COHERENT FREQUENCY REFERENCE GENERATION IN THE NASA DEEP SPACE NETWORK

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Abstract

JPL is nearing completion of a new frequency reference generation and distribution system to replace the DSN FTS Coherent Reference Generator (CRG). The existing CRG selects the online frequency standard, synthesizes standard reference frequencies, and provides fan-out to distribute to users which may be up to 30 km away. Like the existing CRG that is critical to DSN operation, the replacement system must be extremely reliable and preserve the high stability and low phase noise performance of the central frequency standard. In addition, in the replacement system the process and effect of switching to other backup or specialized frequency standards should also be transparent to DSN Operations. Reliability shortcomings of the old system are addressed by upgrading to modern and modular system components, reducing the number of distributed frequencies, and adding redundancy or managing single points of failure.

INTRODUCTION

The generation and calibration of frequency reference signals in the NASA Deep Space Network (DSN) is essential for space navigation and tracking activities. The DSN is a unique capability with extraordinary sensitivity for tracking spacecraft within and beyond the solar system and for detecting very weak natural radio emissions from the far reaches of the universe. The network consists of numerous ground-based antennas and associated systems, including a highly precise and stable Frequency and Timing Subsystem (FTS) that provides frequency, time code, and pulse rate signals to users within a complex.

Currently, the DSN operates three Deep Space Communications Complexes (DSCCs). They are located near Goldstone, California; Canberra, Australia; and Madrid, Spain. The antenna sites are in remote valleys away from heavily populated areas so that weak radio signals are not obscured by radio interference from sources such as power lines, radio and TV stations, and household and industrial electronics. The longitudinal separation between each complex is approximately 120 degrees, with two north of the equator and one south, making it possible for any spacecraft in the ecliptic plane to establish line-of-site communication with at least one ground station at any time. Each complex consists of several large parabolic reflector antennas (diameters of 70 and 34 meters) and associated low noise and ultra-

