A Decade in Time: The Advancement of the APL Time and Frequency Laboratory

Mihran Miranian, Richard A. Dragonette, and Gregory L. Weaver

The APL Time and Frequency Laboratory (TFL) has been in continuous operation since its establishment under the Transit program in 1959. The primary function of the TFL's hardware, then as it is today, is to provide time and frequency reference signals to APL facilities. Since 2002, the hardware architecture of the TFL has been upgraded to achieve the following implementation goals: autonomous operation with high reliability and little or no regular operator attention required; continuous improvement in the accuracy and precision of Laboratory-wide distributed clock signals; isolation of the atomic standards from user load effects via the signal distribution system; and provision of a mechanism for real-time external calibration of TFL timing signals. The upgraded TFL maintains customer signal reliability and quality through electrical isolation between signal distribution channels, redundant signal sources, and a robust distribution system that includes both redundant transmission lines and fiber optic interconnections, eliminating induced noise during signal transmission. This article discusses the TFL's history, current methods used in operation, and the changes brought about by the last 10 years of upgrade activity.

INTRODUCTION

For more than 50 years, the APL Time and Frequency Laboratory (TFL) has determined, maintained, and distributed precise time and frequency reference signals in support of APL sponsors' critical mission needs. This role began during the infrastructure deployment of the Navy/APL Transit program, when it was apparent that there was a need for precise timing to support the world's first global satellite navigation system. Since then, the TFL has played an important role in support of APL's emergence into U.S. strategic space programs and global force projection. This support role includes integration and testing of flight hardware, provision of frequency references for spacecraft ranging and communications, time-stamping of ground receipt telemetry packets, and the research and development of time and frequency devices and distribution systems.

An extensive TFL hardware upgrade was initiated in 2002. Changes were implemented gradually to spread out the costs of the upgrade and to avoid any interruptions in TFL services as improvements were being made. By the time the effort was concluded in 2012, the TFL had been relocated to a new facility (see Fig. 1), the primary atomic frequency standards had been upgraded to current commercial technology, the signal distribution system was nearly entirely replaced by more robust technology, and the precision and accuracy of the UTC(APL) clock signal was improved by a factor of 10 over that which existed in 2002. UTC(APL) is the official designation for the time reference signal maintained by the TFL and is traceable to the international atomic time standard Coordinated Universal Time (UTC). UTC(APL) is now routinely maintained to within 10 ns of UTC.

During these last 10 years of upgrades to its facilities, the TFL has also advanced its international importance through contributing to the formulation of International Atomic Time (TAI). The TFL's atomic clocks are included in the ensemble with atomic clocks from other timing laboratories worldwide to determine TAI and UTC at the Bureau International des Poids et Mesures (BIPM). The TFL maintains traceability to the BIPM, the National Institute of Standards and Technology (NIST), and the U.S. Naval Observatory (USNO) via Global Positioning System (GPS) time transfer.

ROLE OF TIMEKEEPING AND FREQUENCY DISTRIBUTION AT APL

Historical Basis for the APL TFL

The existence of an internationally traceable timekeeping and precise frequency distribution facility for a laboratory as expansive as APL may seem self-evident to most of our colleagues on campus. But in fact, the extent and quality of the APL TFL is unique among institutions in the United States, and even throughout the world.

Today we often take for granted the enabling utility provided by immediate access to world coordinated time and precise frequency. We routinely navigate, record the dynamics of events, and make discerning measurements of electromagnetic phenomena through local access to services such as GPS and Network Time Protocol. In this manner, we can underestimate this dependency and the fundamental need for sources of time and frequency service that can be trusted as immutable to corruption and interruption from uncontrollable externalities, thereby providing a local independent reference for calibration and traceability. The TFL at APL establishes this role as an independent time and frequency source through the distribution of services we describe in the following sections of the article. The evolution of the TFL's capabilities stretches back to the 1960s when traceable time and precise frequency distribution was not a commodity. The call for the establishment of a local time and frequency facility at APL, in fact, originates from our groundbreaking impact on our nation's strategic space program and ship-based ballistic missile program, when no such global distribution existed.

Transit, SATRACK, and Centralized Ground Station Timekeeping for Satellite Navigation

The history and national contribution of APL's Transit and Satellite Tracking (SATRACK) programs have been deservedly archived within the *Johns Hopkins APL Technical Digest* over many decades in the form of, for example, contributions from distinguished APL fellows such as Thomas Thompson[1] and Lauren Rueger.[2] In their recounts, Thompson and Rueger describe how the discoveries leading to space-based radiometric navigation fit immediately into the strategic use of long-range ballistic missiles and global force projection by the U.S. Navy and Air Force.

Figure 1. APL staff members setting their watches and portable timekeeping devices.

