in May 2004. The UCAC astrograph operated remarkably well for having been in use nearly constantly since it started the UCAC project in Chile in 1998, with the longest break in observing being 42 days in 2001 when the telescope was moved from Chile to Flagstaff.

26-inch refractor: The Instrument Shop and Rafferty continued work on upgrading the 26-inch refractor, with the most significant changes being a new right ascension clamp and the replacement of all the electronics.

StarScan: Measuring of the AGK2 plates were completed and Wieder manufactured 21 new plate holders for StarScan to measure RORF plates taken from Black Birch, New Zealand, and Hamburg, Germany. During this reporting period, the Instrument Shop and Rafferty fixed a number of minor problems with the StarScan to keep it operational.

5-inch Clark refractors: Pohlman, Rafferty, and Wieder moved a 5-inch Clark refractor (one of eight built for the 1873 transit of Venus) to the Smithsonian for their Transit of Venus exhibit. The Instrument Shop and Rafferty also prepared and moved another 5-inch Clark refractor to the roof of Building One to view the transit of Venus on June 8th. This 5-inch Clark refractor (#856) was used at Wladiwostok, Siberia for the 1873 transit, at San Antonio, TX for the 1882 transit, and now at Washington for the 2004 transit.

Miscellaneous: Pohlman and Rafferty worked on the paperwork for a new hire for the Instrument Shop, with Pohlman interviewing several candidates, but the position was put on hold due to budgetary problems. The Instrument Shop ordered and received a new Hass Milling Machine, the first new machine the shop has gotten in 15 years. Siemers has mastered the programming and operation of the new mill, with the first job being a magnetic shield for the Rubidium Fountain Clock. The Instrument Shop built several optical components for the Fourier Transform Spectrometer project. Engraving for the year totaled 105 hours of the Instrument Shops time.

H. Miscellaneous

The 125 year USNO program of astrometric observations of planetary satellites with the 26-inch refractor in Washington has come to an end. In the future this program will be carried out at the Flagstaff station of the USNO. The latter portion of this effort was a photographic program, carried out by Pascu, and extended from 1967 to 1998. It included the satellites of Mars, the Galilean satellites of Jupiter, and satellites I-VIII of Saturn. This archive consists of about 2000 multiple-exposure plates. In addition to satellite images, these plates include catalog star images as well as measurable images of the planets. About one third of the plates have not been measured. The archive is being prepared for transfer to an institute interested in using them for the study of the motions of the planets and their satellites.

CCD observations of the Martian satellites were obtained by Rohde with the 61-inch Astrometric Reflector at Flagstaff. These observations are being reduced by Pascu and summer intern P. Ries. Photographic observations of the Martian satellites taken with the 26-inch refractor since 1990 are being measured and reduced by Pascu.

Transfer of the USNO 24 year CCD archive of planetary satellite observations from tape to CD was completed by Ries. These observations of faint inner satellites of the outer planets were made with the Flagstaff 61-inch astrometric reflector by Pascu, Rohde, Seidelmann, and others.

The astrometric and orbital analysis of the 1997 HST observations of Neptune's inner satellites — Proteus, Larissa, Galatea and Despina — was published by Pascu, Rohde and others. A publication on HST BVI photometry of Triton and Proteus is being prepared by Pascu, A.D. Storrs (Towson Univ.), and others. Pascu served on the Ph.D. dissertation committee of Frederic Vachier of the Institut de Mecanique Celeste and Computation des Ephemerides in Paris.

N. Zacharias wrote a contribution to the ''Scan-it'' newsletter and attended special sessions about plate digitization at the IAU and AAS meetings.

Fey continues to work on several astrophysically interesting and relevant projects. Collaborations continue with Dr.

