U.S. Naval Observatory

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This report covers the period July 2002 through June 2003.

I. PERSONNEL

A. Civilian Personnel

Sethanne Howard retired in May from the Astronomical Applications (AA) Department. George Kaplan and Marc Murison were reassigned from the Astrometry Department (AD) to AA in September. Steve Dick was reassigned from the Public Affairs Office to AA, where he has been the acting chief of the Nautical Almanac Office.

Eric Newman joined the Time Service (TS) Department. Nicolette Jardine, Jim DeYoung, and Lara Schmidt departed.

William Wooden was appointed head of the Earth Orientation (EO) Department in February 2003.

Dominic Marcello and Sevan Petrossian (Nancy Vandenberg, Inc.) joined AD as contractors and John Bowles, Stephanie Potter, Jeongin Lee (Universities Space Research Association [USRA]), and Thomas Codella (Tranquillity Base, Inc.) left.

Conard Dahn, Harry Guetter, Joe Hobart, and Betty Riepe retired from the Flagstaff Station. Nick Elias left the Flagstaff Station, NPOI Division. Jeff Pier was appointed director of the Flagstaff Station in April 2003.

B. Summer Students

The USNO summer intern program for high school and college students continued in the summer of 2002. This program, the Science and Engineering Apprentice Program (SEAP), is sponsored by the Department of Defense (DoD) and administered by George Washington University. During the summer of 2002, the 13 interns and the departments in which they worked were: Stewart Berg (TS), Bridget Brett (EO), Andrew Cenko (AD), Justin Doo (EO), Laura Flagg (AD), Andrew Herman (TS), Dean Kang (AD), Vijay Kapur (Library), Steven Movit (AD), Griffith Rees (TS), Paul Ries (AD), Sabrina Snell (AD), and Denis Trofimov (AD). In the fall, D. Pascu (AD) turned over the responsibilities for coordinating the USNO summer intern program to G. Kaplan (AA) and M. Carter (EO). At the end of the reporting period, USNO was preparing to host 11 students during the summer of 2003. Summer intern Snell was a finalist in the 2003 Intel Science Talent Search, based on her work at USNO on linear and accelerated motions in double star systems.

The USNO also made a successful application to become part of the Office of Naval Research's Naval Research Enterprise Intern Program (NREIP). The NREIP program supports 3rd- and 4th-year undergraduates, and graduate students at selected Navy Labs.

II. ASTRONOMICAL APPLICATIONS DEPARTMENT

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 collaborates with Her Majesty's Nautical Almanac Office (HMNAO) of the United Kingdom to produce *The Astronomical Almanac, The Astronomical Almanac Online, The Nautical Almanac, The Air Almanac, and Astronomical Phenomena*. S. Howard, as Chief of the NAO, supervised the USNO portion of this work until 17 March, when Kaplan began serving as Acting Chief. The two almanac offices meet twice yearly to discuss and agree upon policy, science, and technical changes to the almanacs, especially to *The Astronomical Almanac*.

The almanacs for 2004 and *Astronomical Phenomena* for 2005 were published. S. Dick, Howard, Kaplan, R. Miller, S. Stewart, and M. Stollberg participated in the production of these annual publications.

At the end of the reporting period, the next editions were in preparation and on schedule. For the 2005 *Astronomical Almanac*, Stewart updated data for tables of double stars, bright galaxies and globular clusters, and completely revised the table of open clusters using a new catalog obtained from W. Dias (U. Sao Paulo, Brazil). Working with HMNAO, Stollberg incorporated into the 2005 *Astronomical Almanac* a new method for computing the orbital positions of short-period ($<$ 90 days) satellites. The new method uses a mixed-function expansion solution for a satellite orbit that produces coefficients suitable for a straightforward production of offsets for every day of the year. This mitigates the technical difficulties of the older methods that cannot adequately handle short-period satellites. M. Efroimsky and Kaplan made considerable changes in the Glossary section of the book. Many definitions were clarified and updated and put in accord with modern concepts. Stewart updated *The Astronomical Almanac Online* to include a significant improvement in the amount of downloadable data available to users.

The almanac offices plan a gradual introduction of the relevant resolutions of the 2000 International Astronomical Union (IAU) General Assembly into *The Astronomical Almanac* over a period of several years. These changes, incorporating the IAU 2000 precession-nutation theory and the use of a ''non-rotating origin'' in the Geocentric Celestial Reference System, will first be introduced into *The Astronomical Almanac* for 2006. For the latter, complementary data based on both the classical and new (IAU 2000) paradigms will be presented side by side for a considerable period of time. Planning for these changes has been underway, and J. Bangert and Kaplan prepared presentations on this subject for the 2003 IAU General Assembly (GA).

P. Seidelmann (U. Virginia), Howard, and Bangert con-

tinued work on a new edition of the *Explanatory Supplement to The Astronomical Almanac*.

The use of celestial navigation from aircraft has been rapidly declining. In July 2002, USNO requested all recipients of *The Air Almanac* to provide their requirements for the book. The results of this survey, and an earlier survey of the U.S. military, make it likely *The Air Almanac* will move to CD-ROM form, following a brief transition period when it is produced as both hardcopy and CD. Miller produced a prototype CD of the 2004 *Air Almanac* in Portable Document Format (pdf), and finished work on the digital form of the Navigational Star Chart. The latter is on the Department Web site and is used in the 2004 *Air Almanac* prototype CD.

The NAO still receives written requests for special astronomical data tables, although data provided through the Department's Web site (see below) have greatly decreased the number of such requests. Chief Quartermaster B. Wass and Y. Holley handled many of these requests.

B. Software Products

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

STELLA (System to Estimate Latitude and Longitude Astronomically), a celestial navigation software tool developed specifically for the U.S. armed services by AA Department staff, continues to be widely used throughout the U.S. Navy and Coast Guard. An updated version of the software (2.02) was released in May 2003. The new version improves the appearance of the user interface under Windows 2000 and Windows XP systems, and provides other minor updates and corrections. W. Harris made significant progress in the development of a version of STELLA for handheld computers running the Palm OS. There is interest in this product by several Navy organizations and by the Coast Guard.

Design and development work continued on Version 2.0 of the Multi-year Interactive Computer Almanac (MICA; *http://aa.usno.navy.mil/software/mica.html*), a major upgrade of this software product. The new version, which will provide almanac data for the years 1850-2050, features a completely revamped user interface and several new, significant capabilities. A database management system was incorporated to provide support for several new astrometric catalogs within MICA. A new main star catalog was assembled, containing over 230,000 stars recorded in the Hipparcos and/or the Tycho-2 catalogs and incorporating information compiled from the Washington Comprehensive Catalog Database (WCCD) and from the CDS/Simbad database. Other specialized catalogs were also created. Extensive verification tests of the Microsoft Windows and the Apple Mac OS versions of MICA 2.0 are nearing completion, and off-site testing of the product should begin in late 2003. The MICA 2.0 development team includes W. Tangren, Harris, W. Puatua, and Oliversen.

Kaplan revised the Fortran version of the Naval Observatory Vector Astrometry Subroutines (NOVAS; *http://aa.usno.navy.mil/software/novas.html*) astrometry software package, incorporating changes to implement the 1997 and 2000 IAU resolutions on astronomical reference systems and Earth rotation models. Specifically, the revision incorporated Earth rotation algorithms provided by the International Earth Rotation and Reference Systems Service (IERS) at the end of 2002. An extensive battery of tests was conducted and only minor bugs found. When completed and propagated to the C version of NOVAS, the changes will allow for implementation of the new reference systems and Earth rotation models in the almanacs and other AA products. Current plans are to make the new NOVAS package public in 2004.

C. Positional and Dynamical Astronomy

1. Solar System Dynamics

Efroimsky continued his research on the internal symmetry of the Lagrange and Delaunay equations of planetary motion. During this year, he wrote six papers on the topic. Efroimsky also began work on a paper that deals with satellites orbiting a nonuniformly precessing planet, and why the terms in the Hamiltonian do not always coincide with the appropriate terms in the disturbing function.

J. Hilton continued working on the theory of precession. His most significant work was a practical evaluation and comparisons of three new precession theories (Bretagnon *et al.* 2003, *Astron. Astrophys.*, **400**, 785; Fukushima 2003, *Astron. J.*, **126**, 494; and Capitaine *et al.* 2003, submitted to *Astron. Astrophys.*). These comparisons will be the basis for deciding which precession theory will be chosen for future editions of *The Astronomical Almanac*. Since the motion of the ecliptic is strongly coupled to precession and nutation, Hilton also began studying the definition of the ecliptic as part of his study of precession. Hilton prepared a presentation on suggestions for future research in precession for the 2003 IAU GA.

M. Murison and a student, A. Munteanu, are investigating the geometry of solutions, as well as efficient numerical calculations, of the minimum distance problem for two confocal elliptical orbits. They have discovered a promising fast method, which does not require integration of the equations of motion, for determining times of close approaches between any two orbits. They continue to investigate the geometry and nonlinear dynamics of the problem, both analytically and numerically.

The book Asteroids III was published in early 2003. Hilton wrote the chapter on asteroid masses and densities.

2. Positional Astronomy

A paper on the rotation matrix between the International Celestial Reference Frame (ICRF) and the mean reference frame of J2000.0 by Hilton and C. Hohenkerk (HMNAO) was completed and submitted to *Astronomy & Astrophysics*.

Kaplan continued work on his scheme for obtaining the International Celestial Reference System (ICRS) coordinates of the Celestial Ephemeris Origin (CEO) by numerical integration. The CEO is a new fundamental reference point for the measurement of Earth rotation, established by the IAU in 2000. Kaplan created an easy-to-use and flexible Fortran subroutine that performs this computation, given models of precession and nutation provided by the NOVAS subroutine package. By providing ICRS coordinates of the

CEO and celestial pole, the method allows for very simple expressions for terrestrial-to-celestial coordinate transformations and apparent sidereal time. Kaplan prepared documentation on the approach for presentation at the 2003 IAU GA.

Kaplan and V. Makarov (AD) investigated the possibility of detecting sub-stellar companions to main sequence stars, in long-period orbits, using observed accelerations of the primary stars' proper motions. Theoretical detection limits were computed for three proposed space astrometry missions. Summer intern S. Snell detected actual accelerations in the recorded observations of a number of non-orbit double star systems in the Washington Double Star (WDS) Catalog, and was able to experimentally verify some of the Kaplan-Makarov formulas.

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

3. Celestial Navigation

Kaplan and Bangert continued their collaboration with T. Jones (Space and Naval Warfare Systems Center) in overseeing the work of two contractors who conducted feasibility studies of proposed hardware systems for automated celestial navigation.

D. World Wide Web Site

The Department's public Web site (*http://aa.usno.navy.mil/*) continued to grow in popularity. The site handled between 13,000 to more than 23,000 user sessions per day during the reporting period. This is an average increase of about 35% compared to the previous year. Tangren maintained the Web servers.

Several new interactive graphics applications, created by Kaplan, were introduced on the public Web site. One provides the user with a synthetic image of a solar system object, as seen from Earth at a specified date and time, showing the correct orientation, illumination, and surface features. The other displays several projections of the Earth's surface at a specified date and time, showing the day/night terminator. Murison, Tangren, and Kaplan completed a Web page that shows the current Moon phase; the image is renewed every hour. Kaplan also revised the Web pages providing an overview of the ICRS.

