Master Clock and Time Distribution System for the NASA Deep Space Network: Part I

R. L. Tjoelker,[1] M. Calhoun,[1] P. F. Kuhnle,[1] J. Lauf,[1] and R. L. Sydnor[1]

Local generation and distribution of precise, accurate, and stable time and frequency reference signals comprise an essential and central component of the NASA Deep Space Network (DSN). Within each complex, synchronized timing references are required by approximately 100 users located at distances up to 30 km from the central control center and station master clock. In this article, the first of two parts, a highly modular, hot-swappable, and expandable system design for generation, delivery, and synchronization of highly precise and stable timing signals over fiber-optic cables is described. The new timing system is now operational at all three DSN sites—Signal Processing Center 10 (SPC 10), SPC 40, and SPC 60—as well as Cape Canaveral's MIL-71, the DSN Development and Test Facility 21 (DTF-21), and at several JPL development laboratories. Performance tests and operational experience will be reported in Part II.

I. Introduction

The generation, calibration, and synchronization of timing signals is central to space navigation and tracking activities in the NASA Deep Space Network (DSN). The DSN provides a unique capability with extraordinary sensitivity for tracking spacecraft within and beyond the solar system and detecting very weak natural radio emissions from the far reaches of the universe. The network consists of numerous ground-based antennas and associated high-performance systems requiring a highly precise and stable frequency and timing subsystem (FTS) to provide frequency and timing reference signals.

Currently the DSN operates three major Deep Space Communications Complexes (DSCCs); they are located near Goldstone, California; Canberra, Australia; and Madrid, Spain. The longitudinal separation between each complex is approximately 120 deg, with two north of the equator and one south, making it possible for any spacecraft in the ecliptic plane to establish line-of-sight communication with at least one ground station at any time. Each complex consists of several large parabolic reflector antennas (diameters of 70, 34, and 26 m) and associated low-noise and ultra-sensitive receiving systems. Oversubscribed ground-based resources to track multiple flight missions (currently 16 in flight plus 2 rovers on Mars) place a very high demand on availability and reliability of each DSCC subsystem.

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[1] Tracking Systems and Applications Section.

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The frequency and timing subsystem is a key component of the successful operation of each complex. The DSN and the FTS have slowly evolved over the years, growing in both capability and complexity. The recently replaced timing system was developed in the late 1970s and, while historically reliable, had limited capacity, used out-of-date components difficult to repair/replace, and had become increasingly difficult to operate and sustain. In this article, a system-level description for the new master clock and time distribution system appropriate for the DSN or other similarly demanding operational environments is described. The new timing system[2] [1,2] is now operational at all three DSN sites, Signal Processing Center 10 (SPC 10) (May 2005), SPC 40 (October 2005), and SPC 60 (March 2006); Cape Canaveral's MIL-71 (April 2005); the DSN Development and Test Facility (DTF-21) (July 2004); and several JPL development laboratories. Part II, to be published in the near future, will report performance and operational test results.

II. DSN Frequency and Timing Subsystem

The DSN requires both state-of-the-art frequency and timing performance and very high reliability. Each DSCC operates an independent FTS to generate and distribute reference signals to as many as 100 users. These coherent signals are centrally generated and distributed to users at distances up to 30 km, as schematically shown in Fig. 1 for the DSCC at Goldstone, California. The central source of stable frequency and timing for the entire DSCC originates from a single atomic frequency standard, typically a hydrogen maser and often referred to as the "online" standard. Backup frequency standards of varying performance also are available. Sinusoidal frequency reference signals, most commonly at