Roopesh Ojha of the Australia Telescope National Facility, Dr. Joseph Lazio of the NRL, Dr. Glenn Piner of Whitier College, Dr. Mark Claussen of NRAO and Dr. Patrick Charlot of Bordeaux Observatory, France. Fey has been the primary author or co-author on numerous accepted proposals for VLA, VLBA, and MERLIN observing time with a variety of collaborators at institutions both inside and outside the U.S. Fey was author or co-author on several manuscripts prepared for publication in refereed astronomical journals or proceedings. Fey continued to serve on the IAU Working group on the Maintenance of the International Celestial Reference System and was a member of the IVS Analysis Working Group on the ICRF.

Boboltz continues to pursue a program of independent research. He continued collaborations with Dr. Tom Wilson of MPIfR, Dr. Mike Hollis of NASA-GSFC, Dr. Mark Claussen of NRAO, Dr. Kevin Marvel of the AAS, and Dr. Markus Wittkowski of ESO. Boboltz was primary author or a contributing co-author on numerous proposals for observing time on the VLA, the VLBA, and the VLTI. Boboltz was a co-author on an accepted proposal to the ESO Director General Discretionary Fund for travel and student support for joint VLBA/VLTI work in collaboration with Wittkowski. Boboltz was primary author or a contributing co-author on several manuscripts prepared for refereed astrophysical journals and conference proceedings (see publication list below). He was an invited speaker at a conference ''Future Directions in High Resolution Astronomy: The 10^{th} Anniversary of the VLBA'' and presented a talk entitled ''VLBI Studies of Circumstellar Masers.''

VI. NAVAL OBSERVATORY FLAGSTAFF STATION (NOFS)

A. Astrometry

1. Parallaxes and Proper Motions

CCD parallax measurements continue for low-luminosity M and L dwarfs and subdwarfs, white dwarfs, central stars of planetary nebulae, cataclysmic variables, and other rare types of stars. Analysis of the parallaxes of 134 white dwarfs is being completed now; these include white dwarfs of special interest pulsating DAV stars, high-mass stars, halo stars, and magnetic stars. Papers on other types of stars will follow in the coming year. The error for a typical parallax is 0.5 mas, half the mean error achieved by the Hipparcos satellite.

The infrared group led by F. Vrba and including A. Henden, C. Luginbuhl, J. Munn, and B. Canzian continued efforts to obtain parallax and proper motions at infrared wavelengths of L- and T-dwarfs discovered by SDSS or 2MASS. Data are obtained at the 61-inch Strand Astrometric 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. The initial program started in September 2000 and included 22 L-dwarfs and 18 T-dwarfs. A major report presenting preliminary parallaxes and proper motions for these 40 objects, based on data through November 2002, was published in the AJ, with results showing a mean parallax error of 4.31 mas on a mean observation time baseline of 24 nights over 1.72 years. Observations on these 40 objects have continued and results through April 2004 show a mean parallax error of 2.50 mas on a mean observation time baseline of 44 nights over 3.24 years, indicating that parallax errors continue to decrease as expected for the number of observations. Several objects now have infrared parallaxes at or below the 1 mas level. Currently there are 50 L- and T-dwarfs on the program, which is expected to slowly be expanded to 60-70 objects within the next 2 years. During the coming year it is expected that the first objects will be removed from the program as completed.

R. Stone obtained first epoch frames for 18 open and globular clusters for eventual proper motion membership studies. All frames were taken with the 61-in telescope and reach a limiting magnitude of $V \sim 23$. In 5 years, the observations will be repeated and proper motions computed. Extremely good segregation between cluster and field stars is expected when the observing program is completed.

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 Stone. The telescope is used primarily to observe solar system objects, and in the past year, 31,518 observations of asteroids were obtained, as well as 982 of planets and planetary satellites.

3. Solar System Astrometry

The observing contract with JPL was once again renewed, this time with an addition to support travel to related conferences. A. Monet used these funds to attend the AAS/DDA meeting in Cannes, France. Observations were made with all NOFS telescopes, as needed, of near-Earth asteroids, comets, and selected planetary satellites. Targets included comets 26P/Grigg-Skjellerup and Wild 2, and the asteroid (25143) Itokawa.