[1] This work was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

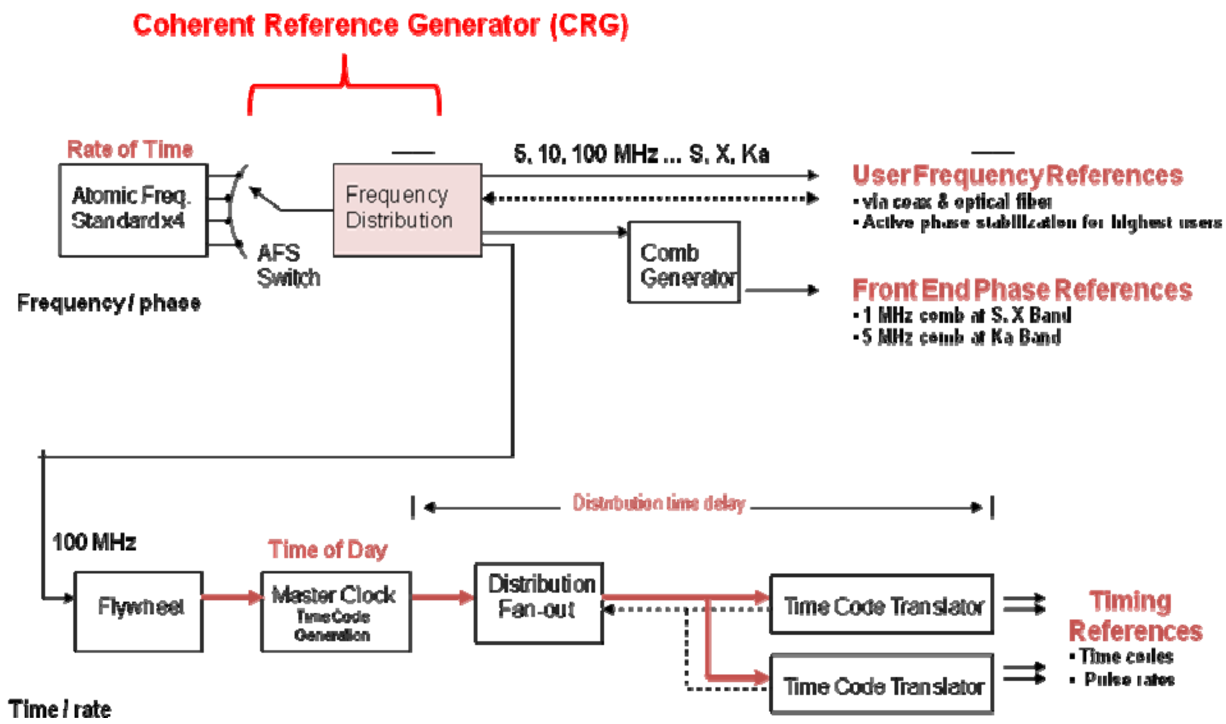

Figure 1. Schematic representation of the present DSN Frequency and Timing Subsystem, indicating the position of the CRG within the frequency distribution chain.

sensitive receiving systems. Oversubscribed ground-based resources to track multiple flight missions place a very high demand on availability and reliability of each DSCC subsystem.

The FTS is a key component to the successful operation of each complex. The DSN and the FTS have evolved over many years, growing in both capability and complexity. The existing frequency reference system, referred to as the Coherent Reference Generator (CRG) **[1]**, was developed in the late 1970s. While historically reliable, the CRG design is vulnerable to critical single point failures, and components have become obsolete. In this paper, a system level description for a replacement system appropriate for the DSN is described.

DSN FREQUENCY AND TIMING SUBSYSTEM

The DSN requires both state-of-the-art frequency and timing performance as well as very high reliability. Each DSCC operates an independent FTS (Figure 1) to generate and distribute reference signals to as many as 100 users. These coherent signals are centrally generated and distributed to users at distances of up to 30 km. The central source of stable frequency and timing for the entire DSCC originates from a single atomic frequency standard, often referred to as the "online" standard. Backup standards of varying performance are also available. Sinusoidal frequency reference signals, most commonly at 5, 10, and 100 MHz, are distributed over a variety of copper coax and fiber-optic cables to users in both the central control area and to antenna sites at greater distances. Significant attention is given to selecting distribution cable properties to minimize thermally induced phase variations and to insulate the cable from external thermal perturbations. Active feedback is incorporated to stabilize the most demanding frequency distribution applications **[2]**, typically for radio science **[3]**.

The timing system consists of a central Master Clock which derives its rate from the online frequency standard. The current system was developed and installed in 2005 **[4,5]**. Time of day and pulse rate reference signals are distributed, with time offsets between each user and the DSCC Master Clock known and calibrated. The calibration of the Master Clock and the online frequency standard at each DSCC relative to Universal Coordinated Time (UTC) is accomplished via Common View GPS time transfer. The knowledge of time offsets with respect to UTC and ultimately to the earth-based timescale UT1 are essential for successful spacecraft radiometric tracking for deep space navigation **[3]**.

EXISTING COHERENT REFERENCE GENERATOR (CRG)

The CRG system, in its simplest sense, is composed of a switch to select the online frequency standard from among four available standards followed by a network of fan-out amplifiers and cables to distribute reference frequencies to multiple users. The system initially installed in the DSN in 1971, using technology developed in the late 1960s, required an operator to manually switch to a backup in case of a frequency standard dropout, with significant time to restore service. In 1986, the DSN Mark IV upgrade **[1]** added an automated microprocessor-based switching algorithm that, in the event of loss of the online signal, brought a backup online within 30 ms. Improvements to stability, spectral purity, and expansion of user capacity were also part of that effort. Still, the 30-ms dropout on occasion caused some critical users to break lock in a way that required operator intervention. With aging, the antiquated designs have become increasingly difficult to support and failure rates have increased to a level unacceptable to the DSN. It was decided to replace the CRG in its entirety with a modern and flexible design.

REPLACEMENT SYSTEM DESIGN

DESIGN CONSIDERATIONS & OVERVIEW

Many years of operations experience has been accumulated and every effort was made to incorporate lessons learned into the new design. The effect of power supply failures is mitigated through the use of redundant supplies, with hot-swap capability so that maintenance can be performed as needed without waiting for the entire tracking complex to be shut down. The possibility that a single module failure could short out the power supply system or contaminate other modules with spurs is prevented by extensive use of distributed regulation, with individual current limiting to each module. Thermally induced phase instabilities are managed through the use of passive temperature compensation of the assembly electronics. Carrier output interruption during frequency standard switching is completely eliminated by the introduction of a frequency flywheel. To the degree possible, the new design would take advantage of off-the-shelf commercial equipment where performance is suitable to DSN requirements, such as power supplies and distribution amplifiers.