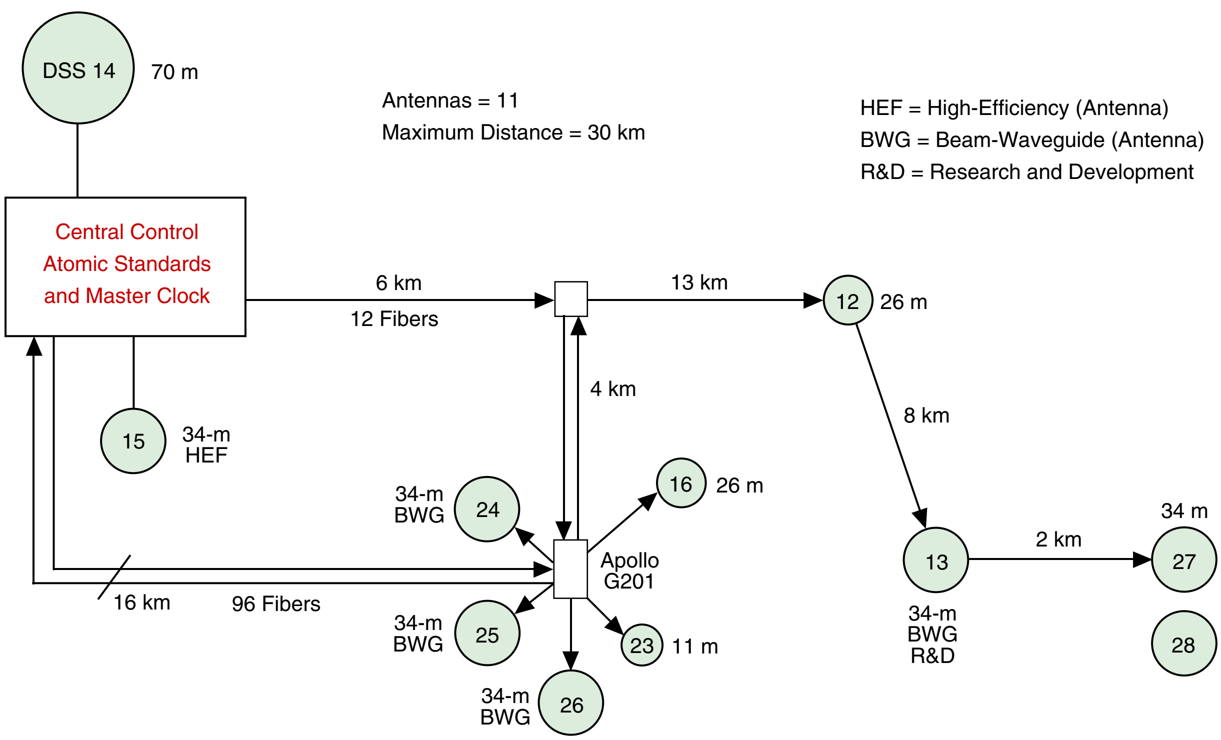

Fig. 1. Schematic view of the antenna layout at the NASA DSCC at Goldstone, California, showing fiber-optic connections and distribution distances up to 30 km.

[2] *Frequency and Timing System Master Clock and Timing Group Replacement*, JPL Technical Requirements Document, DSMS no. TRD-517892, JPL D-22188 (internal document), Jet Propulsion Laboratory, Pasadena, California, March 1, 2002, and Rev. A, April 8, 2003.

5, 10, and 100 MHz, are distributed over a variety of copper coaxial and fiber-optic cables to end users in both the nearby central control area and to antenna sites at greater distances. Significant attention is given to the selection and installation of distribution cables in order to minimize thermally induced phase delays. Active feedback is introduced to stabilize the most demanding frequency distribution applications, typically for radio science [3].

Each DSCC timing system consists of a central master clock and a distribution system capable of providing a synchronized time of day and stable timing rates at all user locations. The master clock receives a frequency reference from the DSCC online frequency standard. The frequency standard syntonization and master clock synchronization are measured and known relative to Universal Coordinated Time (UTC) and other DSCCs via common view Global Positioning System (GPS) time transfer. The knowledge of time offsets with respect to UTC and ultimately to the Earth-based timescale Universal Time 1 (UT1) are critical for DSN tracking activities and successful spacecraft navigation [4]. The master clock time offset from UTC, the user time code translator (TCT) offset from the master clock, and the user reference timing jitter are key performance requirements on the replacement system.

A. Old Timing System

The replaced timing system was developed during a DSN era with fewer antennas and with fewer missions to support. The early DSN focused on planetary flyby missions, culminating with the Pioneer (Jupiter 1974 and Saturn 1979) and Voyager (Jupiter 1979, Saturn 1981, Uranus 1986, and Neptune 1989) missions to the outer planets. These missions had stringent navigation and radio science requirements, with multiple activities that had to occur during brief planetary encounters lasting only a few hours. These DSN activities had a timing requirement that a separate test time be distributed to simulate and rehearse future operations scenarios. This feature, referred to as "simulation time," and the needed monitor and control resulted in a very complicated timing distribution system. Since this era, each DSCC has grown considerably more complex, with multiple antennas and many more missions in flight to track. Furthermore, each complex today has a centralized UNIX-based monitor and control network to operate a mix of complex assets. This system is not time-translation friendly. This much busier and more complicated network interface environment contributed to the obsolescence of the simulation time requirement in the operational DSN.