The FASTT observing program has been expanded to include about 5,700 asteroids, which comprise virtually all known asteroids brighter than $V = 17.3$. Most of the asteroids with identification numbers under 2000 have been observed about 120 times over a period of 5-6 years. Consequently, accurate ephemerides can be completed for them and the same should be true for the expanded list of objects in about 3 years. Approximately 276,000 positions of asteroids were supplied to the International Occultation Timing Association (IOTA) and used to predict occultation paths this past year. Moreover, 982 positions of Uranus, Neptune, Pluto, and 17 satellites of Jupiter, Saturn, Uranus, and Neptune were observed with the FASTT and sent to JPL in support of their efforts.

Stone observed Comet Wild-2 with both the 61-inch and 40-inch telescopes in order to determine accurate positions needed to update its ephemeris prior to the January, 2004 flyby by the Stardust spacecraft.

4. Sloan Digital Sky Survey (SDSS)

J. Pier completed a 2-year term as Chair of the SDSS Advisory Council. He and K. Johnston continue to serve on

the Council. Pier and Munn continue to oversee the SDSS astrometry effort, providing updated astrometric reference catalogs when available as well as oversight and quality analysis of the astrometric pipeline performance.

Identification and spectroscopic classifications have been made for roughly 6,000 white dwarf stars discovered by SDSS to date, along with accurate positions, proper motions, and photometry. Study of SDSS Data Release 1 was completed; work on DR2 and DR3 is in progress. H. Harris, C. Dahn, Munn, and Pier are contributing to this work. Many unusual white dwarfs have been found, including magnetic, DQ, DZ, DO, and other rare types.

Proper motions are measured for objects in SDSS that are also detected on sky surveys. Using the USNO-B catalog, Munn has produced a catalog of proper motions that include corrections to sky-survey astrometry to place the motions on an absolute system. The rms errors in the motions are 3-5 mas/yr in each coordinate. Using the catalog, Munn and H. Harris have studied a sample of 7,000 white dwarfs and their luminosity function.

5. Precision Measuring Machine (PMM)

Canzian completed the recomputation of all star/galaxy image classifications for the PMM USNO-B2.1 catalog. The new classifications were verified against the old classifications for USNO-B2.0. These new computations of the star/galaxy index are part of a more direct recomputation of all components for the USNO-B2.1 catalog.

S. Levine continues to maintain the USNOFS Image and Catalog server, which makes available the PMM scans of the Schmidt photographic sky survey plates (~13,000 plates). These images cover the whole sky and were taken at multiple epochs and in several colors (http://www.nofs.navy.mil/data/FchPix). The USNO-A2 and -B1.0 catalogs are also available through this server, and can be merged with the image data.

Levine has been working to understand contamination in the USNO-B1 catalog by looking at how well we have done in finding high proper motion stars. He finished gathering a subsample of stars from USNO-B with proper motions between 1 and 5 arcseconds per year, and found 10 previously unknown objects, along with several dozen objects with motions between 0.1 and 1 arcsecond per year.

D. Monet spent most of the year ramping down the Precision Measuring Machine program. Highlights include porting all software from DEC Alpha machines to generic Linux machines, working on the YB6 and YB7 catalogs to be used as the reference catalogs for USNO-B2, running and verifying various programs that make binary files that could not be ported between machines, and developing the software to make the Naval Observatory Merged Astrometric Database (NOMAD).

6. Navy Prototype Optical Interferometer (NPOI)

Development and operation of the NPOI continued under the overall direction of D. Hutter and R. Hindsley (NRL). Hutter was named NPOI Project Director in December 2003. Other USNO staff directly involved in the NPOI project included J. Benson, M. Dyck, C. Hummel, Munn, and R. Zavala.

Personnel from other institutions who worked on the project included T. Armstrong, J. Clark, C. Gilbreath, Hindsley, J. Howard, D. Mozurkewich, J. Murphy, E. Oh, T. Pauls, S. Restaino, R. Young, and X. Zhang from NRL. Mozurkewich left NRL, but continues to work on the NPOI under contract. From Lowell Observatory were K. Isbrecht, B. ONeill, J. Shannon, S. Strosahl, D. Theiling, W. Wack, and N. White. White continued as project and site manager for Lowell. Strosahl and Theiling are new Lowell employees. Additional contract employees included L. Ha and J. Walton from USRA and S. Nichols from Interferometrics, Inc. This project also involved a significant fraction of the efforts of the Astrometry Department (AD), Flagstaff Station (FS), and Lowell instrument shops.