Figure 2. Transit float parading past John F. Kennedy at the 1961 inauguration.

Essential to the operation of the Transit global satellite-based navigation was the dissemination of coordinated time, traceable to the USNO and NIST (then the U.S. National Bureau of Standards), to far-reaching tracking stations built across the world. The Transit operation concept of satellite navigation required a centralized processing system that could estimate periodic ephemeris and onboard clock errors and then inject corrections during satellite passes over a master control station. These operational requirements were realized by the installation of the APL Satellite Communication Facility, with its 18-m antenna so prominent on the APL campus, and our first ensemble of cesium beam atomic clocks that ultimately led to the establishment of the APL TFL.

As the success of Transit, which remained operational until 1996, led to the next generation of satellite-based navigation known as GPS, APL applied its expertise in satellite-based navigation in the mid-1970s to the problem of in-flight tracking of submarine-launched ballistic missiles (SLBMs). The resulting system, known as SATRACK (Fig. 3), uses the translation of GPS signals recovered from the in-flight SLBM through an S-band telemetry link transmitted by the SLBM to ground station receivers.[3] The data recorded from the S-band telemetry are sent on for the postprocessing of SLBM tracking and the estimation of guidance control errors. The utility of SATRACK and development of global navigation satellite signal technology in highly dynamic applications remains a core interest of the Global Navigation Satellite System (GNSS) & SATRACK Systems Group within APL's Force Projection Department, which is a principal user of the TFL's precision frequency and timekeeping service.

Along with maintaining the timekeeping needs of the Transit central processing system, the TFL's role in advancing satellite oscillator technology was brought forward as an integral part of the program. In the early 1960s, the state of space-based electronics, specifically quartz crystal oscillators, was undeveloped, and the success of Transit was highly dependent on the frequency stability and reliability of the onboard oscillator. Then, as now, immediate access to the TFL's atomic clocks, with frequency stability performance traceable to the nation's best standards, provided the development reference sources that led to a continuing succession of oscillator frequency stability improvements. This progress of stability improvement has maintained a course of an order of magnitude improvement per decade, realized in today's APL ultrastable oscillator (USO), which can provide onboard frequency stability approaching less than 0.1 parts per trillion over decades of in-flight service, evidenced by several of the most recent USO

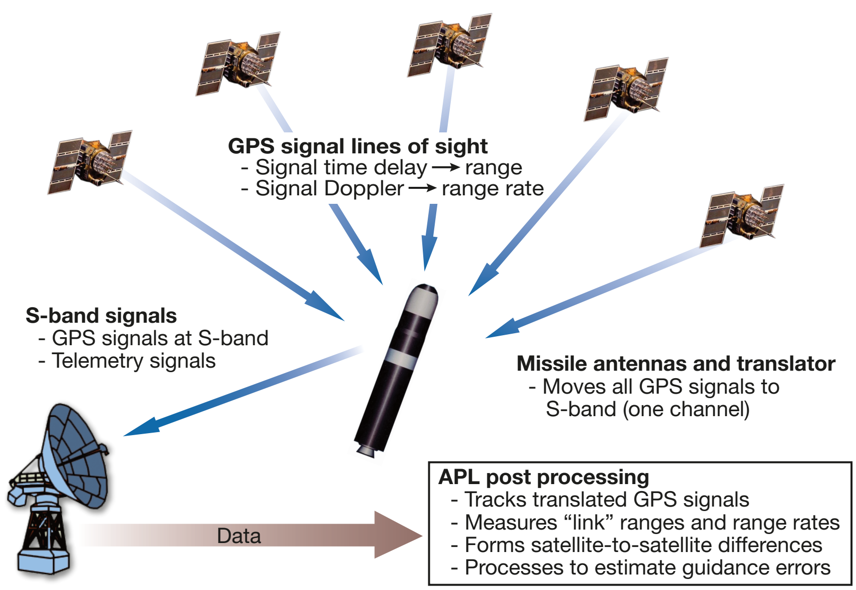

Figure 3. SATRACK signal management diagram.

developments for the NASA New Horizons, Gravity Recovery and Interior Laboratory (GRAIL), and Gravity Recovery and Climate Experiment Follow-on (GFO) projects. Recently, the TFL's role in APL internal research on oscillator development and timekeeping performance verification has been applied to the advent of microatomic clocks, such as the chip-scale atomic clock.[4]