The prior DSN timing system, shown in the shaded boxes in Fig. 2, required five electronics racks to contain a triply redundant master clock and time insertion distribution system (TIDS). The TIDS provided the time distribution to the user interface, referred to as time code translators (TCTs), located throughout each DSCC. The outputs of the three time code generators (TCGs) were majority voted to eliminate a TCG in the event of a failure. The voted clock output then passed to the TIDS, where a unique 100-kHz pulse-width-modulated code (TIDS code) was generated. The TIDS code is similar in structure to the Inter-Range Instrument Group (IRIG-G) time code with the addition of information to carry simulation time, the TCT address, and flag bits to warn users of an upcoming leap second or leap year event. The timing rate at each TCT was derived via a 5-MHz reference also distributed from the TIDS. A multi-conductor cable between the TIDS and each TCT was used to return detailed TCT status monitor data. This detailed monitor information was processed by an integrated TIDS monitor and control system also used to carry out TIDS control functions such as selecting which subset of TCTs to operate with simulation time. A similar monitor and control existed for the master clock, and both systems communicated to the central complex monitor and control system via an IEEE-488 interface bus with insufficient reliability. The highly integrated monitor and control system was built around assemblies fabricated with 1970s wire-wrap technology and Z80 processors. An additional cable for offset calibration and monitoring returned a 1-pps signal back to the central control room from those TCTs that were within approximately 1 km of the TIDS. The need for four separate cables between the TIDS and the approximately 100 TCT users created a large cable management challenge for the DSCCs.

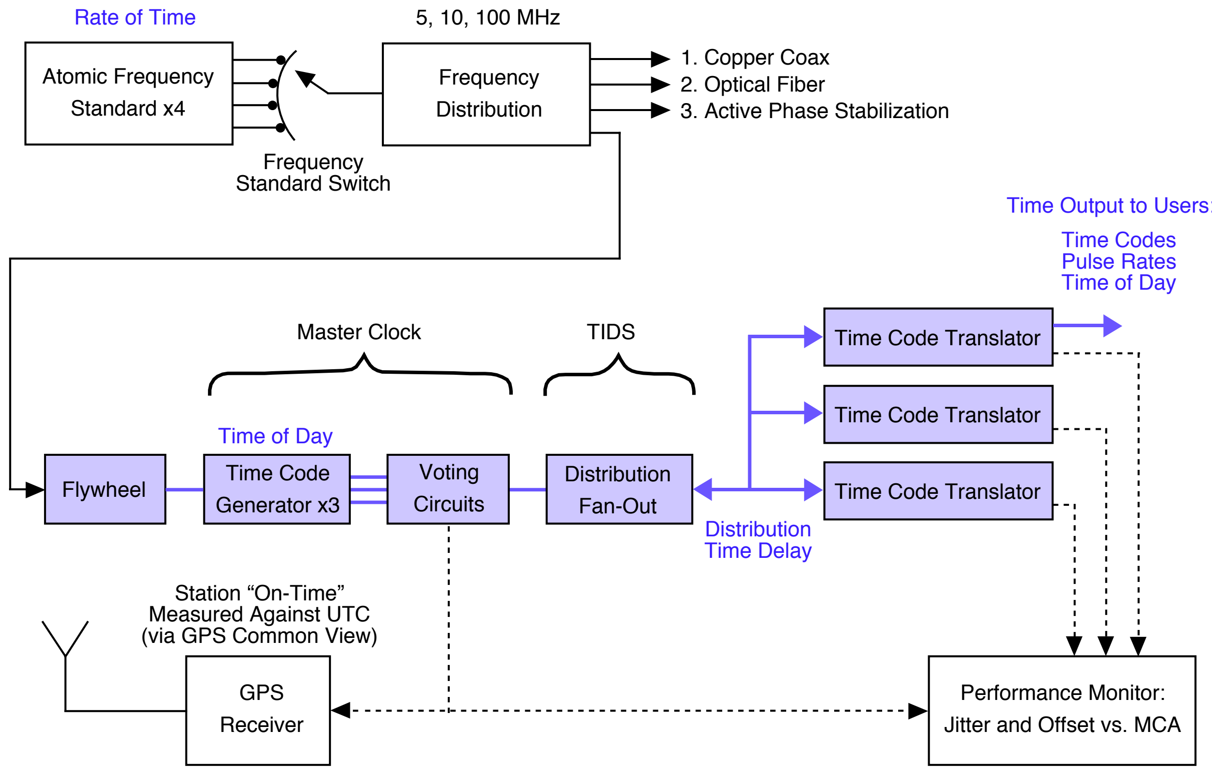

Fig. 2. The DSN frequency and timing subsystem with the shaded boxes representing major components of the old timing chain recently replaced with the system shown in Figs. 3 and 4. For clarity, monitor and control for the three time code generators, the voting circuitry, and the distribution fan-out (TIDS) is not shown.