A new AA Department Web server was created and installed on the Secret Internet Protocol Router Network (SIPRNet). This server provides selected astronomical and navigation information of interest to DoD.

The Department staff continued to answer questions on topics within the purview of the department's 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 wrote a paper describing updates that will be made in *The Astronomical Almanac* for the effect of phase on the apparent magnitudes of Mercury and Venus.

Murison and Efroimsky worked on the Fourier Transform Spectrometer (FTS) project. Murison designed several ''back end'' systems for the FTS, trying to find one that can encompass the wide dispersion coming off the diffraction grating, yet still use only off-the-shelf optical components for focussing onto the detector. He also developed an initial ''big dish'' design for a large-mirror, low-dispersion space-based version of the FTS for use in extrasolar planetary spectral detection and characterization. Murison also researched the science that might be done with an FTS during the upcoming transit of Venus in 2004; results were disappointing.

Murison started exploring the dynamics of the proposed Astrometric Mapping Explorer (AMEX) satellite. The spin period would be the same as the orbital period, and may be able to take advantage of the strong gravity gradients for spin and/or precession stabilization. Numerical results from one of Murison's modeling programs show that the slower scan speed will cause a factor of ~1.5 degradation in the mission accuracy upper bounds imposed by the scanning geometry; this is multiplicative with the worse single-measurement accuracy of the smaller mission. Work on the gravity gradients aspects continues.

Murison worked on a paper describing the mission accuracies of a scanning astrometric satellite imposed by the scanning geometry intrinsic to such a mission. He discovered that, in principle, the mission accuracy bounds should be analytically soluble, given the single-measurement accuracies and the scanning parameters. He has carried the analytical work much further than previously, but he has yet to find a way to solve certain difficult integrals that describe the variances in the cross-correlation matrix.

III. TIME SERVICE DEPARTMENT

A. Master Clock Operations

In order to provide accurate and precise time, USNO currently maintains an ensemble of 71 cesium-beam frequency standards and 15 cavity-tuned masers in three buildings in Washington, DC and at its Alternate Master Clock (AMC) facility at the Schriever Air Force Base in Colorado, and provides clock data to the Bureau International des Poids et Mesures (BIPM). UTC (USNO) has stayed within 6 nanoseconds (ns) of UTC; the rms of UTC-UTC (USNO) was 3 ns.

J. Skinner maintained the operational USNO mean timescales, which are based on Data Acquisition System (DAS) data, and provided clock data to BIPM. L. Breakiron maintained those USNO and AMC mean timescales that are based on data taken with Timing Solutions Corp. (TSC) measurement systems.

Breakiron continued his a study on the practicality of replacing the currently operational mean timescale algorithm with one based on a two-state Kalman filter, publishing a paper showing that DAS data can indeed be used to generate both maser- and cesium-based mean timescales with fre-

quency stabilities comparable to the those generated with the current algorithm with less labor and subjectivity.

P. Koppang worked on the operational MC system as well as timescale and control system research. He investigated utilizing control theory to optimally combine frequency standards into an ensemble.

B. Global Positioning System (GPS) Operations

Under the control of the Time Transfer Division in support of USNO GPS Operations were four Allen Osborne Associates, Inc. (AOA) TTR-12 Precise Positioning Service (PPS) receivers, four STel 5401C PPS receivers, one Motorola Oncore Standard Positioning Service (SPS) receiver, one R100 GPS/GLONASS receiver, and two AOA TTR-6 SPS receivers. One AOA TTR-12 PPS receiver, one STel 5401C PPS receiver, and one Motorola Oncore SPS receiver were in operation at the AMC site. The AMC STel receiver failed in December 2002 and was removed from service.

The AOA TTR-12 PPS receivers became the operational receivers on 9 July 2002 and provided the information to the GPS Master Control Station (MCS) for GPS Time synchronization to UTC (USNO). USNO PPS GPS data were downloaded to the GPS MCS daily. The GPS timescale was maintained to within ± 25 ns of UTC (USNO) (its specification is ± 1 microsecond) and the yearly average error of UTC transmitted from GPS was 5 ns.

L. (Nelson) Moreau provided many users with NIST carrier-phase data and Jet Propulsion Laboratory (JPL) Ashtech receiver data. She and F. Vannicola got the AOA3 receiver repaired and determined the L1 and L2 adjustments for the AOA1 and AOA2 receivers. Moreau installed backup 5 MHz distribution amplifiers and replaced the Ashtech USN1 receiver. She and J. Eler rebuilt a Motorola receiver.

E. Powers and Moreau recalibrated a Motorola receiver at the U.S. Naval Research Laboratory (NRL), a TTR-5 receiver for the Spanish Navy, and a Rockwell-Collins receiver, and installed the AMC Ashtech receiver. Powers participated in working group meetings on two-way time transfer, interoperability between GPS and the EU's Galileo system, and the design of a new USNO receiver simulator. He and Eler installed a Wide Area Augmentation System (WAAS) receiver and hardware in support of a JPL real-time time transfer system. Powers, D. McCarthy, and W. Bollwerk represented USNO at a meeting on the creation of a new GPS Operational Requirements Document, which will list single-nanosecond UTC (USNO) GPS timing requirements.

L. Schmidt adapted code from BIPM to allow the replacement of SPS-modelled ionosphere delays with IGS ionosphere maps. She wrote programs to use the dual-frequency measured ionosphere delay from TTR-12 receivers in all USNO and AMC SPS receivers, improving long-baseline USNO-AMC common-view results. She upgraded software that performs comparisons among multi-channel receivers and between timing and carrier-phase receivers. She, Vannicola, Moreau, and D. Johns negotiated the format for the TTR-12 data flow between USNO and the MCS. Moreau, Vannicola, and L. Schmidt changed the operational tropospheric model used by the TTR-12s to the NATO standard (STANAG) model.

Vannicola supported USNO GPS operations by managing the PPS and SPS receivers, associated hardware, and reduction software; implemented a series of alarm monitors for lack of GPS data, values out of range, loss of SIPRNet connectivity, and L2 interference; monitored the daily 2SOPS downloads of USNO data for GPS time synchronization; performed the necessary secure-communication (COMSEC) duties required to sustain the USNO GPS PPS operations; completed the migration of all operational USNO GPS timing scripts and programs between HP-UX computer systems ''Simon'' and ''Hathor''; and monitored the reduction of the NovAtel GPS and WAAS receiver and common-view data.

Vannicola worked with GPS MCS contractors to set up testing of USNO data files for future transfers via the SIPRNet to the GPS MCS; participated in the revision of document ICD-GPS-202; and implemented the required data format changes and alarm range values set forth in the ICD.

Vannicola provided support to NIMA in troubleshooting their GPS PPS receivers located at USNO, as well as COMSEC receiver keying when necessary.

Moreau and later Breakiron provided GPS support for Vannicola.

H. Chadsey developed processes to reduce carrier-phase data from the EO Department and JPL and to evaluate them in preparation for submission to BIPM.

C. Loran-C Operations

Chadsey tested and installed software in the new LORAN receiver-controller and data-collection computers at USNO and the Flagstaff and Ft. Richardson remote sites. He coauthored a paper with D. Matsakis at a meeting of the International Loran Association.

D. Wide Area Augmentation System (WAAS) Operations

Chadsey regularly monitored the timing data from FAA's WAAS. Powers and Vannicola assisted in the data collection.

E. Computer Operations

Johns wrote utilities to plot USNO and AMC Master Clock, timescale, environmental, and two-way data, as well as maser frequency stabilities and mercury trapped-ion measurements. He implemented the reduction of GPS TTR-12 data; upgraded NTP computer code and authentication procedures; and began converting the timescale programs into the C language.

R. Schmidt procured, installed, and implemented an HP rp7400 server called ''Isis'' and a VA7100 fiber virtual disk array, as well as the associated operating, security, file, and backup systems to provide mirrored storage of critical file systems. He also maintained and upgraded the Hathor R&D server and the USNO and AMC ''Tycho'' Web servers, and repaired or replaced their tape drives.

R. Schmidt and Johns configured and tested new NTP servers. NTP traffic coming into USNO Washington now

exceeds 800 hits/second and that at the AMC and other USNO NTP sites exceeds an additional 400 hits/second.

R. Schmidt continued testing the next generation NTP server using Brandywine PCI synchronized generators to replace VME systems presently in use. He procured replacements for the USNO and AMC SIPRnet and Internet NTP servers and tested code for a GPS-steered rubidium clock designed for SIPRnet NTP.

F. Alternate Master Clock (AMC) Operations

L. Schmidt and later Breakiron maintained AMC timescale operations, which involve 12 cesium clocks and 3 masers.

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

A. McKinley and M. Tran maintained the TWSTT hardware at USNO and the AMC. McKinley upgraded the firmware in many SATRE modems. She, J. DeYoung, G. Luther, and A. Smith mounted a new X-band antenna on Bldg. 78, while Luther and Smith installed a new KU-band antenna. McKinley, Luther, Smith, Tran, and E. Newman got the flyaway antenna operational. Smith, Newman, McKinley, and Luther established and calibrated links between Vandenberg AFB and the Communication Research Laboratory in Japan. McKinley restored the link with NIST, calibrated the system at the Midway Research Center, and implemented a link with the National Physical Laboratory (NPL) in the UK. She also assisted NPL, the Paris Observatory, and Pulstar in the upgrades of their systems. McKinley and P. Wheeler repaired and calibrated the system at the Selfridge Air National Guard Station. McKinley and Wheeler upgraded and calibrated the Bangor station. Smith, Newman, and Luther calibrated the AMC, NIST, and Timing Solutions Corp. stations.

Tran installed new hardware and software to receive data from NIST, and installed new SATRE modem software. He determined and corrected temperature effects on TWSTT transceivers.

Koppang, DeYoung, Johns, and McKinley restored Vandenberg AFB's Kalman-filter steering of their master clock toward USNO via TWSTT.

L. Schmidt set up TWSTT monitoring and TSWTT-minus-common view processing at USNO and the AMC. Breakiron took over the data monitoring after her departure.

H. Systems Engineering

The Systems Engineering Division maintained the Master Clock (MC) hardware, installed a new building for a backup Uninterruptible Power Supply (UPS), and completed the essential data flow operations to Linux-based control computers.

Eler brought the Bldg. 78 weather station up to full operation; installed LAN connections and time-measurement cabling; and managed all PC operations. He, A. Kubik, Moreau, and Powers installed a receiver and computer for GPS data collection.

King maintained a whole array of computer equipment, including new workstations and PCs used as instrument controllers and data collectors at USNO and the AMC. She installed redesigned environmental data acquisition processes, a new dial-out alarm system for clock-chamber emergencies in Bldg. 52, and new instrument controllers for the MC measurement scans and GLONASS data collection. She created a Web site on Hathor for GUI access to data processing and control. She implemented data transfer from the data collection computers to, and file housekeeping on, Isis. She developed software to monitor AnaCom Anasat transceivers, the power status of the MCs, and data from the new SATRE TWSTT modems.

Kubik installed the new Linear Ion Trap frequency Standard (LITS) and maser NAV20; repaired the Time Announcer; and maintained the USNO and AMC cesium and maser ensembles and the UPS. He also designed and built a circuit to monitor the power level of all USNO timing systems. He and Smith maintained all the clock environmental chambers.