Over the last 10 years, APL's investment in TFL equipment, algorithms, and time transfer quality for enhanced traceability has begun to meet the challenge of mitigating compromised operations under contested GPS and adverse ionospheric conditions from the recent escalation of space weather.[5] The development of an autonomous APL timescale algorithm, created from the ensemble of hydrogen maser and cesium beam atomic clocks to monitor and steer the TFL master clock, maintains the accuracy of UTC(APL) with independence from GPS anomalies.[6] From a resilience aspect, the TFL's time transfer using common-view GPS between the geographically disperse USNO in Washington, DC, and the NIST facility in Boulder, Colorado, nonetheless provides a routine check against any short-term anomalies in atomic clock behavior that may occur from time to time. Finally, because the USNO and APL share the same horizon, local perturbations in the ionosphere, from space weather phenomenon such as scintillation, can be discovered and handled through the differential viewpoint of GPS at NIST in Boulder, Colorado.[7] As the facilities of the APL TFL continue to expand, APL can look forward to supporting next-generation photonic-linked time and frequency transfer, perhaps over distances as far as the USNO.

UTC(APL) AND APL TIMESCALE OPERATION

Key to the upgrade of TFL facilities over the last 10 years has been the procurement of three hydrogen masers and several cesium beam frequency standards, such that the TFL now has sufficient capability to maintain ±10 ns accuracy to UTC. To enhance the support of this accuracy to UTC, we have established an autonomous timescale algorithm to monitor our clock ensemble and aid in the prediction of UTC(APL) used in the frequency steering of the master clock output.

The APL Atomic Clock Ensemble

The APL atomic clock ensemble consists of three hydrogen masers and three high-performance cesium beam frequency standards. These clocks provide precise time and frequency signals in support of critical APL projects, which include integration and testing of flight hardware, frequency references for spacecraft ranging and communications, time-stamping of ground receipt telemetry packets, and the research and development of time and frequency devices and distribution systems.

The clocks are also used to formulate the APL timescale, a weighted frequency average of all the clocks in our ensemble. No two physical clocks run at the same rate. It is often said, "A man with one clock always knows what time is, but a man with two clocks never knows what time it is." Therefore, the contributing clocks to the timescale are all normalized to have the same rate before the frequency average is calculated. Normalizing the clocks also prevents frequency changes in the timescale when a clock is added or removed. This gives the timescale more stability than any of the other contributing clocks, and it can be used to evaluate the performance of the each clock in the ensemble (see Fig. 4). The phase offset of each clock is measured against UTC(APL) every second, and the data are stored in our clock database. This is necessary because we must continually monitor each clock to detect frequency changes that might affect the support to our users and the computation of the timescale.

Realization of UTC(APL)

TAI is a uniform timescale derived by the BIPM as an ensemble of hundreds of atomic clocks from

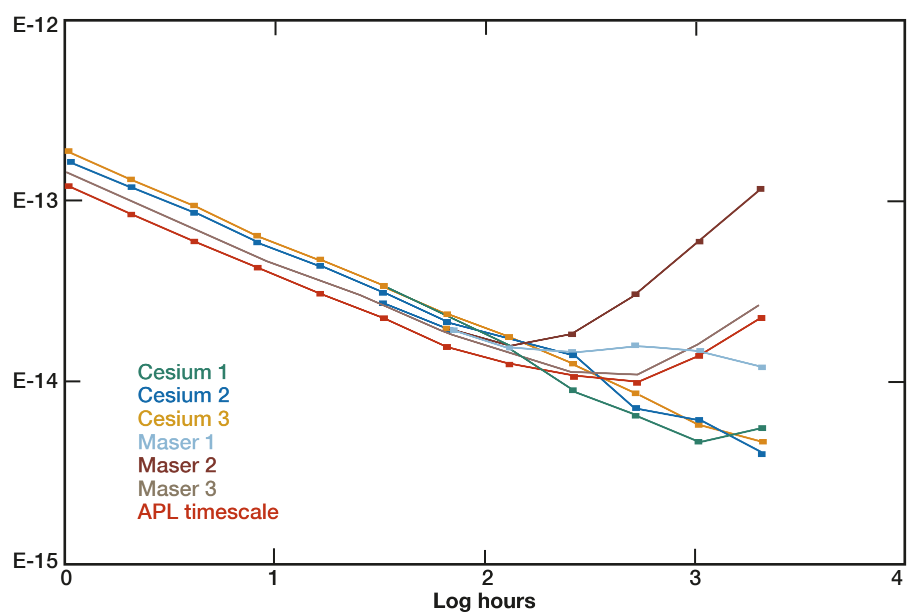

Figure 4. Performance of APL's ensemble of contributing clocks against timescale.

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BUREAU INTERNATIONAL DES POIDS ET MESURES
ORGANISATION INTERGOUVERNEMENTALE DE LA CONVENTION DU METRE
PAVILLON DE BRETEUIL F-92312 SEVRES CEDEX TEL. +33 1 45 07 70 70 FAX. +33 1 45 34 20 21 tai@bipm.org

1 - Coordinated Universal Time UTC and its local realizations UTC(k). Computed values of [*UTC-UTC*(*k*)] and uncertainties valid for the period of this Circular. From 2012 July 1, 0h UTC, *TAI-UTC* = 35 s.