Observations using the coherent combination of two to six telescopes continued on a variety of astrometric and imaging projects, including wide-angle and binary star astrometry, H-alpha emission in Be stars, rapid stellar rotation, and surveys for multiplicity among the bright stars.

Stroshal and Theiling were trained as telescope operators, while Wack continued in that capacity. Useful scientific data were obtained on 182 nights, resulting in 17,053 scans, a new annual record. The record for number of observations on a single night was also broken five times during the reporting period, the record now standing at 262.

Part of Tycner's Ph.D. thesis is presented in the paper The Circumstellar Envelope of Zeta Tauri Through Optical Interferometry (Tycner, et al. 2003). The results of analysis performed by N. Ohishi (National Astronomical Observatory of Japan) during a three-month visit to the NPOI during the previous year are summarized in Asymmetric Surface Brightness Distribution of Altair Observed with the Navy Prototype Optical Interferometer (Ohishi, Nordgren, and Hutter, 2004). Eleven additional NPOI-related papers were submitted for publication in the proceedings of various conferences.

Several major in-house construction projects continued during the reporting year: Isbrecht, Nichols, and O. Neill completed most of the work to provide a remote alignment capability of the optics in the beam combiner, between the beam combiner and fast delay lines, and in the vacuum feed system between the siderostat stations and the beam combining laboratory. The optics can now be aligned from a laptop computer that communicates with the control electronics and alignment actuators over the NPOI internal network.

Howard completed the design of a new tip-tilt corrector for the siderostat stations that will allow angle tracking at a much higher servo rate. Fabrication of the first of these units is well advanced, and subsystems are undergoing tests. Howard also completed the design of gate valve assemblies to be installed in various locations in the vacuum feed system to permit compartmentalization of the array for servicing and to mitigate the effects of any vacuum system failure. Fabrication and component acquisition for the gate valve assemblies are well advanced.

The AD instrument shop also completed the fabrication of

the last three imaging siderostats, and Isbrecht completed the wiring harnesses for same. Design work began for a new-style shelter for these units (White and Howard). Relocation of one of the presently operational imaging stations, to provide better uv-plane coverage and higher resolution, also commenced. The shelter, siderostat, and control electronics for this station were relocated, and the remaining components of this station (tip-tilt corrector and acquisition camera) will be moved shortly.

Another major project has been the design and construction of an internal metrology system to gauge the distance between the beam combining optics and the astrometric siderostats (Hutter, Benson, and Clark). The prototype of this system (for two astrometric stations) was completed early in the period and extensively tested. The application of the data from this system was shown to reduce the residuals of single-night wide-angle astrometric solutions to 2 microns of optical delay, corresponding to approximately 10 mas on the longer astrometric baselines. All the components for the final version of this ''C-term'' metrology system, for all the astrometric stations, were subsequently installed and plans made for extensive astrometric tests over a number of nights.

Work continued by the vendor (Nu-Tek Precision Optical) on the fabrication of the large beam compressors for the astrometric stations. All the beam compressor mounts were completed and delivered, and the mirrors are now undergoing final figuring and testing.

Other activities worthy of note included the completion of a major portion of a completely new data analysis pipeline for the NPOI (Benson), including new software for coherent fringe addition and fitting, bias corrections, and visibility calibration. This software package was used extensively in processing the observations for the survey of bright TPF candidate stars for multiplicity reported in Hutter *et al*. (above). Zavala also used the latest version of the Oyster package (Hummel) to model known binaries observed as ''control'' sources for the TPF survey project.

A new master schedule for the remaining construction on the NPOI was completed by Clark and Hutter. NPOI staff also served as referees for various scientific journals, served on NASA proposal review boards, and conducted numerous tours of the NPOI for visiting scientists, engineers, and members of the general public.