Tran measured the channel delays in all 1PPS amplifiers; upgraded the environmental chamber alarm system; and managed the operations of the TSC time measurement system.

I. Clock Development

Koppang and T. Swanson co-authored a Frequency Control Symposium (FCS) paper on the mercury-based LITS, which has achieved a frequency stability in the low parts in 10^{-16} at a sampling time of 10^6 seconds and a frequency drift of $< 210^{-16}$ /day over 60 days. S. Peil, S. Crane, and C. Ekstrom completed the design of many key elements for a rubidium-based fountain clock, which was presented in another FCS paper. Crane and Peil upgraded the cesium-beam fountain clock.

J. GPS Carrier-Phase Research

TS participated in a BIPM pilot project to use code data from carrier-phase GPS receivers for time transfer under the management of Powers.

K. Miscellaneous

Breakiron served as chairman of the USNO Editorial Review Board and served as treasurer and editorial chairman of the Precise Time and Time Interval (PTTI) Systems and Applications Meeting Executive Board. He edited the Proceedings of the 34^{th} PTTI Meeting and this Observatory Report.

L. Schmidt organized and chaired the tutorials session for the PTTI Meeting.

Vannicola maintained the PTTI Meeting Web pages that included general information as well as the 34^{th} Meeting's Advance Program and meeting information in html and pdf formats; coordinated the PTTI 2003 Call for Papers; and continued to serve as a member of the PTTI Executive Committee.

IV. EARTH ORIENTATION 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, and as an Operations Center, Correlator, and supporter of observing stations within the International Very Long Baseline Interferometry (VLBI) Service.

A. VLBI Operations

The VLBI Correlator Facility continues as an International VLBI Service (IVS) Correlator Facility. During the reporting period 56 Rapid 24-hr experiments for determining Earth Orientation, 107 UT1 intensive sessions, 8 Celestial Reference Frame experiments, 5 Terrestrial Reference Frame experiments, and 3 sessions from the 2002 Continuous Observing Campaign were processed. The Correlator continues to be the primary rapid-turnaround processing center for Earth orientation monitoring. K. Kingham leads the VLBI effort with support from M. Carter and A. Myers.

During the reporting period, the Correlator began routine correlation of eight-station experiments. Efficiency enhancements, including better tape pass finding, less time in wait-states, and better handling of subnets, were installed. An immediate result was the processing of all backlogged experiments. By June 2003, the Correlator had reduced the backlog to zero. Most experiments are now being processed within a month of observation, provided the recording media arrives within a reasonable time.

Also during the period, the first two Mark 5 playback systems were installed. The original Mark 5 prototypes were used to convert the UT1 Intensive sessions to all Mark 5 recording in November 2002. The prototypes were upgraded to full production Mark 5A playbacks in May 2003. Early experience with the Mark 5 media has been very successful, with more robust reproduction of recorded data and reduced processing times. The overall performance improvement should allow an increased amount of processing in the next year.

B. GPS Analysis

The Department continued to contribute rapid, ultra-rapid, and tropospheric products for GPS satellites to the International GPS Service (IGS). The software used to create these products was GIPSY/OASIS II Versions 5 and 6, which were written by JPL. Modifications to existing procedures have improved the quality of all products. J. Rohde leads the GPS effort with support from V. Slabinski, P. Kammeyer, Carter, Myers, and D. Pascu (AD).

The introduction of the faster HP J6700 workstation in October 2002, running HP Unix Version 11, allowed the Department to upgrade to GIPSY/OASIS II Version 6. This new combination of hardware and software executes the solutions at approximately twice the speed of the older workstations running GIPSY/OASIS II Version 5. As a direct result of this new efficiency, the density of the rapid and ultra-rapid networks used in the global solutions was increased from 34 to 40 sites.

A significant amount of analysis was done using GIPSY/OASIS II Version 6 hosted on a PC running Linux. Rapid solutions were executed for backup, testing, and comparison purposes without the expense of purchasing an additional workstation. The speed of execution and the quality of these results compare very favorably with the performance of the HP J7600 workstation. Changes to procedures were routinely tested here before being implemented on the production workstations.

As mandated by the IGS, the daily rapid and twice-daily ultra-rapid GPS orbit files were changed from sp3a format to sp3c format in November.

Improvements to our Solar Radiation Force (SRF) model, which is based on the Center for Orbit Determination Europe SRF model, have greatly improved the predicted half of the ultra-rapid orbit files.

The average weighted root mean square (wrms) for the rapid satellite orbits was 3.2 cm; the average root mean square (rms) clock solution was 68 picoseconds (ps); the average number of receiver clocks solved for was 100.5; and the on-time submission rate was 98%. The corresponding values for the previous year were 5.6 cm, 90 ps, 73.3 clocks, and 96%.

The average wrms uncertainty in the ultra-rapid satellite orbits was 18.5 cm; the average rms clock solution was 4.91 ns; and the on-time submission rate was 87%. The corresponding values for the previous year were 33.2 cm, 5.18 ns, and 88%.

C. Earth Orientation Parameter (EOP) Combination and Prediction

The Department serves as the Rapid Service/Prediction Center for the International Earth Rotation and Reference Systems Service (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.

A few changes have occurred which affect the performance of these rapid EOP solutions. In January software formats were modified to handle the new IVS VLBI data formats. In February, the software was modified to allow the editing of all data techniques used in polar motion and UT1 combination solutions. In addition, data editing was introduced into the nutation software. Due to the improved accuracy of the Bulletin A daily solutions, the twice weekly nature of VLBI 24-hr sessions, and personnel limitation, the frequency of the Bulletin A rapid solution was reduced from twice-weekly to weekly on 1 July 2002.

In September, a study to evaluate the potential improvements by introducing USNO and IVS Combination 24-hr

VLBI products into the Bulletin A rapid service/prediction EOP series was initiated. By November, results clearly indicated that the robustness of the Bulletin A, especially for the nutation angles, could be improved by the addition of these two VLBI series. It was decided that the USNO and IVS Combination 24-hr VLBI products would be introduced into the operational Bulletin A (both daily and weekly) and Mark III solutions in early January 2003.

In late 2002, USNO prepared for the implementation of the IAU 2000 resolutions by creating a dX and dY series with respect to the IAU 2000A Precession/Nutation Theory. Hence, additional files that contain the dX and dY series were created. The complete replacement of the IAU 1980 Theory of Nutation and the IERS Precession/Nutation Theory should be completed by late 2003 or early 2004.

The EOP combination and prediction program is currently investigating improvement of the current methods employed to estimate the biases between the different Analysis Center datasets and C04. In addition, the automation of the data retrieval and updating software for VLBI and Satellite Laser Ranging (SLR) data sets should be operational by mid-2003.

The data available from the IERS Rapid Service/ Prediction Center consist mainly of the data used in the IERS Bulletin A. These data include the following: x, y, UT1-UTC, dy, de from the Institute of Applied Astronomy (IAA) VLBI; NASA Goddard Space Flight Center (GSFC) VLBI, USNO VLBI, and the IVS-combination VLBI; UT1-UTC from Saint Petersburg University and GSFC 1-day Intensives; x, y, UT1-UTC from the Center for Space Research, University of Texas LAGEOS 3-day SLR; x, y from Delft University of Technology 3-day SLR; x, y from the IAA and Russian Mission Control Center 1-day SLR; x, y, LOD from the International GPS Service; UT from USNO GPS; UT from Natural Resources Canada (EMR) GPS; an atmospheric angular momentum UT1-like quantity produced at USNO using National Centers for Environmental Prediction models; x, y, UT1-UTC, dy, de from the IERS Rapid Service/Prediction Center; x, y, UT1-UTC, dy, de from the IERS Earth Orientation Center; and predictions of x, y, UT1- UTC from the IERS Rapid Service/Prediction Center.

The data described above are available from the Department in a number of forms. A weekly machine-readable version of the IERS Bulletin A containing the current 90 days worth of predictions may be requested via electronic mail from *ser7@maia.usno.navy.mil* or *http://maia.usno.navy.mil/*. Internet users can also direct an anonymous ftp to maia.usno.navy.mil and change to the ser7 directory, where the IERS Bulletin A and more complete databases can be accessed including the daily Bulletin solutions. Web access is available at *http://maia.usno.navy. mil*.

D. Miscellaneous

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 IERS Workshop on Combination Research and Global Geophysical Fluids, the GSFC Global Water and Energy Cycle Workshop, the European Geophysical Society GA, and the fall American Geophysical Union meeting. Kingham was elected to a second term on the Directing Board of the IVS and continues to serve on the IVS Observing Program Committee. Wooden joined the IERS Directing Board as head of the Rapid Service/Prediction Center and provided the Center status for the IERS Workshop in Paris. Wooden also participated in the International Telecommunication Union's Special Colloquium on the Future of the UTC Time Scale in Torino in May. Slabinski presented a paper on an application of the Efroimsky gauge velocity in orbit perturbation theory at the Division on Dynamical Astronomy (DDA) meeting in Ithaca in May.

The Rapid Service/Prediction Center Annual Report for 2002 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 2003. The USNO IGS Associate Analysis Center Biennial Report was submitted to the IGS for publication.

The Department has played an active role both in supporting and in coordinating the Science and Engineering Apprentice Program. Also, Johnson and Carter assisted in giving tours to the public.

V. ASTROMETRY DEPARTMENT

A. Washington Double Star Program

Observations of 3,867 objects were obtained using the speckle system attached to the USNO 26-in Refractor. Observers include D. Hall, W. Hartkopf, G. Hennessy, B. Mason, D. Pascu, T. Rafferty, S. Urban, and G. Wycoff. While the primary observing program at Washington continues to emphasize stars of importance to DoD, rapidly moving systems, and ''neglected'' double stars, additional datasets include: bright pairs, potential rectilinear motion systems, calibration pairs, systems with orbits, and those having uncertain motion. The bright pairs dataset has been expanded to include all pairs out to an arcminute in separation. Data obtained from this project during 2001 have been published by Mason *et al.* (2002, *Astron. J.*, **124**, 2254). Observations from 2002 have been analyzed and submitted for publication. To guard against project interruption due to mechanical difficulties, a backup speckle system utilizing an earlier ICCD was constructed and tested by Rafferty on the USNO 24-in Reflector, giving USNO a complete backup system: detector, computer, and telescope.

In 2002 the speckle camera was used on the 4-m telescopes of KPNO and CTIO. The observing program consisted of nearby G dwarf stars, continuing the work started in 1996 to investigate the multiplicity characteristics of solar-type stars of different ages (Mason *et al.* 1998, *Astron. J.*, **116**, 2975). Final reduction is complete and the results are being prepared for publication. The implications of these results for SIM are discussed in Section C below. Reduction and analysis of ~1300 observations from the 100-in telescope of Mt. Wilson continue by Hartkopf.

The annual double star contribution for the *Observer's Handbook*, *Astronomical Almanac*, and a new section for the *Explanatory Supplement to The Astronomical Almanac* were prepared, as well as a chapter on speckle interferometry for the three-volume book *Big Science from Small Telescopes*

edited by T. Oswalt. Analysis of the complex multiple system Finsen 332 continues by Mason and Hartkopf.