Date 2013 0h UTC	FEB 26	MAR 3	MAR 8	MAR 13	MAR 18	MAR 23	MAR 28	Uncertainty/ns			Notes
MJD	56349	56354	56359	56364	56369	56374	56379	u_A	u_B	u	
Laboratory *k*				[*UTC-UTC*(*k*)]/ns							
AOS (Borowiec)	-10.9	-11.5	-11.8	-11.7	-10.9	-9.0	-7.2	0.3	5.2	5.2	
APL (Laurel)	-2.5	-3.7	-4.5	-4.0	-1.9	-1.5	-1.8	0.3	5.2	5.2	
AUS (Sydney)	406.1	405.2	403.7	402.8	401.0	407.0	414.9	0.3	5.2	5.2	
BEV (Wien)	-48.3	-36.5	-31.2	-21.9	-15.1	-4.6	5.5	0.3	3.4	3.4	
BIM (Sofiya)	91.4	91.6	108.6	116.1	120.8	127.8	144.8	1.5	7.2	7.3	
BIRM (Beijing)	216.8	221.9	220.3	221.7	226.2	219.9	223.3	1.5	20.1	20.1	
BY (Minsk)	-27.5	-24.1	-25.5	-31.6	-38.3	-	-	1.5	7.2	7.3	
CAO (Cagliari)	-	-	-	-	-	-	-				
CH (Bern-Wabern)	13.6	19.3	14.5	8.6	4.5	3.2	0.1	0.3	1.8	1.9	
CNM (Queretaro)	-10.2	-9.4	-7.5	-10.1	-13.7	-14.1	-16.6	2.0	5.2	5.6	

Figure 5. Section of the monthly BIPM report showing UTC(APL) listed among the world's contributing laboratories.

laboratories all over the world. Time and frequency laboratories that contribute atomic clock data to the formulation of TAI must have an official time reference, which acts as a common reference to all of the clocks at the laboratory. This common reference can then be used to transfer clock data from each clock at the laboratory to the BIPM. UTC(APL) is the official time reference of the TFL, and it is traceable to UTC via GPS time transfer. UTC is a nonuniform timescale that is adjusted to compensate for the variations of the rotation of the Earth by adding or subtracting leap seconds, as is UTC(APL). UTC differs from TAI by an integer number of seconds and is the time reference used for most timing purposes.

Steering UTC(APL) to UTC requires that we know the phase and frequency offset of UTC(APL) referenced to UTC at the time of the steer adjustment. However, these data are not available because the monthly report (*Circular T*, Fig. 5) from the BIPM, which reports the offsets of all the laboratories that contribute clock data, is at least 10 days in arrears and grows to 40 days until the next report. Therefore, we must have a method to estimate our daily offset of UTC(APL) by coordinating the performance of the APL master clock to the latest BIPM report. A daily estimate is derived by an algorithm developed at APL that uses the historical performance of the master clock from the *Circular T* reports and its current performance when compared with the APL timescale.[8] On the basis of the estimate, a new frequency offset is determined and sent to the high-resolution offset generator to steer the master clock.

The master clock signal originates as the 5-MHz output of APL hydrogen maser no. 1, which has been designated out of the six available ensemble clocks to be the APL master clock. The 5-MHz signal is then passed through the high-resolution offset generator where the frequency can be advanced or retarded to steer the master clock's phase to UTC. The high-resolution offset generator converts the adjusted 5-MHz to a one-pulse-per-second (1PPS) signal, which is the measurable realization of UTC(APL). Our goal is to maintain UTC(APL) to within ±10 ns of UTC. Figure 6 shows the performance of UTC(APL) before and after the installation of the high-resolution offset generator and our move to the new laboratory in Building 200. In both instances, the performance of UTC(APL) was significantly improved. The epochs of Fig. 6 are given by the Modified Julian Date (MJD), which is a continuous day count used by the scientific community to simplify date interval recording. APL is one of only four laboratories in the United States and the only nongovernment laboratory that contributes clock data to the definition of TAI (Fig. 7). The TFL monitors the time of two of the other U.S. contributing laboratories, UTC(USNO) maintained by the USNO and UTC(NIST) main-

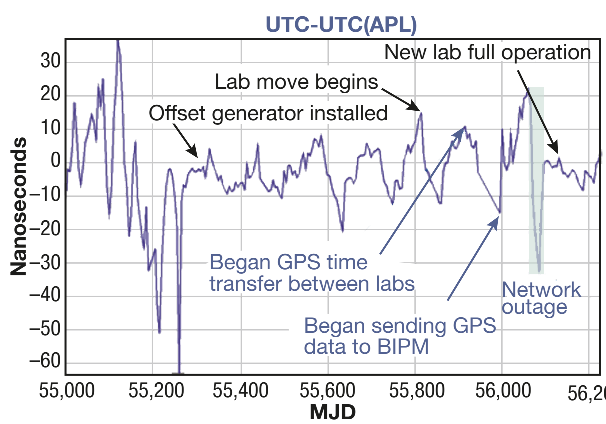

Figure 6. Timekeeping of UTC(APL) from June 2009 to October 2012.