B. Photometry

1. Individual Objects

Vrba continued to participate in the international effort, led by W. Herbst (Wesleyan U.) and C. Hamilton (Rice U.) to obtain photometry of KH15d, a young star located in NGC 2264 which undergoes a eclipse of circumstellar material once about every 48 days, likely from two areas of circumstellar material in an orbit of 96-day period. The intent of this year's photometric monitoring was to study color changes during times of ingress and egress from the eclipses. As with previous years' data, little color variation is seen over the entire orbital period. The new data show that the width of the phased eclipse continues to grow at about 2 days per year. A paper describing results from the 2002-2004 observing campaigns is in final preparation.

W. Hartkopf, B. Mason, and T. Rafferty (all of the Astrometry Department) are using the USNO speckle camera (normally employed at the USNO 26-inch refractor) at the USNO 61-inch reflector to extend their double-star investigations to fainter objects.

The 40-inch telescope is being used by Henden in automated time-series photometry mode to study new SDSS cataclysmic variables. To date, approximately 150 nights of photometry have been acquired, with most of the SDSS CVs having at least 4 hours of exposures. Some of this photometry has been published in the SDSS CV paper series; the remainder is being prepared for a photometric paper series.

The 1.3-m telescope was used by Henden to provide calibrated V and Ic photometry in two 4x4 degree patches of sky that also included portions of two SDSS astrometric calibration fields. These two patches will be used to calibrate wide-field survey camera photometry.

Henden used the 40-inch and 61-inch telescopes for both optical and NIR photometry and imagery of the peculiar novae V838 Mon. Several papers were written in conjunction with U. Munari (U. of Padova).

Henden collaborated with M. Karovska (Harvard U.) on U-band photometry of Mira in support of Chandra observations. These images show considerable variation due to the secondary star in the Mira system (Mira B). Analysis of the datasets is in progress.

IM Peg was observed by Henden with the 61-inch telescope for a photometry contract with SAO. Images were taken every month, and stacked to increase dynamic range and psf-fit. These images are being used to test for any long-term variability of stars in the field of IM Peg, the target for the Gravity Probe-B satellite.

A new FU Ori type object, V1647 Oph (also called McNeils Nebula) was discovered in early 2004. Henden observed this object with the 40-inch and 61-inch telescopes using both CCDs and the ASTROCAM near-infrared camera, in collaboration with other SDSS scientists. Two papers containing the imaging results have been published.

Levine worked with A. Bosh (BU/Lowell Obs.), C. Olkin (Lowell Obs.), R. French and C. McGhee (Wellesley Coll.) to observe the occultations of stars Tycho2 1343- 01615-1 and Tycho2 1343-01900-1 by Saturn and its rings on the 15 and 24 November UT respectively. The occultation on the 15th was observed on the 61-inch with ASTROCAM at NOFS through very patchy clouds. The occultation on the 24th was to be observed from the IRTF at MKO. Unfortunately, it was necessary to evacuate the IRTF about half an hour before the event due to winds gusting to over 90 mph.

Levine has put the past 18 years worth of optical and IR data taken on the 61-inch telescope at USNOFS on disk, and has organized data for efficient retrieval of the images. As a first project using these data, Levine hosted A. Krupicka (Colorado Coll.) at NOFS who spent the summer there under the auspices of the NSF Research Experience for Undergraduates program working with Levine on time series dif-

ferential photometry using the archival image data from the 61-inch telescope.

Levine is working with S. Barnes (FIT) on a project to use archived images from the parallax program at NOFS to look for slowly rotating field stars, and working out the implications for stellar gyrochronology.

2. Star Clusters

Henden, S. Kafka, and K. Honeycutt (Indiana U.) finished their reductions of the time-series photometry acquired with the 40-inch and 1.3-m telescopes of the open cluster NGC 6939. Ten new variables were discovered near the cluster and a paper was published giving the variability parameters for each star.