Plans for the USNO Double Star CD 2004 are underway. The CD will contain the same four catalogs as before: the WDS summary catalog, the 2nd Delta-M catalog, the 6th Orbit catalog, and the Interferometric catalog. While all of these have increased in size, the CD will also include new lists of neglected doubles, a complete WDS/ADS/BDS cross-reference, improved positions for most stars, new calibration doubles, a Catalog of Rectilinear Motion Systems, and a sample Washington Multiplicity Catalog (WMC; described below).

The USNO filled 581 data and observing list requests over the reporting period. Hartkopf continued his duties as Vice President of Commission 26 (Double and Multiple Stars), and work continued on the WMC in preparation for Special Session #3 at IAU-GA #25. The WMC is designed to take into account all types of double stars (visual, interferometric, photometric, spectroscopic, etc.) and place them in a WDS-like hierarchical scheme. This was developed prior to IAU-GA #24, and at a Multi-Commission meeting held at that time it was decided that the WMC was the preferred method and a sample WMC would be presented at IAU-GA #25. A preliminary version of this sample $\frac{1}{2}$-hour band was presented at the Commission 26 meeting in Merida, Mexico by Hartkopf.

Continuing collaborations for the double star program include D. Berger (GSU/CHARA), D. Barlow (U. Victoria), F. Benedict (U. Texas), T. ten Brummelaar (GSU/CHARA), N. Evans (Harvard/CfA), F. Fekel (TSU), D. Gies (GSU/CHARA), E. Griffin (U. Victoria), R. Griffin (Cambridge), T. Henry (GSU/CHARA), E. Horch (RIT), P. Ianna (U. Virginia), H. McAlister (GSU/CHARA), E. Nelan (StSci), D. Pourbaix (Brussels), L. Roberts (Rocketdyne), C. Scarfe (U. Victoria), D. Soderblom (STScI), A. Tokovinin (CTIO), N. Turner (GSU/CHARA), P. Tuthill (U. Sydney), D. Wallace (GSU/CHARA), and A. Wehrle (JPL).

In addition to those named above, personnel working on the WDS project and catalogs also included Dean Kang (Rutgers) and Laura Flagg (Wilson HS).

B. Astrometric Space Missions

During the previous reporting period, due primarily to technical problems obtaining detectors and associated cost overruns, NASA announced that it was not confirming the Full-sky Astrometric Mapping Explorer (FAME) mission for Phase C development, and withdrew future funding support.

The observations and science that would have resulted from a successful FAME program remain compelling, which is why efforts to continue development of an astrometric space mission have continued in the current reporting period. These activities, discussed below, include further work on the FAME program, discussions with the German DIVA program, and preparation of a proposal to NASA for the AMEX program.

FAME: The Full-sky Astrometric Mapping Explorer (FAME) is a space astrometric mission to measure the positions, parallaxes and proper motions of 40 million stars between 5th and 15th magnitude to an accuracy of 50 microarcseconds (μas) at 9th magnitude. A collaboration between USNO, NRL, Lockheed Martin Advanced Technology Center, and Harvard Smithsonian Center for Astrophysics, the FAME program was selected by NASA in October 1999 as one of two missions to begin development within the NASA Medium-Class Explorer program. As mentioned above, due primarily to technical problems obtaining detectors, and associated cost overruns, in January 2002 NASA announced that it was not confirming the FAME mission for Phase C development and withdrew future funding support.

An alternate supplier of detectors was selected shortly before the withdrawal of NASA funding support. Fabrication and testing of these detectors continued into the current reporting period. Fabrication and preliminary testing of these detectors were highly successful, and detailed testing continues at the NASA/GSFC Device Characterization Laboratory. The results of fabrication and testing of the FAME detectors will have significant impact on the development of detectors for future space astrometric missions. Significant progress has also been made during the reporting period on continued development of the FAME data reduction pipeline, optics subsystem definition, and simulation of the impact of detector radiation damage on astrometric accuracy. Like detector development, continuing work in these areas is directly relevant, and critical to the success of future astrometric missions.

In May 2003, the USNO FAME team, led by K. Johnston (PI), issued a 49-page report detailing the status of the FAME program at the end of Phase B, programmatic lessons learned, programmatic progress since Phase B, and prospects for future astrometric missions.

DIVA: The DIVA program is a German-led (PI: S. Röser) astrometric and spectrophotometric space mission, similar to the FAME program, but with relaxed astrometric requirements and scientific goals. The DIVA program is funded largely by the Deutsches Zentrum für Luft-und Raumfahrt (DLR), the German Space Agency. In October 2002 the DIVA program invited the USNO to participate in the DIVA project. Discussions included USNO funding support for the DIVA mission (to close a funding gap) through submission of a NASA Mission of Opportunity proposal in May 2003 (decision anticipated in October 2003). Unfortunately, DLR funding constraints necessitated full funding commitment for the DIVA program by the end of 2002. As the DIVA funding gap could not be closed by December 2002, DLR support for the DIVA program was withdrawn.

AMEX: The Astrometric Mapping Explorer (AMEX) is an astrometric and photometric space mission derived from both the FAME and DIVA programs. In May 2003 a 139-page funding proposal was submitted to NASA to support the AMEX mission through the NASA Small Explorers (SMEX) program. AMEX is a space astrometry mission that will measure the positions, proper motions, and parallaxes of 40 million stars. The astrometric accuracy will be the finest yet achieved. For 9th magnitude stars the positional accuracy (per coordinate) will be 150 μas, the parallax accuracy 150 μas, and the proper motion accuracy 150 μas/yr. AMEX is a collaborative effort between the USNO, NASA's JPL, the DLR, Astrium (Friedrichshafen, Germany), and members of

the former FAME and DIVA science teams. Detailed responsibilities include: USNO: Principal Investigator, data analysis, science management; JPL: project management, instrument design and development; Astrium: S/C bus design and development, S/C integration; DLR: launch vehicle, mission operations.

The selection process for the NASA SMEX program involves initial proposal submission, which occurred in May 2003, then selection (anticipated in October 2003) of ~ four missions to perform a Phase A concept study (anticipated due in April 2004). From those ~ four Phase A concept studies, NASA anticipates selecting two missions for flight. At the end of the reporting period, the AMEX program was waiting to hear the results of the first selection process for a Phase A concept study.

C. Space Interferometry Mission (SIM)

A. Fey, D. Boboltz, R. Gaume, N. Zacharias, and 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 8th SIM Science Team Meeting held in Pasadena, CA. Gaume, Zacharias, and Johnston attended the 9th SIM Science Team Meeting held in Baltimore, MD. Fey, Johnston, and Boboltz prepared a progress report of work done during FY02.

The following tasks were identified as suitable for collaboration with A. Wehrle's Key Science Project: 1) Quasar Radio Stability and 2) Quasar Optical Stability. VLBA data from a joint experiment with Wehrle's SIM Science Team to measure quasar stability at radio wavelengths was analyzed. Images of the sources were made and phase referencing was attempted. The pilot program to investigate the temporal stability of optical centroid positions of a sample of ICRF sources, using the 1.5-m Strand Astrometric Telescope at Flagstaff, AZ, was continued (for details, see last year's Report). Now all of the 14 sources on the list have been observed at least once. A total of 63 frames have been obtained, with 0552+398 being observed most (15 frames).

Results of astrometric observations of 19 radio stars conducted with the VLA in A configuration in conjunction with the Pie Town VLBA antenna were published (2003, *Astron. J.*, **126**, 484). Comparing the positions of our radio stars with the Hipparcos Catalogue, we find that at the epoch of our observations, the two frames are aligned to within formal errors of approximately 3 milliarcseconds (mas). This result confirms that the Hipparcos frame is inertial at the expected level. The same set of stars was also observed with the MERLIN array. Eleven of the 15 stars were detected with approximately 50 mas resolution. The MERLIN observations are currently being analyzed. An additional 48 hours of VLA+PT time were awarded (through the peer-reviewed proposal process) to observe an additional 40 radio stars. These observations have been made and the data are in the process of being analyzed. An additional 48 hours of MERLIN time was also awarded to continue observations of these radio stars. The MERLIN data will be added to our VLA data to get improved proper motions.

A pilot project of spectral-line radio observations of the SiO maser emission in the circumstellar envelopes of asymptotic giant branch (AGB) stars continued. 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 US. Observations conducted over the past year in relation to this research include VLA experiments AB1088 (observed June 2003) and AB1087 (observed August 2003) and VLBA experiment BB154 (observed December 2002). The VLBA observations were conducted quasi-simultaneously with VLTI observations of the same two stars. Preliminary results on one of the stars, S Ori, were presented at a VLBA meeting in June 2003. The VLA experiment AB1088 was a continuation of a previous pilot project to survey over 100 SiO maser stars with the VLA. An additional 15 stars were observed with the VLA, which will bring the total number of mapped SiO maser sources to 36 once the data are reduced.

A program of southern hemisphere astrometric/imaging experiments continues. A number of experiments have been observed with the Australian Long Baseline Array (LBA). These data are in the process of calibration and analysis. Imaging observations will allow for modeling of the systematic effects introduced by intrinsic structure in astrometric solutions. R. Ojha (Australia Telescope National Facility [ATNF]) visited the USNO to analyze and image LBA data taken on southern hemisphere ICRF sources. Several experiments were calibrated and images were made for about 60 sources. Preparing the results for publication was discussed. A draft paper on several of the more interesting sources was also planned. Source intensity information was extracted from the data for use in future astrometric experiments.

The speckle observations discussed in Section A above included observations of apparently single stars for possible consideration as SIM Grid stars. While the SIM team has decided to populate the grid with fainter, more distant stars than those observed, it appears that they can be used as SIM Guide Stars. In addition, many of these are on the SIM planet search program. Preliminary results from this effort were presented at the SIM Key Project Science Team meeting at STScI in June by Mason and D. Soderblom. There appears a very good correlation between age and multiplicity fraction – younger stars are more likely to be binary. The implication would be that younger stars might be better choices for planet searches. Mason, Hartkopf, Urban, Gaume, and Johnston met with the JPL team of M. Shao, A. Boden, and Wehrle regarding SIM Guide Stars. Mason and Hartkopf presented an analysis of which stars are best for Guide Stars, and of the others, which can be investigated via ground-based techniques prior to SIM launch. A sample of the USNO grid star selection set was reported in Horch *et al.* (2002, *Astron. J.*, **124**, 2245). Mason's collaboration on a SIM Key project (PI: T. Henry, GSU/CHARA) as co-investigator continued. This project is described by Benedict *et al.* (2003, *Proc. SPIE*, **4852**, 110).

D. Fundamental Reference Frames

1. Radio

Hall, Boboltz, and Fey continue to analyze both IVS-R4 (former NEOS) and IVS-R1 experiments through the CALC/SOLVE software. These included 50 weekly IVS-R4 experiments (R4039- R4088) and the 52 weekly IVS-R1 experiments (R1037-R1088). The resulting daily solutions of the IVS-R4 experiments are the official versions submitted to the IVS.