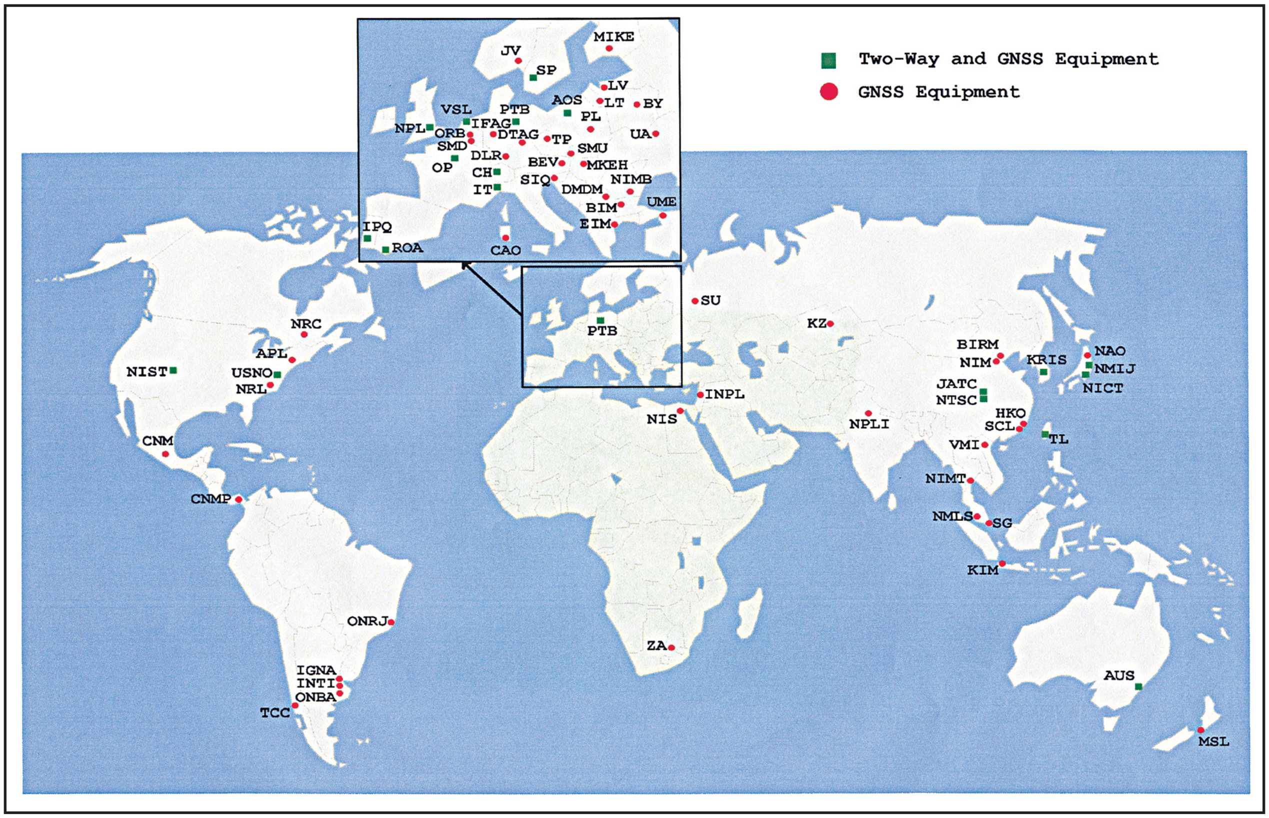

Figure 7. Locations of laboratories around the world that contribute to TAI, which is determined by the BIPM.

tained by the NIST in Boulder, Colorado, via GPS time transfer. Although the TFL maintains traceability to UTC(USNO) and UTC(NIST), it is noteworthy that it operates completely independent of these laboratories with regard to steering UTC(APL) to UTC.

THE 2002–2012 UPGRADE OF THE TFL OPERATIONS

Overview of the TFL in the Early 2000s

In 2002, the TFL was providing high-quality timing signals to APL customers, although the technology deployed was aging. Figure 8 is an annotated photograph of the TFL in 2002. The cesium atomic clocks, GPS common view time transfer receivers, and other hardware used to distribute TFL timing signals throughout APL are visible in the figure.