Over the years, several different TCT models have been developed to accommodate different time codes and pulse rates required by various users. Distribution delays could be removed to a resolution of 100 ns using delay compensation switches accessible on the rear panel. Typical achieved TCT jitter stability was at the 1- to 2-ns root-mean-square (rms) level, with some of the more recent versions capable of ~700 to 800 ps rms. The initiation of leap seconds, leap year, or the setup of simulation time was performed via the monitor and control system, which historically also could be controlled through each DSCC local area network. The leap second or year activities also required that manual switches at the master clock be set, effectively defeating any benefit of centralized control.

Given the complexity of the old system, the reliability has been very good, although increased anomalies have occurred in recent years due to age. The stability performance has been sufficient for most DSN activities, although hardware and firmware have been difficult to sustain for quite some time. Furthermore, given the critical nature and relatively few failures of the old system, station operators had little opportunity to interact or gain familiarity with the old clock and TIDS. This had the undesirable effect of a near operational paralysis when it came to making decisions or troubleshooting clock anomalies.

III. New Timing System Design

A. Design Considerations and Goals

The central design philosophy for the new system is that it be viewed foremost as a precision reference system with focus on the need for very high reliability and operability. Performance improvements were incorporated where they were feasible and did not compromise reliability. The replacement system must be easier to operate by personnel with little or no expertise in the timing system. Many of the design features and detailed requirements are captured in the task technical requirements document.[3] In summary, the key considerations and goals driving the new design were

- Design as a precision reference with operability considerations.
- Eliminate central/network control and individual TCT addressability.
- Simplify status data to only high-level information for easy interpretation and action.
- Simplify setup interface and add coarse time recovery to an IRIG-B signal from a GPS receiver.
- Use fiber-optic cables for distribution, and reduce multiple existing DSN cables.
- Integrate 1-pps loop-back monitor fiber to verify offset and jitter at each user.
- Use a hot-swap modular approach with a common chassis and power supplies.
- Include redundant power supplies fed in parallel from line power and uninterruptible power.
- Design the distribution to be modular and expandable to accommodate future growth.
- Standardize the TCT design to a single mainframe, and maintain the existing user form factor.
- Use a TCT plug-in module approach to meet varying user output needs.
- Develop with the involvement of a commercial timing company for non-recurring engineering and production of high-quantity modules.
- Design to a 20- to 30-year operational life, and document and archive the design to meet long-term DSN sustaining needs.
- Integrate master clock flywheel capability and add user holdover capability.
- Improve master clock set-ability from 100-ns to 10-ns increments.
- Improve user synchronization set-ability from 200 ns to ± 5 ns.
- Improve pulse-to-pulse jitter from ~ 1 ns to <200 ps (<30 ps actually achieved).
- Automate leap year and provide the year in the distribution code. Manually set leap second insertion.
- Provide output codes: RETMA Standard (RS-232) serial, NASA36, IRIG-B, Parallel Binary-1 (PB-1), and Parallel Binary Coded Decimal (BCD).
- Provide output time pulse rates: 1, 10, 100, 1 k, 10 k, 100 k, and 1 M PPS.

B. System Design Overview—Major Assemblies

The new timing system design comprises three major hardware assemblies, interconnected via a fiber-optic infrastructure and shown in Fig. 3. These components replace the shaded boxes shown in Fig. 2. Timing signals originate in the master clock assembly (MCA). The MCA is set to UTC and generates a system time code (STC) for distributing time of day and timing rate information to the entire DSCC. This distribution is accomplished by passing the STC over fiber-optic cable to a distribution assembly (DA). The DA is filled with 10 distribution modules (DMs), each of which reconstitutes the STC and transmits the signal either to a second DA for additional fan out or to a time code translator (TCT) that provides the end-user timing-reference interface. The TCT compensates for transmission delays from the master clock and can generate a variety of time codes and pulse rates as required.

[3] Ibid.