Boboltz and Fey continue to work on the production of global VLBI solutions for the purpose of estimating Earth Orientation Parameters (EOP) and the International Celestial Reference Frame (ICRF). The global EOP solutions USNO_2002c and USNO_2003a were completed and submitted to the IVS. The most recent solution (in this case USNO_2003a) is updated twice weekly and resubmitted 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 Earth Orientation Department. The global CRF solutions CRF2003a and CRF2003b were also completed. 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 SUR01, SUR02, CRF-15, CRF-16, CRF-17, CRF-18, CRF-19 and CRF-20. Several more experiments, including CRF-21 and SUR03, were scheduled and observed and are currently awaiting correlation. Additional experiments scheduled and observed specifically for the purpose of increasing the sky density of sources in the southern hemisphere included CRF-MS7, CRF-DS5, CRF-DS6, and CRF-DS7. The resulting daily solutions of the CRF experiments are the official versions submitted to the IVS.

Fey and Hall initiated analysis of VLBI Intensive experiments for UT1 estimation by parameterizing a global solution to estimate an EOPI (UT1 only) series. This series was made available to the Earth Orientation Department for testing purposes.

Fey completed work on a global VLBI astrometric solution for the construction of ICRF Extension 2. A draft manuscript presenting and describing the results of the solution was prepared and forwarded to co-authors. The manuscript is intended for *The Astronomical Journal*.

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.

In support of the International Celestial Reference Frame, the VLBA astrometric/geodetic experiments RDV36, RDV37, RDV38, RDV39, RDV40, and RDV41 were observed. Imaging of the experiment RDV12 was completed. The USNO Radio Reference Frame Image Database currently contains 3,060 images at S/X bands of 452 sources. A VLBA proposal was prepared and submitted to NRAO to continue the RDV series of VLBA observations of ICRF sources into the year 2004.

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. A new section was added to the USNO Radio Reference Frame Image Database to incorporate the resultant K- and Q-band images. USNO will use results of this project to determine whether higher radio frequencies could be used to define future realizations of the ICRF.

A joint USNO/ATNF proposal, submitted to the JPL Deep Space Network in support of a joint southern hemisphere imaging and astrometry program, received approval. Telescope allocation was for a total of 600 hours at DSS43 (70-m at Tidbinbilla, Australia) spanning 5 years.

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.

2. Optical

Optical observations for the radio-optical link program continued with a long-term proposal at the 0.9-m KPNO and MOSAIC camera. M. Zacharias prepared finding charts for ICRF Extension 2 sources. All observing runs were prepared by M. Zacharias. The September 2002 run was conducted by T. Rafferty, while the December 2002 and May 2003 runs were conducted by N. Zacharias, with 40, 25 and 48 sources observed, respectively. Simultaneous CCD imaging (2,455 frames) was performed with the USNO Astrograph (in the same, narrow, bandpass) to link the counterparts to the optical, Hipparcos frame (HCRS). Hennessy enabled 8-mm tape drive access from the IRAF package to allow older FITS files of the RORF project to be read in. M. Zacharias loaded FITS data from our 2.1-m KPNO RORF run and developed the software interface to enable the reduction of CCD frames taken at CTIO and KPNO, using UCAC data as the reference star catalog.

M. Assafin (U. Federal do Rio de Janeiro) and N. Zacharias wrote a paper about optical, extragalactic link data obtained with the Astrograph and the 0.9-m CTIO and 1.6-m LNA telescopes. N. Zacharias gave an invited talk about the USNO extragalactic, optical reference frame link program at the ADeLA 2002 meeting in Brazil. M. and N. Zacharias prepared a poster paper with similar, updated contents for the IAU XXV GA in Sydney. N. Zacharias determined the system rotation misalignment between a set of radio star observations (on the ICRF) and the Hipparcos Frame, and wrote a section about the results for a paper (D. Boboltz et al.). A null result was obtained at the 2000.9 epoch: axis misalignments are about 1 to 2 mas, with a formal error of 3 mas per axis. N. Zacharias wrote the ''Maintain the Link to the Hip-

parcos Catalogue'' section for the IERS Annual Report of the joint Paris Observatory and USNO ICRS Product Center.

E. USNO CCD Astrograph Catalog (UCAC)

Between July 2002 and June 2003, the USNO CCD Astrograph completed 8,540 fields and took 31,964 frames from its location at the USNO Flagstaff Station (NOFS). By end of June 2003, a total of 78,606 fields were completed, which is 92.3% of the sky. T. Tilleman and S. Potter began the reporting period as the UCAC observers. In August 2002, Potter resigned to continue her education. Prior to hiring D. Marcello in December 2002 as our second observer, Tilleman took many double shifts to cover virtually all clear nights, and was assisted, only in October, by Rafferty. This extra effort on her part ensured that the observing schedule did not fall behind. Marcello was trained to observe by Rafferty and N. Zacharias. Rafferty handled most of the instrumental problems with support from DiVittorio (NOFS), while Hennessy, Tilleman, and B. Canzian (NOFS) handled intermittent computer problems and upgrades. Hall checked incoming data tapes and updated the archive. Tilleman reduced dark frames, while N. Zacharias handled flats and special fields. M. Zacharias performed the daily quality control, extracted data for various requests, and developed more reduction software.

It was decided to make a second, preliminary release catalog of the UCAC data, termed UCAC2. N. and M. Zacharias constructed position-only catalogs, including all survey observations up to 7/8 December 2002, containing 58 million stars that form the basis for the UCAC2 data release. N. Zacharias applied systematic error corrections to the positional data, matched the 2MASS catalog with UCAC2 to include the infrared photometry, and performed external comparisons with other catalogs. D. Monet (NOFS) provided a catalog based on the V-plates of the SPM and NPM project, termed ''Yellow Sky.'' The plates making up the Yellow Sky were completely scanned on the PMM, Flagstaff. These data form the basis for the faint star ($V > 12$) proper motions of UCAC2. Urban and Wycoff performed an extensive analysis on the Yellow Sky data and removed systematic errors as well as possible. For the brighter stars ($V < 12$), the same data used in the Tycho-2 proper motion work were utilized, with some modification primarily in the older Astrographic Catalogue data and the inclusion of remeasured AGK2 plate data (see Section G below). Urban and Wycoff compiled the proper motions for 48 million of the 58 million UCAC stars. Only those stars with proper motions were kept in the UCAC2 catalog. The combined UCAC2 data were packaged by N. Zacharias, who also supplied access software. An extensive catalog introduction for users was written by N. Zacharias and Urban; the latter also oversaw the CD production. The UCAC2 contains positions and proper motions for 48,330,571 sources (mostly stars) and 2MASS photometry for 99.5% of them. Sky coverage extends from the south celestial pole to about $+45$ degrees declination. Positional errors are 15 to 25 mas for stars in the 10 to 14^{th} mag range, and 70 mas at the limiting magnitude of 16. Proper motion errors are 1 to 2 mas/yr for stars to 12^{th} mag and 4-7 mas/yr for the fainter stars. Copies of the three-disk UCAC2 set are now available and will be distributed at the IAU GA in Sydney.

F. Planets/Satellites

The astrometric and orbital analysis of the 1997 HST observations of Neptune's inner satellites – Proteus, Larissa, Galatea and Despina – was completed by Pascu, Rohde, and others. The astrometric accuracy of the observations ranged from 6 mas for Proteus to 17 mas for Galatea. Only mean motion corrections could be accurately derived from these observations. However, our analysis indicated that other parameters were in need of correction, at least for the orbit of Proteus. A publication is in preparation.

The 125-yr USNO program of astrometric observations of planetary satellites with the 26-in Refractor has come to an end. It will no longer be supported by USNO without external funding. A proposal for financial support to continue these observations was submitted to the NASA ROSS program by Johnson (EO) and Pascu.

Speckle interferometer observations of close approaches of the Galilean satellites were made with the 26-in Refractor by Pascu, Kaplan, Mason, and others. Such observations can only be made when two satellites are less than 12 arcsec apart, since that is the largest field available with our camera. These observations are not rare for the Galileans and are very precise due to reduction of the atmospheric component of the error and in minimizing uncertainties of calibration. Calibrational studies of the speckle camera for use at large separations were made by summer intern Paul Ries, Pascu, Mason, and Hartkopf.

Transfer of the USNO 22-yr CCD archive of planetary satellite observations from tape to CD/DVD was begun by Ries. These observations of faint inner satellites of the outer planets were made with the Flagstaff 61-in Astrometric Reflector by Pascu, Rohde, P. Seidelmann (USNO retired), and others.

G. Washington Proper Motions

Much of the work is incorporated in the production of the UCAC2 catalog and can be found in Section E above. One item not explicitly detailed was the work with the StarScan measuring matching and the German AGK2 plates.

The StarScan measuring machine is designed for submicron measuring accuracy on photographic plates. StarScan has been at USNO for several years, but modifications over the last few years by L. Winter (now at Hamburg Obs.), E. Holdenried (USNO retired), and Rafferty have made it a robust, automatic instrument. The AGK2 plate set, containing 2,000 plates exposed in Bonn and Hamburg Germany during 1928-1930, are on loan to USNO from the Hamburg Observatory. These plates have a limiting magnitude of $\sim$12, and cover the sky from -5 to $+90$ degrees. Their intrinsic accuracy is about 60-70 mas, making them a valuable resource for proper motion work.

From 1 July 2002 through 1 June 2003, all 2,000 plates of the AGK2 program were measured. Some of these were remeasurements prior to StarScan being modified to allow for

firmer clamping of its plate-holding mechanism. Urban, Wycoff, Mason, Hartkopf, Rafferty, Hennessy, Hall, and Pascu were involved in the loading of the plates. Urban and Wycoff were responsible for initial data handling, record keeping, and archiving.

N. Zacharias has conducted initial data reductions and quality control routines. His coding to determine parameters for the mapping of the CCD footprints onto the x,y table coordinates are now generated from the measures themselves. This improvement made a small-scale systematic pattern, previously seen in the data, disappear. Systematic errors (~0.5 micron), depending on the scan direction, were discovered and can be solved in software. Plots of differences between direct and reverse measurements were used in determining which plates required remeasurement.

The initial data reduction using the Hipparcos catalog as reference data showed that the Bonn plates suffer from magnitude and color equation; the Hamburg plates do not seem to suffer these same errors. Since the immediate desire is to put some AGK2 data into the UCAC2 catalog, it was decided that the Bonn data would be handled in the future and only the data from the Hamburg plates would be used. Positions for about 950,000 stars between declinations +20 to +60 were produced. Positional accuracy of 50 to 100 mas in the B = 9 to 12 magnitude range were obtained. The data were incorporated into the UCAC2 proper motions. N. Zacharias presented a paper, co-authored by Urban, Rafferty, Holdenried, and Winter (BAAS, **35,** #6.01), for the DDA meeting presenting these results.

In September 2002, a massive computer failure occurred, necessitating action by several current and former employees, namely Hennessy, Holdenried, Winter, Rafferty, and Urban. By mid-October, the system was again running properly. In addition to the clamping mechanism mentioned above, an automatic cut-off mechanism when air pressure becomes low was installed by Rafferty and Pohlman, making the instrument less susceptible to damage during power or compressor failures. Other electronics modifications, mostly in removing unneeded wiring and updating existing components, were performed by Rafferty.