In 2002, the primary atomic standards were three APL-designed and -built NASA Research hydrogen masers (shown in Fig. 9), which had been operational for more than 20 years. Secondary atomic standards were a mix of state-of-the-art circa 2002 cesium clocks and older-generation models. The NASA Research masers provided APL customers with 5- and 10-MHz reference signals with exceptional phase noise and short-term stability characteristics not found in commercially available atomic standards. The cesium standards provided long-term stability for timing signals such as 1PPS and IRIG-B clock signals.

Signal distribution included 1-, 5-, and 10-MHz reference frequency signals and 1PPS and IRIG-B timing signals. APL users included the Dual Precision Clock System (DPCS) program, the Midcourse Space Experiment (MSX) and Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite programs, SATRACK, and APL Space Department facilities. Signals were distributed via a combination of coaxial and fiber optic cables. Fiber optic lines were used for longer signal runs between buildings. Signal distribution via RF coaxial cable was supported by high-isolation distribution amplifiers that were a combination of commercial and APL-designed and -built units. The APL amplifiers were designed and built in the 1970s and 1980s and have been in continuous operation since that time.

Fiber optic signal distribution was enabled via a partnership between the APL TFL and a local commercial vendor to develop custom analog fiber optic transmitters that did not modulate the analog input signals. The fiber optic systems became operational in the early 1990s, and many of these transmitters are still in use today. LED transmitters were used in combination with multimode optical fibers. Fiber optic signal transmission had the advantage of providing immunity from noise induced in

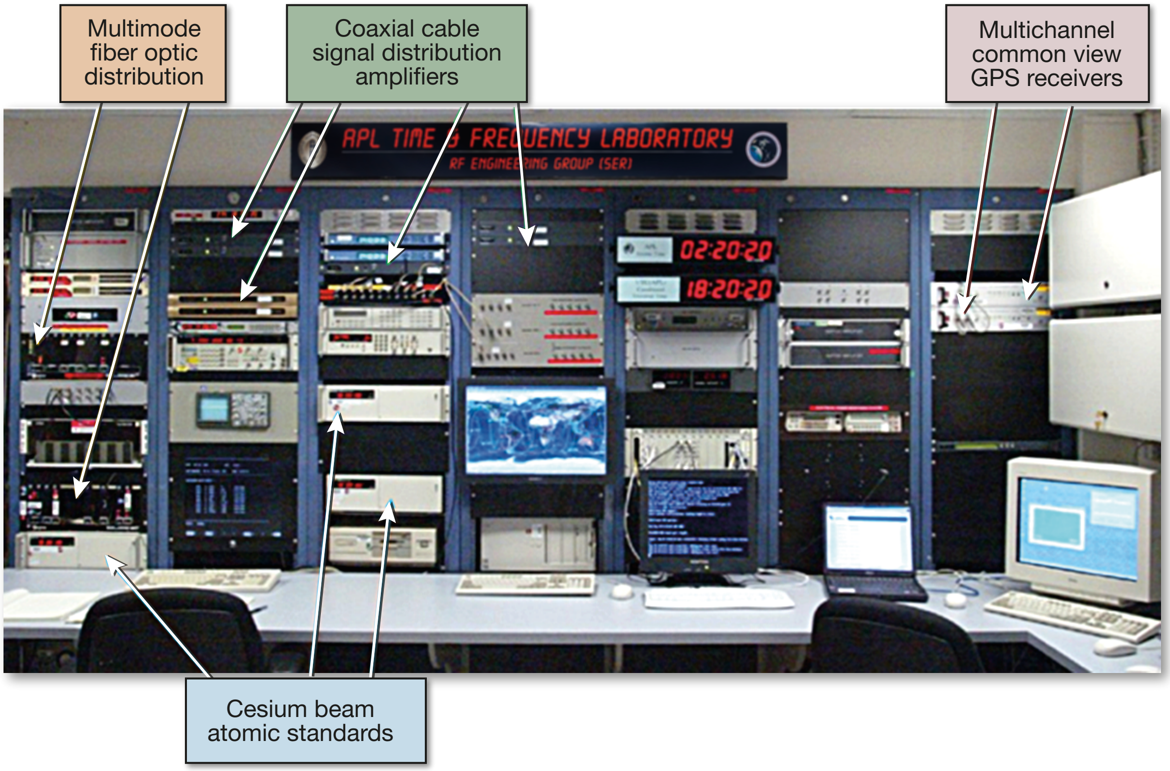

Figure 8. APL TFL circa 2002.

the transmission lines by power cables routed along the same interbuilding cableways as TFL signal cables.