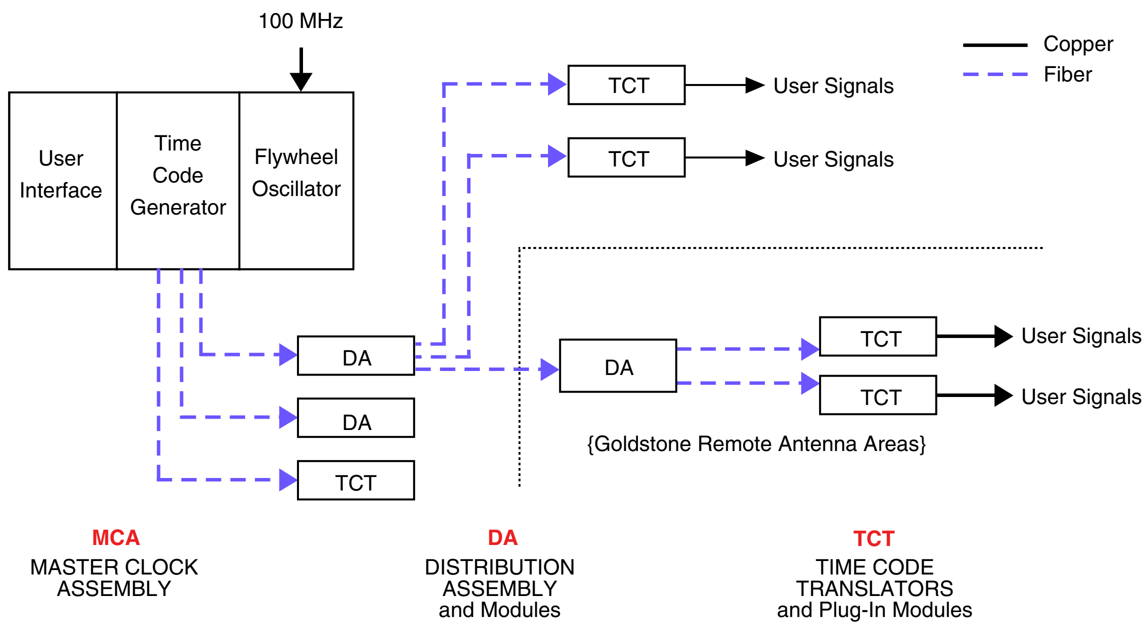

Fig. 3. Major assemblies and fiber-optic distribution fan-out hierarchy of the new timing system design.

A more detailed view of the modules in each major assembly is shown in Fig. 4. For future flexibility and sparing, both the MCA and the DA reside in identical chassis with dual hot-swap power supplies. The new TCT is a standardized mainframe in a 1-unit (1U) chassis, preserving the same form factor of the prior timing system in user racks. The back of the TCT can accommodate four plug-in modules to provide different time code and pulse rate outputs.

The master clock assembly contains five modules, four of them unique: a front-panel user interface that incorporates a few simple operator setup and slew functions, a 100-MHz flywheel, a single time code generator, and dual redundant power supplies. The user interface allows an operator to "jam-set" the time code generator either manually or using an externally generated IRIG-B signal (which can be derived from a low-cost GPS receiver). The rate of time accumulation then is dependent on the DSCC 100-MHz reference frequency, typically derived from a hydrogen maser. The station time, as defined by the master clock, can be manually slewed in any combination of decade step sizes from 10 ns to 100 ms. The master clock has knowledge of the current year and implements leap-year rollover automatically. Provision is made to manually set a leap-second event (add or subtract) for any day of the year. During normal operation, the stability of the generated timing rates traces directly to the DSCC atomic frequency standard. For uninterrupted operation in the event of loss of the 100-MHz reference frequency, the master clock assembly incorporates a temperature-compensated crystal oscillator (TCXO) phase-locked loop flywheel designed with a holdover function to drift less than 3 ms over 24 hours.

The distribution assembly contains 13 modules, three of them unique. The input module receives the optical system time code generated in the MCA time code generator and fans the signal out to as many as 10 output modules. The signal from any of the 10 output modules then can be transmitted either to a second-stage distribution assembly or directly to a new TCT. The optical time code signal transmitted by the distribution assembly is identical to the signal generated by the TCG. This means that there can be an unlimited number of fan-out stages between the TCG and the end-user TCT, and there is no limit to the number of users that can be connected to the master clock.

The final stage in the distribution chain is a time code translator. The new TCT receives the optical system time code and uses the embedded carrier to phase lock a 100-MHz TCXO identical to that in the