Vrba continued collaborations with V. Straizys, A. Kazlauskas (Vilnius Obs.), and R. Boyle (Vatican Obs.) to obtain Vilnius photometry of reddened young stellar clusters, using the Tek 2048x2048 CCD at the USNO 40-inch telescope. Results for M67, NGC 1750, and NGC 1758 were published this year in Baltic Astronomy.

3. Extragalactic Objects

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.

Canzian and Henden observed several nights to collect photometric data on the exceptionally bright gamma-ray burst GRB030329. Altogether the light curve of the burst was followed for 92 days. Frames were also donated by foreign (Tautenberg, Germany) and U.S. collaborators. Canzian processed and did instrumental photometry on all frames, which Henden put on an absolute photometric system. Canzian is the lead on the paper, in progress, reporting photometry of this source.

Canzian observed about one night per month on the 61-inch, taking K′-band frames with ASTROCAM of spiral galaxies displaying (optical) multiple-arm morphologies. He is analyzing the images to understand the circumstances (involving star formation history and dust content) under which optical and IR morphologies are similar or different. Canzian follows up the IR observing with additional nights on the 40-inch or 61-inch to collect V-band frames of the same spirals for comparison with the K′-band frames.

Canzian also obtained B-band and I-band imaging at the 40-inch of galaxies of various morphological types in collaboration with R. Buta (U. of Alabama) for a book illustrating the de Vaucouleurs galaxy classification system.

Canzian observed about one night a month on the 61-inch telescope to conduct a survey in I-band of elliptical galaxies classified in the RC3 as doubtful to find those that are actually S0 galaxies as revealed by the presence of spiral structure. The program was spurred by publication of a serendipitous discovery of one such galaxy with an 8-m telescope. Follow-up by Canzian with the 40-inch showed that an 8-m telescope was not necessary, and spiral structure was detectable with a 1-m class telescope.

Henden continued his research on GRB afterglows. He obtained field-calibration photometry for GRB030723, GRB030913, and GRB040422. He performed psf-fitting for all of the photometry for the GRACE consortium on GRB030323, and helped write the recently accepted paper on that burst. He collaborated with C. Kouveliotou (MSFC) on a successful grant for the AAVSO JANET high-energy amateur network. Henden contributed sections to several other GRB papers published this year.

C. Instrumentation

The partnership of USNO, NOAO, and NASA-Ames to build 2048x2048 InSb infrared arrays at Raytheon Vision System (RVS) continues. This array, called ‘‘Orion,’’ is two-side buttable, with 25-micron pitch pixels. It uses a mother-board packaging concept that allows for close buttability for 2x2 mosaic applications. During the reporting year a fabrication run of the slightly redesigned readout multiplexer was completed with a high yield, leaving the project with a large number of science grade readouts. Progress in detector fabrication has been slower, while waiting for RVS to bring into operation their new InSb processing equipment, which is now complete and promises to improve the quality of the InSb detectors. Results for arrays completed with the new readouts and InSb processing are expected shortly with the anticipation that science grade arrays will be produced.

Canzian, M. DiVittorio, and Vrba participated in Science Definition Team meetings and a Concept Design Review meeting for the proposed 4-m class telescope to be constructed in collaboration with Lowell Observatory and The Discovery Channel. They are helping to define the properties of the optical system and the instrument suite. Canzian has constructed a spreadsheet model of the telescope from which to derive infrared emissivities that contribute to the telescopic background. This model will guide background mitigation strategy in the infrared.

As part of USNO’s interest in the Lowell DCT telescope project, a contract was let with Mauna Kea Infrared to do a conceptual design study for an infrared imager/spectrograph for this telescope. The design study is based on using a 2x2 mosaic of 2048x2048 Orion arrays as the focal plane detector and will give baseline answers to fundamental questions such as cost, size, weight, and whether spectroscopic capabilities are even feasible for such a large-field imager.

F. Harris completed and placed into service the array camera for the 1.3-m telescope. All functions and features desired were made operational. Readout time is 63 seconds for the entire 48-megapixel field, with typical read noise of 11 e- rms. Liquid nitrogen hold time was measured in excess of 36 hours with the focal plane at a temperature of -77.8 degrees C. First-light images were made.