APL TFL timing signals were calibrated via GPS common-view clock comparisons against time standards at NIST and USNO. Before 2002, single-channel common-view GPS receivers were used to record GPS data from one GPS satellite at a time according to a schedule provided by the BIPM. Because the GPS receivers had only a single tracking channel, care had to be taken to ensure that data were recorded simultaneously at the TFL and at NIST (and USNO) on the same GPS satellite.

Between 2000 and 2002, a new generation of multichannel GPS common-view receivers became available that allowed the TFL receiver to simultaneously track all GPS satellites in view. Two multichannel receivers were installed and became operational late in 2002. This advancement provided a much larger data sample size to improve the accuracy of the TFL's GPS common-view time transfer. With the single-channel receiver, up to 15 satellites were tracked on any given day, whereas with the multichannel receiver, up to eight GPS satellites could be tracked at one time.

Overview of the TFL Hardware Today

The TFL of today is nearly a complete technology upgrade of the facility that existed in 2002. Figure 10 shows a photograph of the laboratory. To avoid interruptions in service, and to remain within budgetary requirements, the evolution of the TFL has been gradual over the past 10 years. The laboratory itself has been relocated from its original location in Building 4 to the current facility in Building 200. The ensemble of

Figure 9. APL-designed and -built NASA Research masers.

Figure 10. Photo composite showing the new laboratory through the bay window, the clock vault showing the masers, and the clock measurement system.

atomic standards has been upgraded with new hydrogen masers, and the signal distribution system has been updated with next-generation fiber optic equipment. The common-view GPS equipment has been replaced with a third-generation GPS receiver, allowing even greater improvement in the calibration of TFL timing signals.

The most outwardly noticeable change in the TFL is its location and addition of a clock vault. The facility was previously located in the same room in Building 4 for more than 30 years. The first phase of the hardware migration from the old to the new location began in September 2011. During the first phase, a single-string laboratory was set up in Building 200 using a combination of new equipment and existing redundant equipment. This created a fully functional laboratory that lacked redundancy and a still somewhat redundant laboratory in Building 4. Both facilities were operated in parallel until it was established that the new facility in Building 200 met expectations.

Early in 2012, phase two of the move, which involved moving all the atomic standards and nearly all the other remaining equipment into the new facility, was completed. Only a small repeater station was left in Building 4, which contains distribution amplifiers and fiber optic transmitters to maintain TFL signal links to customers that have direct fiber optic links from Building 4

Figure 11. Building 4 signal repeater station.

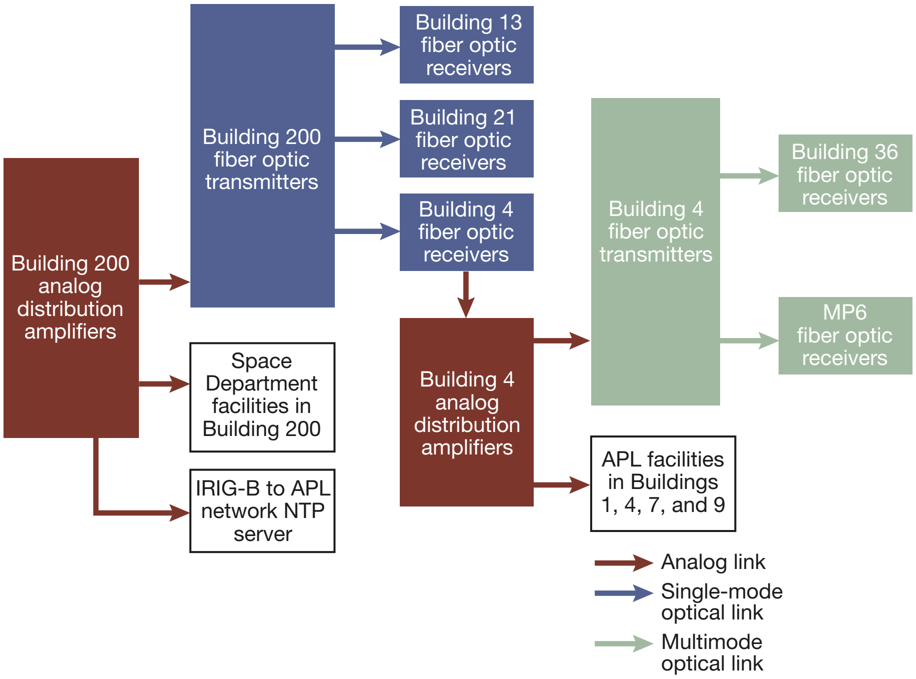

Figure 12. APL time and frequency signal distribution network.

to their facility. Figure 11 shows the current repeater station in Building 4.