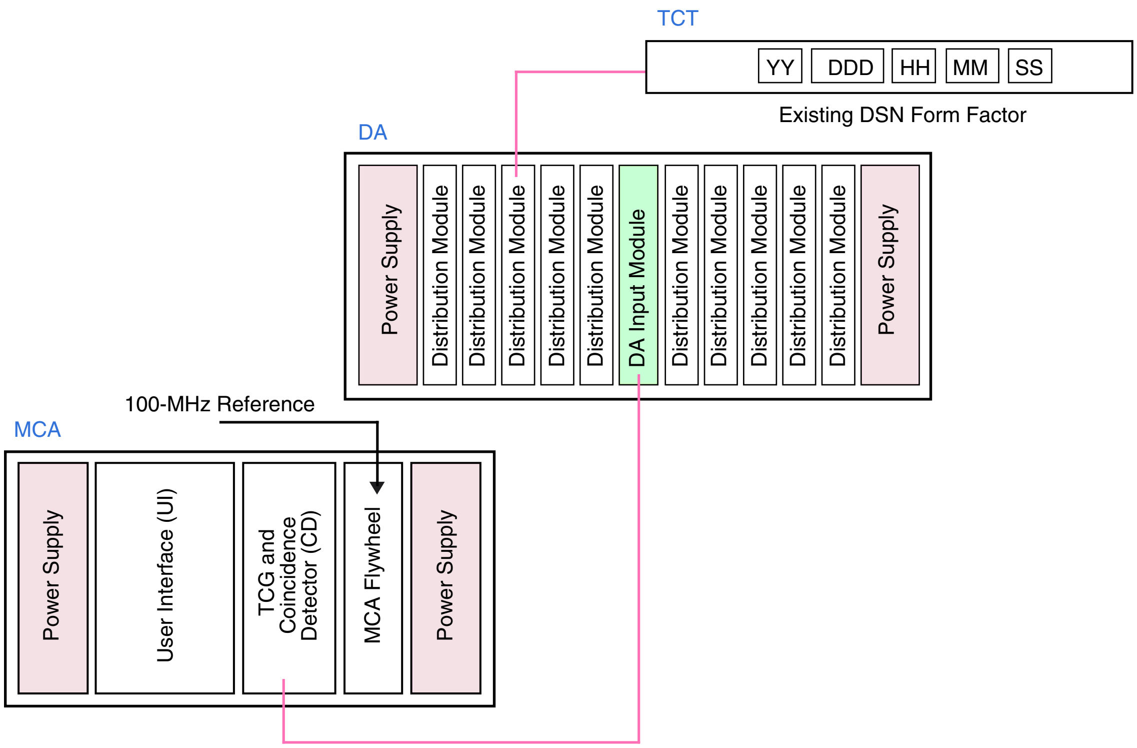

Fig. 4. New timing system showing detailed module configuration.

MCA flywheel; 100 MHz provides a resolution that can accommodate time distribution delay set-ability at the 10-ns level. Delay compensation is accomplished by setting hidden dip switches inside the TCT mainframe chassis. These switches ordinarily are adjusted only during initial installation and calibration. The system time code and rate are derived from the optical signal and sent to one of four identical, rear plug-in module slots within the TCT. Any of the four slots then can be populated with a module configured to produce either pulse rates ranging from 1 pps to 1 Mpps in decade increments, or a range of common time codes such as IRIG-B, NASA36, BCD, PB-1 etc. The distribution system time code and the 100-MHz output of the TXCO are made available at the plug-in connectors in order that future timing needs can be accommodated simply by designing a new plug-in module with the appropriate output.

C. Dual-Flywheel Approach

The new system design incorporates a "dual-flywheel" implementation. The first flywheel resides in front of the MCA time code generator, and a second is built into every TCT that resides at every user interface. This provides significant operational robustness over the present timing system and secondary benefits as well.

The MCA flywheel now resides in the MCA chassis and benefits from the chassis dual-redundant power supplies and module hot-swap-ability. In each chassis, one power supply is attached to line power and the other to an uninterruptible power supply (UPS). The main purpose of the MCA flywheel is to hold MCA time in the event of loss of the 100-MHz frequency standard reference from either failure or change of the online atomic frequency standard. While in holdover, the timing offset from UTC will slowly degrade, although the complex will continue to operate for many critical applications until the reference signal can be restored.

In the new system design, a second flywheel is included in each individual TCT. With a TCT flywheel, time code outputs and pulse rates continue to be generated in the event of timing signal interruption anywhere in the distribution infrastructure. This holdover is allowed for up to 12 hours, more than sufficient time to diagnose and repair the distribution-related anomaly and to keep basic operation of the affected user going through an antenna track.

The TCT holdover flywheel also enables a capability to deliver stable frequency references via the timing distribution system. Since the 100-MHz TCXO is phase-locked to the embedded optical system time code, near-hydrogen-maser stability can be delivered at the TCT user outputs with appropriate voltage-controlled oscillator (VCO) loop bandwidth and handling of the fiber-optic cables. These data will be reported in Part II. This capability gives the DSN FTS a separate capability for distributing the very low phase noise and high-stability frequency reference signals (see, e.g., [3]). While specialized frequency distribution systems support the highest performance users, especially very long baseline interferometry (VLBI) and radio science, many users, such as telemetry and monitor/control functions, often do not require such levels of performance. Significant simplification to the DSN equipment and cable infrastructure may result if such users derived moderate performance reference frequencies from this timing system. The ability to distribute frequency references with the new timing system has already been put to use and has benefited several unique applications at JPL [5] and the DSN.