Levine developed software to run the array camera on the 1.3-m telescope in stare mode. This software was then merged with the existing NOFS observing software, and it can also be run in stand-alone mode for hardware debugging. Work was begun on the software for scan mode operation as well.

F. Harris modified the control electronics for the intensified-CCD guider camera for the 1.3-m telescope, and aided Stone in testing the guider camera on the night sky. F. Harris corrected documentation and made modifications to the DFM control circuitry for the 1.3-m telescope. The

mirror-support airbag control circuits required iterated adjustments. The telescope-mount position encoder systems required modification, and has been resistant to (lightning) damage since.

A major effort is underway to automate observing at the 61-inch telescope, beginning with ASTROCAM observing. The system now runs completely autonomously: opening up at twilight, selecting stars from its scheduled queue, moving to the field, finding the guide star, registering the field with a short exposure, estimating exposure time, finding and marking rotation stars for each field, closing up at the end of the night or upon a remote shutdown command, etc. There remain a small number of steps for efficient operation, such as automatic control of the flat field lamps and disabling power to the saddlebag camera electronics for improved lightning protection that will be implemented during the next year.

Henden has begun the port of the ASTROCAM observing code from its home on an old Silicon Graphics workstation to a more modern Linux computer. Approximately 900 separate software modules have to be inspected, rewritten to handle the different compiler and computer environment, and added to a CVS repository for future ease in maintenance. This project will be completed during the next year.

To increase the temporal resolution possible with the ASTROCAM near IR camera, Levine spent time rewriting parts of the ASTROCAM control code to decrease the overhead involved with exposures using small subarrays. In the end, he was able to reduce the overhead to 0.5 sec for a 256x256 subarray of ASTROCAM (giving a 1-second cycle time when used with a 0.5-second integration time). Previously, the overhead for such a subarray had been almost 1.8 seconds. This mode was used by Levine to observe a Saturn occultation on 15 November 2003.

Henden and DiVittorio worked on the fast Dalsa camera, installing the proper software on a Windows computer and acquiring several image sets on the 40-inch telescope. Preliminary centroiding results indicate that a tip/tilt system built around this camera can improve the image full-width-half-maximum under normal seeing conditions by about 50%. They hope to have a full tip/tilt system running during the next year.

D. Monet continues to assist with telescope and CCD control software.

D. Theoretical Studies

Levine continued studying gravitational microlensing of extended disk-like objects in an effort to determine how the disk structure affects the observable properties of the microlensing light curve. The ultimate goal is to see if we can in fact learn about the internal structure of astrophysical disks.

Levine has been working with D. Hunter (Lowell Obs.) and V. Rubin (DTM) on the dynamics and kinematics of dwarf irregular galaxies.

Levine is working on a project to determine the spatial density profile of a putative stellar halo around the LMC based upon star counts from the USNO-A/B catalogs.

E. Other Scientific Studies

Canzian, DiVittorio, and Henden submitted a white paper supporting IR/optical astronomy at the Flagstaff Station through innovative new projects of military interest. The principal endeavor would be a northern-sky survey in the 3-5 micron band using a new 4-m class telescope.

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. the USNO-B1 catalog and PMM image data) are compatible with the emerging NVO framework. The USNOFS Image and Catalog server now makes catalog data available in the XML/VOTable format being defined by the NVO effort.

Vrba continued working with H. Fliegel and L. Warner (The Aerospace Corp.) and A. Chaudhary (Applied Optics Corp.) on photometric monitoring of GPS satellites. The resultant B-, V-, R-, and I-band light curves 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 of the newer Block IIR spacecraft appear to show similar darkening, albeit over much smaller ages on orbit. Work is now concentrating on understanding shadowing effects and observations of vehicles shortly after launch. During the year Vrba presented talks on this work at the 2003 AMOS Technical Conference, the 2004 GPS Performance Analysis Working Group meeting, the 2004 AMOS Space Surveillance Workshop, and the 2004 MIT Space Control Conference. Vrba is working on a major paper describing optical monitoring of GPS satellites between 1999 and 2003 at USNO.