H. DoD Requirements

Urban briefed National Reconnaissance Office (NRO), Aerospace Corporation, and NRL personnel on the status of astrometric issues, potential shortcomings, and possible solutions to avoid discontinuity in meeting requirements. Details on the URAT and AMEX projects were emphasized. Urban and S. Diaz attended an NRO Technical Forum. Discussions with Defense Advanced Research Projects Agency personnel and Urban, D. Monet, Johnston, and Gaume regarding the Space Surveillance Telescope were held. Urban performed work requested by Boeing on a classified project. This involved generating a catalog based on specific criteria and utilizing the Hipparcos, Tycho-2, and WDS databases and in-house software. Questions arising during the year from Raytheon and Northrop Grumman were answered. Urban began a newsletter titled *Astrometry News* aimed at keeping DoD and contractors informed on astrometric issues.

I. USNO Robotic Astrometric Telescope

N. Zacharias presented the proposed USNO Robotic Astrometric Telescope (URAT) project at the Council meeting on 19 February, and wrote a ''white paper'' about this topic, with contributions from Urban, Rafferty, and Gaume. The goal of this project is to densify the optical reference frame beyond the UCAC limit of 16th magnitude and derive positions on the 5 to 10 mas level to about R = 18 with a limiting magnitude of ~21. Access to bright stars (3 to 7 mag) can be an option, allowing for a direct link between the Hipparcos and extragalactic reference frame. A single, large detector is envisioned to cover a 3-deg field of view with this specialized 0.9-m aperture, fully robotic telescope to meet emerging DoD needs with a new, deep all-sky survey.

Urban and N. Zacharias initiated a contract with Ecole et Observatoire des Sciences de la Terre (EOST) for an optical/mechanical study regarding the URAT design. From EOST, USNO received details of three possible optical designs for the URAT telescope. N. Zacharias, with ZEMAX software assistance from Hajian, evaluated the designs and provided feedback to EOST. Both alternative designs quickly turned out to be inferior to the original design from U. Laux (Tautenburg Obs.) that USNO has in mind. EOST is currently performing a tolerance analysis and costing estimates for the entire telescope manufacturing. N. Zacharias obtained information from Rockwell regarding CMOS detectors. Urban and Diaz presented the project and a point paper at the NRO Tech Forum's ''Fifteen Minutes with a Program Manager.''

J. Instrumentation

The Instrument Shop, under the leadership of J. Pohlman and including the instrument makers G. Wieder, J. Bowles, D. Smith, and T. Siemers, continued work on projects for the Astrometry Department, as well as for some of the other USNO departments. As 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 time working on instrumentation.

John Bowles retired from the Instrument Shop on 30 September after 22 years of federal service. Bowles started working in the Instrument Shop in 1980 and worked on various projects including the UCAC Astrograph, the Navy Prototype Optical Interferometer, the Sloan Digital Sky Survey, the Fourier Transform Spectrometer (FTS) project, the Mount Wilson Optical Interferometer, the Cesium Fountain Clock, and the Photographic Zenith Tubes from the early 1980s used both in Washington and Richmond, FL.

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

metrology (c-term) system for the use with the siderostats. The Shop also completed six more quad cell systems and shipped them to Flagstaff.

FAME: The Instrument Shop manufactured several more CCD substrate mounts for testing a new run of CCDs.

Atomic Fountain Clock: The Instrument Shop continues manufacturing parts for another Rubidium Fountain Clock for Time Service, including transition flanges, cleanup cavity tops, a detection body, and parts for the magnetic shield assembly.

UCAC Astrograph: Rafferty continued the maintenance and troubleshooting problems for the UCAC Astrograph located at NOFS. During each visit to NOFS, Rafferty made upgrades to the instrumentation. The UCAC Astrograph continues operating remarkably well for having been in use nearly constantly since early 1997 when it started the UCAC project in Chile.

26-in Refractor: The Instrument Shop and Rafferty started work on upgrading the 26-in Refractor. Rafferty started by removing all the unnecessary electronics and parts from the tube of the instrument. He then cleaned the tube, treated it with a chemical to deactivate and remove the rust, and primed and painted it. Rafferty also built a prototype console and started moving some of the functions from the old console to the new. He started work on designing and building new electronics for the declination clamp and slow motion. After the failure of the power supply used with the clock drive of the telescope, Rafferty designed a new gear train that would allow the synchronous motor to be operated at the standard 60 Hz instead of at a different frequency as is required now, but it proved more cost-effective to use a new power supply instead. The Instrument Shop also designed, built, and tested a new right ascension clamp for the 26-in. The Shop also repaired one of the wheel units of the 26-in dome.

StarScan: Rafferty designed and built new electronics for StarScan to raise and lower the rotation disk, and to shut down the motors when there is a drop of air pressure. Raising and lowering the rotation disk results in a significant improvement of the measures of the AGK2 plates. He also repackaged most of the other electronics for the machine. Setting up a stepper motor and controller in his office, Rafferty was able to write software to operate the stepper and test changes he later made to the StarScan software. He also fixed a number of minor problems with the StarScan to keep it operational.

24-in Reflector: The Instrument Shop and Rafferty continued the upgrade work on the 24-in Reflector in Washington. All the optics were removed and cleaned, and improvements to their mounts made. An encoder was added to the secondary to display the focus setting. Rafferty took some out-of-focus CCD images for DiVittorio to check the quality of the optics. The optics were found to be very good. Rafferty and Pohlman designed a new back end for the 24-in to hold the optics and fiber adapter required for the FTS. Rafferty worked on getting the telescope to guide correctly. For the guiding tests, he installed the old 1K $\times$ 1.5K CCD camera (used on the UCAC Astrograph for testing) onto the 24-in. Though all the electronics were in place to allow guiding with a ST4 auto guider, the AC servo drive system on the 24-in was not working correctly. Adjusting the servo system, Rafferty started taking CCD images to test the tracking. He found the 24-in could guide well for 5-min exposures, but showed elongated star images for 10-min and longer exposures, likely caused by flexure between the guide scope and the main optics. While it would have been better to use an off-axis guider instead of a separate guide scope, since secondary mirrors of Cassegrain systems are very sensitive to flexure, Rafferty decided to go with the latter because the former would be a major piece of equipment to build and he had a complete separate guide scope that had originally been on the Astrograph. A 5-min exposure with a CCD camera was about the longest Rafferty had hoped to use. After the Instrument Shop completed the new back end for use with the FTS, Rafferty ran some tests on it and felt it was ready for use. He also designed a simple speckle camera using the spare ICCD camera he had repaired, and started taking test data with the speckle camera of widely separated double stars. The results were very good. He plans to move the speckle camera from the 26-in to the 24-in when the 26-in needs to be taken out of service for upgrade work.

12-in Refractor: Near the end of the reporting period, Rafferty started work on the 12-in Refractor. Little has been done to the telescope since it was refurbished around 1980 and it is very much in a need of work. He corrected a few minor problems with the telescope and designed new electronics for the right ascension clamp, slow motion, and the declination slow motion. The Instrument Shop built the enclosure necessary and Rafferty wired the electronics.

New encoders: One major task Rafferty was hoping to undertake was replacing the encoders currently used on the 26-in and UCAC Astrograph, using the 24-in as the test-bed. Though he had discussions with instrumentation people at KPNO, Lowell, and DiVittorio at NOFS, there is no clear consensus of the best one to use. It would be desirable to use the same encoders on the telescopes operated by the Astrometry Department and NOFS.

The Instrument Shop and Rafferty removed the 18-in Reflector from the roof of Bldg. 52A to the 52A lab area after cleaning and reassembly (the telescope had been used during early testing of the FTS). The Shop also built several optical components for the FTS project, including corner cube mounts, a Styrofoam enclosure for temperature control, and many small mirror mounts.

Engraving for the year totaled 123 hours of the Instrument Shop's time.

K. Miscellaneous

Dr. Christian de Vegt (Hamburg Obs.), a good friend, colleague, and long-time USNO collaborator, died suddenly in July 2002.

M. Ratner (SAO/CfA) contacted Urban regarding obtaining data for use in a study on Gravity Probe-B. Urban forwarded the data to him and G. Gatewood (U. Pittsburgh) for their analysis.

Urban continued as Chairman of the Densification of the Optical/Infrared Working Group of the IAU.

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

Pascu served on the Ph.D. dissertation committee of Valery Lainey at the Institut de Mécanique Céleste et de Calcul des Èphémérides in Paris.

Boboltz continues to pursue a program of independent research. Over the past year, he collaborated with T. Wilson (Max-Planck-Institut für Radioastronomie) on 22- and 43-GHz VLA continuum observations of hyper-compact HII regions towards the star-forming region W3-IRS5. Boboltz also collaborated with M. Hollis of NASA/GSFC on 43-GHz VLA observations of ethyl cyanide toward the Large Molecule Heimat in the Sagittarius B2 star-forming region. Boboltz continued to serve on the NRAO Users Committee, and began participating in the Life Cycle of Stars Working Group for the Square Kilometer Array project.

Fey continues to work on several astrophysically interesting and relevant projects. Collaborations continue with J. Lazio (NRL), G. Piner (Whitier College), M. Claussen (NRAO), and P. Charlot (Bordeaux Obs.). 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 including, e.g., ''The Variable Radio Source T Tauri,'' published in *The Astronomical Journal*.

Rafferty continued classifying position descriptions along with Bangert and McCarthy.

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. An analysis of L and T dwarfs was published in 2002, and a paper giving parallaxes of about 100 white dwarfs is being prepared now. The accuracy for a typical parallax is 0.5 mas.

The infrared group led by F. Vrba and including Guetter, A. Henden, C. Luginbuhl, J. Munn, and B. Canzian continued efforts to obtain parallaxes and proper motions at infrared wavelengths of L and T dwarfs discovered by SDSS or 2MASS. Data are obtained at the 61-in Strand Astrometric Telescope in the J- or H-band with the ASTROCAM imager, which uses an ALADDIN 1024 $\times$ 1024 InSb detector, providing an approximate 6.2 $\times$ 6.2 arcmin field of view. The initial program started in September 2000 and included 22 L dwarfs and 18 T dwarfs. This year an additional 3 L dwarfs and 8 T dwarfs were added to the program, which is now running at near full capacity.

It was decided to make public preliminary parallax and proper motion results for the initial 40 objects based on data through November 2002. Although the data to that point covered time baselines of only 2.1 years for about half the objects and 1.3 years for the other half, with mean parallactic errors of 3.9 and 4.9 mas, respectively, the proximities of the L and T dwarfs still lead to astrophysically meaningful distances for these highly studied objects, which transition the mass range between the least massive stars and giant planets. The preliminary results were initially presented at the January 2003 Seattle meeting of the AAS. One of the objects, 2M0415-09, was found to be the least luminous and coolest T dwarf known, based on these parallax results. This was announced via a press release and press conference given by Vrba at the meeting, with the IR group as co-authors. Subsequently, a full paper presenting these results has been prepared and will be submitted to *The Astronomical Journal* in 2003.

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

The FASTT continued to make CCD observations this past year under the direction of R. Stone. The telescope has been in full production since 1997, and a paper describing its automated operation, accuracies achieved, and observational programs will appear in the October 2003 issue of The Astronomical Journal. Further efforts were made to improve the accuracy of the derived positions. A magnitude-related effect caused by charge transfer inefficiency was found and is now removed by calibration. Most of the observations taken are of solar system objects: the outer planets, satellites of these planets, and over 2000 asteroids. Some stellar observations were taken as well in support of various occultation events. A proposal has been submitted to NASA requesting funds so that the FASTT observing program can be continued and expanded to over 5,000 asteroids.