Currently the TFL operates an ensemble of six commercial atomic frequency standards, including three hydrogen masers and three cesium clocks. One maser was procured annually from 2002 through 2004 to allow for the 12 months required to manufacture and calibrate each new maser. The other three standards are commercial cesium clocks that have been in operation since 2002.

Because they are sensitive to changes in environmental conditions, the atomic standards are housed in a clock vault room adjacent to the main TFL room. The vault has limited personnel access and a dedicated air-handling system that controls temperature to within ±1°F and relative humidity to within 5%. Installation in the vault room has led to substantially improved noise performance from all the atomic standards over that previously observed. Temperature and humidity are also controlled in the main laboratory room, but with a more relaxed allowable temperature and humidity range than the clock vault.

Timing signal distribution is accomplished using all COTS hardware that has been procured gradually over the last decade. Figure 12 illustrates the current TFL signal distribution network. Primary signal distribution includes 5-, 10-, and 100-MHz reference frequency signals and 1PPS and IRIG-B timing signals. A combination of coaxial cables connected to distribution amplifiers for customers within Building 200 and fiber optics for users located elsewhere are used for signal distribution. Users include APL USO development; the TIMED, MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER), Solar TErrestrial RElations Observatory (STEREO), Van Allen Probes, and New Horizons satellite programs; SATRACK; and Space Department facilities in Building 200. Timing signals are distributed to Buildings 4, 7, 9, 13, 21, and 36, MOD6, and MP6 on the APL campus.

All fiber optic signal links originating from the TFL consist of single-mode optical fibers connected to transmitters generating intensity-modulated laser optical output. Single-mode fiber, which has much lower loss than multimode fiber, is used because of the long distances (>1 km in some cases) between Building 200 and the end users. This combination of hardware has substantially improved transmitted signal quality over that observed using the older multimode equipment. A timing signal from the master clock is provided to APL Network Time Protocol servers, which distribute APL Atomic Time over the network to the digital time displays at numerous locations about APL, and for synchronization of computers connected to the APL network.

The all-in-view single-frequency GPS receivers added in 2002 have been replaced by a newer generation of dual-frequency receivers that allow the measurement of the ionospheric delay of the GPS signals, which improve the ability to resolve the true time difference between the satellite and the receiver. The new receivers also make it possible to use GPS Precise Point Positioning and carrier phase time transfer to improve the measurement of the time difference between metrology laboratories. Daily GPS time transfer is performed against references from both the USNO and NIST as a quality check of the performance of UTC(APL).

SUMMARY AND FUTURE OUTLOOK

The move to the new APL TFL was carried out successfully, with no adverse impact on APL users and minimal disruption in our contribution to the formulation of TAI. This was accomplished by maintaining two laboratories during the transition and by following a three-phase plan, which was accomplished with only a few setbacks. The clocks were moved while powered to minimize start-up time and frequency drift. We now have a controlled environment clock vault, which improves the stability of our clocks and the maintenance of the APL timescale. This will also improve our ability to estimate the difference between UTC and UTC(APL) for the purpose of steering to UTC. The uncertainty of UTC(APL) in time transfer with the BIPM has improved from 1.5 ns to 0.3 ns; this improvement is attributable to the new GPS receiver/antennae installation in Building 200 that allows the use of GPS Precise Point Positioning time transfer. After more than 50 years of service to space missions operation from the old TFL, the new TFL will now begin a new era in timekeeping for the enhanced requirements of future space and national security programs.

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The Authors

Mihran Miranian joined the Senior Professional Staff in 2003 and works within the RF Engineering Group of the Space Department. He is a time and frequency analyst and is in charge of the operation of the TFL. In 2003, he retired from the USNO, where he was the Deputy Director of the Time Service Department. **Richard A. Dragonette** is a member of the Senior Professional Staff and is currently a project manager in the Force Projection Department. He has also served as the TFL Hardware System Engineer since 1989. Mihran and Richard have worked in tandem over the last 10 years to achieve the current capabilities of the TFL. Mihran has principally worked on the algorithms and automation required to maintain UTC(APL), while Richard has overseen the design, integration, operation, and maintenance of TFL's hardware systems and distribution system. **Gregory L. Weaver** is a member of the Principal Professional Staff and also works within the Space Department's RF Engineering Group. He is a technologist with extensive background in the frequency control industry and has held positions as a senior design engineer, technical manager, and marketing strategist during his 30-year career history. Gregory has led the majority of USO developments since 2003. He routinely assists in the evaluation and research for improved TFL operations and has contributed with Mihran and Richard on many publications regarding the TFL and its capabilities. For further information on the work reported here, contact Mihran Miranian. His e-mail address is mihran.miranian@jhuapl.edu.

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