Vrba joined the SHIPP (Southern Hemisphere Infrared Parallax Program) proposal as a Faculty Associate, along with D. Golimowski (Johns Hopkins U.), T. Henry (Georgia State U.), and P. Ianna (U. of Virginia). SHIPP is a proposal to NSF to build and use an infrared imager similar to ASTROCAM for Southern Hemisphere astrometry at CTIO.

D. Monet was involved with the LSST and Pan-STARRS Science Teams, and also worked with the SST and Kepler programs. All tasks concern generation and usage of astrometric catalogs.

F. Miscellaneous

Henden attended the Research Training Network Workshop on GRBs (Santorini, Greece) and presented an invited paper on the role of amateurs and small telescopes for GRB research.

Henden gave an invited presentation on the ASTROCAM astrometry results at the USRA Science Council Meeting in April 2004.

With collaborators C. Moore, D. Duriscoe, and A. Richman (National Park Service), Luginbuhl continued work on the development and characterization of a camera and photometric system for gathering all-sky photometric measures of sky brightness in the Johnson V band. In side-by-side measurements made with W. Lockwood (Lowell Obs.) at the Mars Hill site near downtown Flagstaff, a systematic offset

was noted, where the NPS system was measuring sky surface brightness as about 0.2 to 0.4 magnitude fainter than the photoelectric system on the 21-inch telescope. Three potential sources of error were identified as probable contributors to this offset: photometric nonlinearity of the CCD device at low signal levels, due to the presence of charge traps distributed throughout the Kodak 261E CCD used in the camera; a 10 nm blueward shift in the system response as compared to the Johnson standard; the presence of sodium emission (due to both HPS and LPS lighting) in the blue shoulder region of the system response, where the NPS system differs most strongly from the standard system. The camera system was used during the June lunation to gather more than 25 data sets at the Flagstaff Station. These data will be used, not only to characterize the current state of the night sky at the Station, but also to investigate hourly and nightly variations caused by changes in extinction and amount of light produced from artificial sources during the night. This system will be described in a paper planned for submission to the Publications of the Astronomical Society and Pacific (PASP), under preparation.

In collaboration with W. Lockwood (Lowell Obs.) and N. Barlow (N. AZ. U.), Luginbuhl continued work on the Flagstaff Lighting and Land-use Project, where they seek to produce a model of Flagstaffs outdoor lighting. With support from the NASA Space Grant program, J. Selders (N. AZ. U.) gathered information on lighting used on the Northern Arizona University campus, to help fill in a large gap in the model. This work is planned for submission to the PASP.

Luginbuhl gave an invited presentation at the IDA annual meeting titled ''Sports Lighting - Off the Field,'' describing his research in modeling the illuminances, total lumen outputs, and upward directed lumen fluxes of a variety of sports lighting designs using different luminaire technologies. This work will be submitted to the Leukos (Journal of the Illuminating Engineering Society of North America). He also gave an invited presentation ''The Loss of Our Night Skies—Why?'' on the general topic of light pollution at the Seventh Oxford Conference on Archaeoastronomy held at Northern Arizona University. This paper will be published in the proceedings of the conference.

As part of the new NASA contract awarded for observations of asteroids with the FASTT, NOFS was invited to submit a supplemental proposal for an education/public outreach program (E/PO) related to the contract work. A. Monet worked with two local educators to develop an E/PO proposal to create an educational video entitled ''What is a Planet?,'' and this was submitted to NASA. A decision had not been announced at the time of this report.

A. Monet continues to serve on the Board of Directors for the Flagstaff Festival of Science. She worked with colleagues at NOFS and Lowell Observatory to organize the annual Asteroid Naming Contest, ran the Open House at NOFS during the Festival, and arranged for speakers and in-school presentations. Nearly every member of the staff at NOFS and NPOI contributes in a substantial way to the annual Open House, which is the single biggest public outreach event at the station each year.

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