3. Solar System Astrometry

In the past year, the FASTT made 34,022 observations of asteroids and 1,151 of the outer planets Uranus, Neptune, Pluto, and 17 satellites of these planets. The planetary observations are part of an ongoing project to improve the ephemerides of these objects and to support various existing and proposed spacecraft missions to the outer planets. The observations of asteroids are being used to refine their orbits, determine masses of asteroids dynamically, and predict occultation events. Many occultations of asteroids were observed successfully during the past year, largely because of the accurate astrometry being provided by the FASTT.

The observing contract with JPL was once again extended. Observations were made with all NOFS telescopes, as needed, of near-Earth asteroids, comets, and selected planetary satellites, primarily in support of space missions, but also for improvement of planetary ephemerides, astrometric accuracy for prediction of occultations, and improved targeting for radar ranging.

The asteroid 5535 Annefrank was a flyby target of the Stardust mission in November 2002. Observations were made with both the 8-in and 61-in telescopes over the summer and early fall, and astrometric positions provided to JPL. The flyby was successful. Two comets were also observed: Wild 2, a later target of Stardust, and 26P/Grigg-Skjellerup,

a possible target of the Contour 2 mission. Some of the outer satellites of Jupiter were observed for ephemeris improvement. Observations of Grigg-Skjellerup were made with both the 61-in and the 1.3-m telescopes.

4. Sloan Digital Sky Survey (SDSS)

USNO continued its involvement with the SDSS. Both Munn and J. Pier supported the astrometric effort. A paper describing the SDSS astrometry, ''Astrometric Calibration of the Sloan Digital Sky Survey'' by Pier, Munn, Hindsley (NRL), Hennessy (AD), S. Kent (Fermilab), R. Lupton (Princeton), and Z. Ivezic (Princeton), was published in the March 2003 Astronomical Journal. Pier continues to be involved in SDSS management as chair of the SDSS Advisory Council, while Munn continues to support the SDSS Operational Database.

Pier was awarded the USNO's Simon Newcomb Award for his scientific and leadership contributions to the SDSS.

Studies of white dwarf stars observed by SDSS are proceeding on several fronts. An overview was prepared by H. Harris, Dahn, Munn, and Pier, and more specific papers will be published in the coming year on magnetic white dwarfs, hot DQ stars, and DO stars. A complete catalog of white dwarfs in Data Release 1 is nearly completed. It includes spectroscopic classification and accurate positions, proper motions, and photometry for roughly 2,500 newly discovered white dwarfs and for several hundred previously known stars.

Proper motions have been measured for SDSS stars 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. The catalog will be published in late 2003, and is being used for studies of subdwarfs, white dwarfs, and carbon stars.

5. Precision Measuring Machine (PMM)

The public release of USNO-B1.0 occurred in September 2002. Since that time, copies of the catalog have been distributed to various astronomical data centers and other users. A general release was not done, and the plan is for USNO-B2 to be ready by the end of 2003. A paper discussing the USNO-B1.0 catalog appeared in the February 2003 issue of *The Astronomical Journal*.

The YB6 catalog is being prepared to support USNO-B2. It incorporates the yellow and blue astrograph plates, and uses 2MASS data to further remove systematic errors associated with photography. A general release of YB6 is not planned.

The PMM has scanned all major photographic survey plates and is now idle. Barring any compelling demands for the digitization of additional plates, it will be decommissioned.

Canzian has repeated the computation and checked the results of all star-galaxy classifications on all relevant plate material (POSS-I SO and SE, POSS-II SJ and SF, ESO-R, SRC-J, and AAO-R) for the USNO-B2.0 catalog. The classifications for USNO-B2.0 compare favorably with SDSS classifications (based on deeper, digital data). Classifications for the two surveys agree 85–95% of the time, depending on magnitude. The PMM classification data will be incorporated into the USNO-B2.0 catalog by D. Monet and S. Levine for release to the Air Force and to the public.

Levine continues to maintain the FS 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-B1.0 catalog is now available through this server, as well as from the major data centers.

As part of the ongoing vetting of the USNO-B1.0 catalog, Levine has been working to understand how well we have done in finding high proper motion stars. He finished gathering a sample of stars from USNO-B with proper motions between 1 and 5 arcsec/yr, and found 11 previously unknown objects.

Levine worked with A. Bosh (Boston U. and Lowell Obs.) using the USNO- B1.0 catalog to find stellar occultation candidates for the outer planets in the solar system.

6. Navy Prototype Optical Interferometer (NPOI)

USNO staff working on the project included J. Benson, D. Dodd, H. Dyck, N. Elias, C. Hummel and D. Hutter. Hutter continued as project manager for the USNO group. Elias left for employment elsewhere and Dodd was transferred to another project at the Flagstaff Station.

Personnel from other institutions who worked on the project included J. Armstrong, J. Clark, C. Gilbreath, R. Hindsley, J. Howard, D. Mozurkewich, E. Oh, R. Young, and T. Pauls from NRL. Mozurkewich continued in his position as project manager for the NRL group. From Lowell Observatory were K. Isbrecht, B. O'Neil, J. Shannon, W. Wack, and N. White. White acted as project manager for Lowell. Additional contract personnel included L. Ha and J. Walton from USRA and S. Nichols from Shriever AFB. Capt. C. Barry from the Naval Reserve also helped.

Observations using three or more telescopes continued on a variety of imaging projects this reporting year, including studies of H-alpha in Be star binary orbits. O'Neil and Wack continued as the telescope operators. Useful scientific data were obtained on 132 nights, resulting in 9,253 individual scans. On one notable night, observer Wack obtained a total of 206 scans, a new single-night record.

Four scientific papers were published in *The Astronomical Journal* during the year. These were ''The Effect of TiO Absorption on Optical and Infrared Angular Diameters of Cool Stars'' by H. Dyck and T. Nordgren (U. Redlands; ''An Observational Test of the Spherical Model Atmospheres for the M Class Giants: The Case of Delta 2 Lyrae'' by J. Sudol (NOAO), J. Benson, H. Dyck and M. Scholz (U. Heidelberg); ''First Observations with a Co-phased Six-Station Optical Long-Baseline Array: Application to the Triple Star Eta Virginis'' by C. Hummel, J. Benson, D. Hutter, K. Johnston, D. Mozurkewich, J. Armstrong, R. Hindsley, C. Gilbreath, L. Rickard, and N. White; and ''A Method for Internal Calibration of Optical Interferometer Data and Application to the Circumstellar Envelope of Gamma Cassiopeiae'' by C. Tyc-

ner (U. Toronto), A. Hajian, D. Mozurkewich, J. Armstrong, J. Benson, C. Gilbreath, D. Hutter, T. Pauls, and J. Lester (U. Toronto). The observations described by Sudol *et al.* represent a part of Sudol's Ph.D. thesis obtained at the NPOI. Those described by Tycner *et al.* represent a part of Tycner's Ph.D. thesis.

Five papers also appeared in print in February 2003 in the *Proceedings of the SPIE*, vol. **4838**. These were ''NPOI: A progress report'' by D. Mozurkewich, J. Benson, and D. Hutter; ''Interferometric measurements of stellar intensity profiles'' by M. Wittkowski (ESO) and C. Hummel; ''Simultaneous 6-station observations with the NPOI'' by J. Benson, C. Hummel, and D. Mozurkewich; ''Coherent integration using phase bootstrapping'' by C. Hummel, D. Mozurkewich, J. Benson, and M. Wittkowski; and ''Array metrology system for an optical long-baseline interferometer'' by D. Hutter and N. Elias. Elias also published a paper entitled ''Optical interferometric polarimetry'' in the *Proceedings of the SPIE*, vol. **4843**. Hummel presented a talk describing observations of Eta Virginis at IAU Colloquium No. 191 in Merida, Mexico in February 2003.

Two major new in-house construction projects were started in the reporting year. The largest project was the removal of the old periscope systems used to feed the incoming light from the array to the fast delay lines. These were replaced by new periscopes that allow the incoming light to be redirected into the long delay lines before passing to the fast delay lines. This will allow use of the maximum 440-m baselines available on the array. Work on the exchange was begun in September 2002 and finished in March 2003.

The second 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. The goal is to reduce baseline errors and to achieve the desired accuracy of 1 mas for astrometric observations. This system was prototyped during the reporting period and is now being tested using stellar observations and upgraded to its final status.

Large beam compressors for the four astrometric telescopes were designed and contracted to Nu-Tek Precision Optical. The vendor began fabrication on the first of these in January. Problems with the concrete piers in the array were solved through the use of an outside engineering firm to develop a plan for concrete repair work. A local concrete company completed the repairs in November. Work continued with the installation and alignment of the metrology system in the north astrometric telescope. N. Ohishi (Nat. Astron. Obs. of Japan) spent 3 months at the NPOI, funded by the Japanese Ministry of Education. During her visit, she worked with archival observations of the oblate star Altair. M. Wittkowski (ESO) also visited, and worked on coherent integration problems during his stay.

B. Photometry

1. Individual Objects

Henden was a co-PI on HST proposals to study the peculiar novae V838 Mon. Four epochs of observations were made, with the results reported in Nature. UBVRI monitoring of the nova and its light echo were performed with both the 40-in and 61-in telescopes during the entire period.

Henden observed the field of IM Peg in support of the Gravity Probe-B satellite. UBVRI photometry of all neighboring stars was performed with the 40-in telescope to search for variables; one eclipsing variable was found. Deep H alpha and [OIII] images were made to look for nebulosity. Test images were made with the 61-in telescope to see if the better seeing and decreased scattered light with that telescope would enable the study of stars closer to the target object.

Henden observed the secondary eclipse of the 3.5-yr period eclipsing variable OW Gem. This eclipse is only 0.1 mag in depth and takes place over a full month. A paper on this unusual binary was written and accepted by *The Astronomical Journal*.

Henden is working with P. Szkody (U. Washington) on the new cataclysmic variables discovered by the SDDS. Time-series photometry of all such candidates is in progress with the 40-in telescope. Three SDSS CV candidates were monitored during simultaneous XMM observations.

Levine worked with A. Bosh (Boston U. and Lowell Obs.) to observe the occultation of star P131.1 by Pluto, and the occultation of star TYC1310-02402-1 by Saturn. The aim is to learn more about the atmosphere of Pluto and the rings and atmosphere of Saturn. First results from the Pluto event appeared in Nature (Elliot et al., 2003).

Stone continues follow-up photometry of asteroids determined from the FASTT observing program to have large light variations. Light curves have been determined for eight of these objects, and surprisingly, many asteroids showing large light variations (amplitudes exceeding 0.7 mag) have very long periods (days instead of hours). Further observations are planned.

Vrba continued to participate in the international effort, led by W. Herbst and C. Hamilton (Wesleyan U.) to obtain photometry of KH15d, a young star located in NGC 2264 which undergoes an eclipse of circumstellar material once about every 48 days, likely from two areas of obscuration in an orbit of 96-day period. The intent of this year's photometric monitoring was to study color changes during the orbit. In all, 58 nights of multi-color optical observations were obtained at the USNO 40-in telescope. The observations showed no color changes over 3.5 mag of light variations, except for a slight bluing when the object is faintest. These results, when combined with spectroscopic results, are consistent with the extraordinary conclusion that we are observing a planetesimal-phase protoplanetary disk edge-on, with a weak stellar bipolar jet revealed when the star is apodized by the disk aggregations. The manuscript ''Fine Structure in the Circumstellar Environment of a Young, Solar-like Star: the Unique Eclipses of KH15d'' by W. Herbst, C. Hamilton (Wesleyan U.), Vrba, *et al.* will appear as a letter to the *Publications of the Astronomical Society of the Pacific*. Direct Hubble Space Telescope imaging is planned in the coming year.