D. Synchronized Hot Backup

The new MCA design incorporates only a single TCG. This is a major departure from the previous timing system, which had three separate TCGs and associated voting circuitry. This decision was driven in part by analysis indicating that the voting circuitry and flywheel were more likely to fail than a single TCG configuration and that the entire user set could now flywheel even through a master clock failure. In addition, by incorporating the flywheel into the MCA chassis with dual hot-swap power supplies, some of the prior vulnerability of a stand-alone flywheel also has been reduced.

Since the entire MCA can be constructed in a single 4U chassis, our approach for redundancy in event of MCA failure is to operate with a synchronized hot backup (Fig. 5). A second MCA assembly resides near the online MCA and is synchronized at setup using the same 100-MHz input frequency. The TCG output of each MCA is compared in coincidence to monitor for possible failure. In the event of this rare occurrence, distinguishing which TCG failed should be straightforward. If the online MCA fails, multiple failure alarms will be present in the distribution assemblies following the MCA. To recover, an operator simply must move the TCG output fiber to the adjacent backup clock. Furthermore, since all TCTs have a holdover flywheel, the only impact to timing users resulting from a master clock change may be a slight degradation in stability performance during the changeover. There would be no reference signal discontinuity.

E. DSN Fiber-Optic Distribution Approach

The DSN timing system is highly integrated into the existing DSN infrastructure. Transitioning from a copper-cable infrastructure to a fiber-optic infrastructure during continuous station operation has been a large undertaking. The new design provides significantly improved cable organization and simplification with the replacement of four copper cables per TCT by a single fiber-optic cable.

The majority of DSCC timing users reside at distances less than 2 km from the master clock and receive the distributed signal using multimode fiber-optic cables. Each cable contains four fibers. One transmits the system time code, and another one serves as the 1-pps monitor loop back return. This loop-back return signal is collected at the distribution module (DM) and fed to an existing time analysis system [6] for verification of offset and jitter of the entire set of timing signal users with respect to the MCA. The other two fibers serve as spares.

For fiber-optic cable distribution to antennas less than 2 km from the MCA, a single 12-fiber cable was installed to a breakout box in each antenna. This cable can support up to 6 independent TCTs or DAs. Presently each antenna typically has 2 TCTs to support antenna pointing and uplink/downlink activities.