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

Guetter, Vrba, Henden, and Luginbuhl completed a paper describing USNO efforts to densify and improve intermediate brightness JHK standard star values on the CIT photometric system, based on several years of IRCAM observations, which was published in *The Astronomical Journal*.

2. Star Clusters

Henden, in collaboration with R. Honeycutt (Indiana U.), monitored the open cluster NGC 6939 for several months, using the 40-in and 1.3-m telescopes of NOFS along with the 0.9-m telescope at KPNO. Many new variables have been discovered, but the enormous dataset will take time to fully process and analyze.

Stone continues to obtain photometry and astrometry of clusters with the 61-in Strand telescope in order to determine cluster memberships. Most of the first-epoch CCD frames have been taken, and the study includes extremely young clusters, intermediate aged clusters, very old Galactic clusters, and some globulars. Currently, there are 18 clusters in the observing program.

Vrba continued collaborations with V. Straizys, A. Kazlauskas (Vilnius Obs.), and R. Boyle (Vatican Obs.) to obtain Vilnius photometry of reddened stars in the Pelican Nebula, Collinder 428, and several other star formation regions using the Tek 2048 $\times$ 2048 CCD at the USNO 40-in telescope. This work also produced the first photometric parallaxes of reference stars in support of the USNO optical CCD parallax program.

3. Extragalactic Objects

Canzian worked on several research projects to study extragalactic objects. One project uses imaging data from the 61-in telescope to uncover previously unknown spiral structure in S0 disk galaxies that are misclassified as ellipticals. Telltale faint spiral structure in the S0 disk can be found at the level of a few percent perturbation in brightness. About 60 such galaxies with dubious elliptical classification are being observed for this project. Preliminary results indicate 40–60% of galaxies with dubious elliptical classification are indeed disk galaxies and have spiral structure.

Canzian is also using ASTROCAM on the 61-in telescope to image spiral galaxies in the K-band. Disk galaxies with multiple spiral arms are being studied to learn about differences between blue-light morphology and near-IR morphology. Stellar population, dust content, and star formation history probably all are factors influencing the differing optical and near-IR appearance of multiple-armed galaxies. Preliminary target selection is being done with the 40-in and the 1.3-m telescopes. Deep optical follow-up imaging of the galaxies observed with the 61-in is being obtained with the 40-in.

Henden observed many gamma-ray burst fields, discovering two optical transients as well as providing UBVRI calibration for over a dozen GRB fields.

The bright burst GRB030329 was extensively observed by Henden, Canzian, H. Harris, and Vrba, with photometry acquired over a 2-month period on nearly a daily basis. A paper on this GRB afterglow is in preparation. The gamma-ray burst team is collaborating with S. Klose's group at Tautenburg to study the afterglow. The photometric data are being analyzed to understand the gross physical characteristics of the burst as well as the photometric fine structure induced by the surrounding medium.

Henden also performed psf-fitting photometry for all images taken by the GRACE consortium on the afterglow for GRB030226, and for the JHK dataset from the VLT for the soft gamma-ray repeater field SGR0526-66.

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

C. Instrumentation

Canzian, M. DiVittorio, and Vrba participated in Science Definition Team meetings for the provisional 4-m telescope to be constructed in collaboration with Lowell Observatory. 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.

F. Harris worked with J. Geary (SAO) in the setup and testing of the FAME CCD test camera, and aided D. Monet with exchange of CCDs within the camera for radiation-damage tests. F. Harris worked with A. Rhodes to construct a replacement front with a window for the camera, allowing visual observations on the 61-in Strand telescope.

F. Harris removed from service CCD camera ND5, which had been used for photometric observations on the 40-in telescope. The camera suffered multiple electronic faults, to be repaired pending delivery of the array camera for the 1.3-m telescope. The anti-reflection coating on the face of the CCD has been damaged.

The 1.3-m telescope, built by DFM Engineering, has been operated with a SITe 2K $\times$ 4K CCD detector giving a 20 $\times$ 40 arcmin field, while a six-CCD mosaic camera is being completed. The telescope has been used this year for photometry of stars, galaxy morphology, searches for asteroids and for space debris in geosynchronous orbit, and tests of the astrometric accuracy.

Stone continues to develop software for the USNOFS 1.3-m telescope. A study of CCD frames taken on different nights and reduced to the UCAC2 star catalog shows accuracies of $\pm$35 mas in each coordinate. An improvement in accuracy is expected when the focal-plane errors are calibrated and removed from the reductions.

F. Harris continued design and testing of circuitry to support the array camera for the 1.3-m telescope. Camera-head circuits were completed, and work continued to implement all features of the electronic interface between camera head and data computer. Dodd assisted F. Harris with completing several sub-assemblies for the 1.3-m telescope CCD array camera and other CCD projects. These sub-assemblies included a new FIFO CCD controller board to replace existing non-FIFO controller used on the 40-in telescope and a camera interface box to allow new-style array CCD camera system to be operated using the old-style electronic controller at the 1.3-m telescope.

F. Harris researched the impact to FS of a proposed AT&T cell-phone tower, to be located 1.0-mile line of sight to the 61-in Strand and 40-in Ritchey telescopes. A test apparatus was constructed using the single-CCD camera for the 1.3-m telescope, and taken to the proximity of an existing AT&T facility in downtown Flagstaff. No unambiguous detection of interference to the CCD camera was found, and he reported on his results to staff and the County zoning board. The cell tower was defeated by the zoning board due primarily to property-value concerns of adjacent private landholders, and due to FS concerns that the tower's ''fall zone'' could completely block the sole access road to FS.

Henden and Munn spent a fair amount of time improving the observing efficiency of ASTROCAM. Henden interfaced with Munn's new telescope commands to provide automatic acquisition of guide stars, robotic movement of the telescope to park and flatfield positions, control of the guide camera, opening and closing of the dome slit, etc. The ultimate goal of this effort is to fully automate ASTROCAM observations.

The partnership of USNO, NOAO, and NASA/Ames to build 2048 $\times$ 2048 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 motherboard packaging concept that allows close buttability for 2 $\times$ 2 mosaic applications. To date, four complete hybrid modules have been fabricated, with good cosmetics. During the year, the readout multiplexer was slightly redesigned to improve yield. Several more devices are to be built in the coming year using the new readout. The paper ''Orion: A 1-5 Micron Focal plane for the 21st Century,'' describing the Orion project status, was presented at the 2002 Waikoloa, HI SPIE meeting, authored by A. Fowler, K. Merrill, J. Ball (NOAO), Vrba, Henden, and C. McCreight (NASA/Ames).

Also given at the Waikaloa, HI SPIE meeting was a paper describing the design and performance of the ASTROCAM imager used in the infrared parallax program, ''ASTROCAM: An Offner Re-imaging 1024 $\times$ 1024 InSb Camera for Infrared Astrometry on the USNO 1.55-m Telescope'' (Fischer et al., 2003).

D. Theoretical Studies

Levine is working on a project to determine the distribution of mass in a possible halo for the LMC using number counts derived from the USNO-A 2.0 catalog. The initial results of this work show that the center of the possible LMC halo is misaligned with respect to the center of the bar, and almost coincides with the centroid of the planetary nebula population. The putative halo also shows little if any of the tidal distortion that might be expected given the LMC proximity to our Galaxy.

Levine is working on building self-consistent models for temporally periodic potentials. This is an extension of the basic idea pioneered by Schwarzschild (1979), and the aim is to help us to understand better asymmetric galaxies.

Levine is 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.

E. Other Scientific Studies

Henden presented an invited paper on the status of ground-based photometry at a GAIA conference. He gave a workshop on CCD photometry at the IAPPP annual meeting in California.

D. Monet is part of the Pan-STARRS Science Team and the LSST Science Working Group. Activities this year included attendance at several meetings as well as preparing various papers supporting astrometry in general, and how it drives the requirements in particular.

D. Monet worked on USNO's AMEX satellite project. Issues included CCD testing as well as obtaining transmission-grating spectra to test the photometric scheme.

Pier and Levine have been involved with the National Virtual Observatory (NVO) effort. Part of the aim is to make sure that the USNO data products (e.g. USNO-B catalog, and PMM image data) are compatible with the emerging NVO framework. 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.) on photometric monitoring of GPS satellites. The resultant B-, V-, R-, and I-band lightcurves as a function of Sun-observer-GPS phase angle are fit to models of reflected light specularity in order to understand surface degradation. Observations of numerous Block II and IIA satellites show that the satellites' surface reflectivities decrease at a rate of about 10%/yr. Similar observations are now concentrating on the newer Block IIR spacecraft. Vrba attended the joint American Aeronautical Society/American Institute of Aeronautics and Astronautics meeting on Space Flight Mechanics at Ponce, Puerto Rico, where he presented the talk ''Brightness Loss of GPS Block II and IIA Satellites on Orbit.'' A. Chaudhary (Applied Optics Corp.) has been working on refined modeling of the lightcurves that takes into account shadowing and the exact aspect angle of the space vehicle at the time of observation. His work seems to be the next step in understanding the photometric results and he was asked to join our team.

F. Miscellaneous

Canzian regularly presents several lectures each year for the NAU Elder Hostel program. Canzian conducts tours for drop-in visitors, for National Guard reservists visiting Camp Navajo, and for students participating in the MIT Space Camp, hosted by J. Elliot (MIT). He also conducted tours for University of Redlands summer astronomy students hosted by T. Nordgren.

Upon the retirement of Harry Guetter, A. Monet was asked to take on greater responsibility for E/PO, which had been one of Guetter's tasks. For the most part, this has meant giving visitors tours of the facilities, but has included some special events as well. In September 2002, she was elected to the Board of Directors of the Flagstaff Festival of Science.

VII. GENERAL

S. Dick (AA) published his history of USNO, *Sky and Ocean Joined: The U.S. Naval Observatory, 1830-2000*

(Cambridge University Press, 2002. The book received the John Lyman Award of the North American Society for Oceanic History for best book in 2002 in Science & Technology. Dick received USNO's Captain James Melville Gilliss Award for extraordinary dedication and exemplary service. He is also the author (with James Strick) of the forthcoming volume: The Living Universe: NASA and the Development of Astrobiology (Rutgers University Press). Dick has authored more than 100 publications, including: Plurality of Worlds: The Origins of the Extraterrestrial Life Debate from Democritus to Kant (Cambridge University Press, 1982); The Biological Universe: The Twentieth Century Extraterrestrial Life Debate and the Limits of Science (Cambridge University Press, 1996); and Life on Other Worlds (1998), the latter translated into four languages. He was also editor of Many Worlds: The New Universe, Extraterrestrial Life and the Theological Implications (2000).

Dick is on the Editorial Board of several journals, including the Journal for the History of Astronomy, and is an associate editor of the International Journal of Astrobiology. He was Chairman of the Historical Astronomy Division of the AAS (1993-1994) and President of the History of Astronomy Commission of the IAU (1997-2000). He is President-elect of the Philosophical Society of Washington.

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