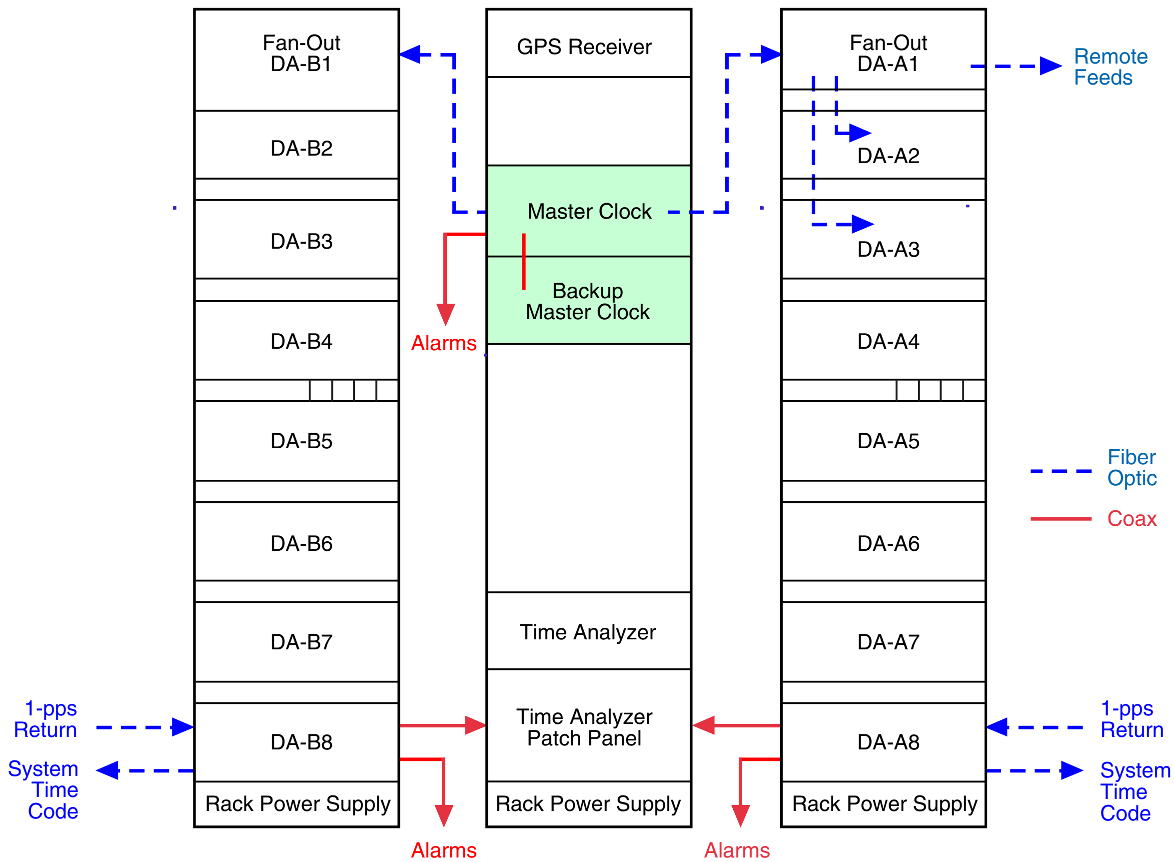

Fig. 5. Schematic rack layout showing the master clock, synchronized hot backup, and distribution configuration.

For longer distances between 2 and 30 km, single-mode fiber-optic cables are used. Historically, timing signals from the old TIDS were transmitted over these lines using a variety of commercial hardware. With the new system, the ad hoc hardware has all been replaced with a distribution module that accommodates a single-mode fiber-optic transmitter and receiver.

In all cases, efforts have been made to keep the system modular while minimizing the number of connectors required. The trunk cables to each antenna are cut to length. Because it is possible that this system may be used for some future frequency reference distribution, attention was paid to minimizing connector count.

F. Monitor and Control Approach

In the busy operational DSN environment, the approach to monitor and control is an important consideration. The DSN frequency and timing subsystem has little need for real-time configuration changes (in contrast to pointing an antenna, which requires a new configuration for every spacecraft track). In the FTS, needed configuration control actions are the selection of the online frequency standard and the setting of a leap-second event. The addition or subtraction of leap seconds is a relatively rare event currently occurring on average much less than once a year. The new timing system carries "year" information in the system time code, and leap-year rollover is now automated.

In the DSN operational environment, operators already have an overabundance of status and fault information to analyze. By design, for the new master clock, the only information provided to operations is that which facilitates isolation of a failure to the module level. Local alarm indications at the TCT, visible as lighted front panel light-emitting diodes (LEDs), are summed together and communicated back up to the DA simply by blanking the 1-pps monitor return signal. A missing pulse detector (MPD) circuit in each DA module alarms an LED visible at the transmitter module. Each DA chassis has one alarm representing the summed alarms of all 10 modules. This alarm is passed further up the chain or collected by a status summary monitor computer visible to the DSN operator's monitor and control console. With modularity, and simple go–no go monitor and alarm information, oversubscribed personnel can maintain FTS operations with little understanding of the nuances of the precision timing system.

By design there is no central or remote control of the master clock and distribution system. After initial configuration through the MCA front-panel interface and calibration of distribution delay to each TCT, interaction with the MCA and distribution system is minimal. By keeping the design simple, eliminating software and detailed monitor and control, and incorporating the dual-redundant flywheel scheme, few failures that could negatively impact DSN operations are anticipated over the estimated 20- to 30-year operational life.

IV. Summary

A new timing system including a master clock and fiber-optic-based time distribution network has been designed, developed, tested, and implemented to meet the demanding needs of the NASA Deep Space Network for years to come. The design provides new levels of timing performance and is highly modular and expandable, and a simple monitor and control approach makes the system easy to operate. Some of the module non-recurrent engineering and most hardware production were performed with support from private industry. In addition to being much more operable, the new timing system hardware currently is available commercially, and the design is fully documented and archived at JPL. In event of loss of time, the clock can be easily recovered with a single button jam reset to an IRIG-B signal from a low-cost GPS receiver. The internal synchronization performance has been improved by a factor of 10 and the timing jitter reduced by a factor of 50.

Currently the new timing system is operational at all three DSN complexes, SPC 10, SPC 40 and SPC 60, as well as at Cape Canaveral MIL-71, the DSN test facility DTF-21, and several JPL development laboratories. A follow-on article providing performance data and operational experience is in preparation and will be published soon.

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