The introduction of a flywheel to the system has important implications for the system architecture that may not be immediately obvious. The flywheel, with a low-cost and reliable VCXO oscillator, takes much of the reliability burden off the much more complicated atomic frequency standards. The DSN requires that coherent 5-MHz, 10-MHz, and 100-MHz reference signals be distributed. The possibility of using separate flywheels for each frequency was dismissed, not only because of increased cost and

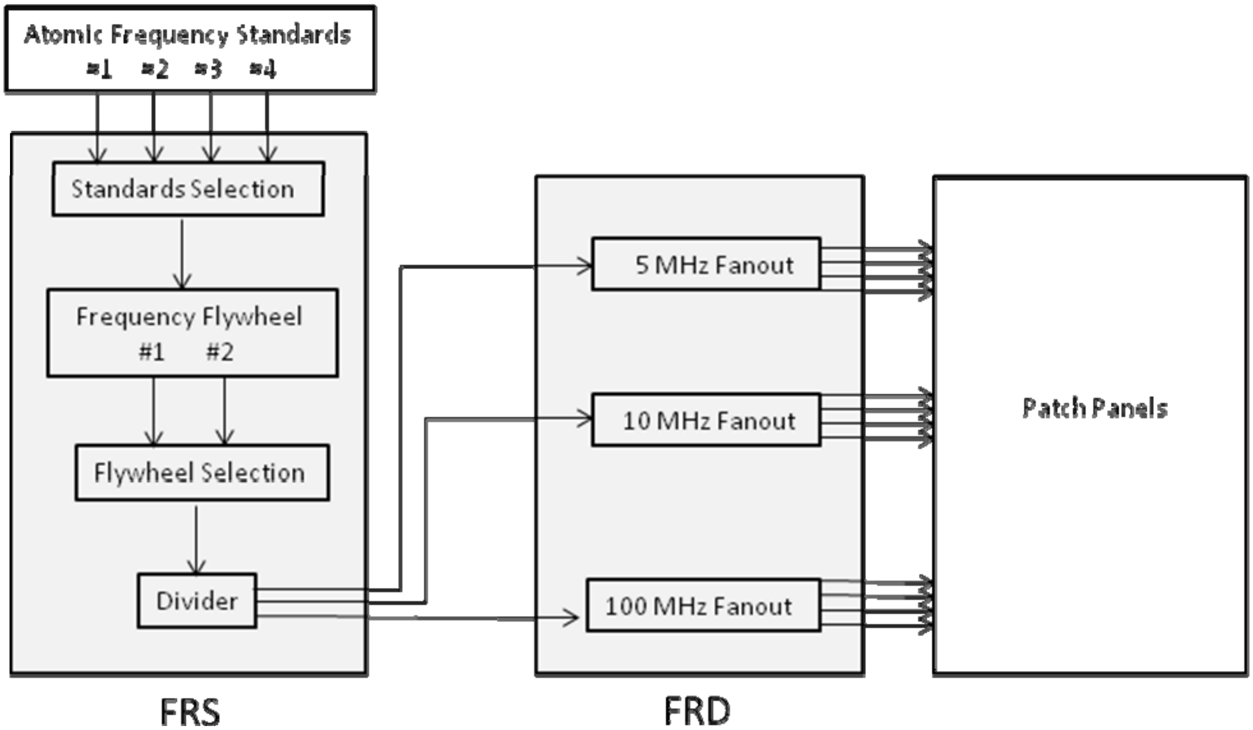

Figure 2. Replacement system conceptual design.

complexity, but also because of potential detrimental effects on phase coherence. The flywheel operates only at 100 MHz. This also results in a three-fold reduction in the number of input cables and switches.

Because the characteristic phase noise of a 100-MHz VCXO is lower far from the carrier than even a top-quality 5-MHz VCXO, the choice of 100 MHz for the flywheel allows significant improvement in phase noise, far from the carrier, even with a lower cost 100-MHz VCXO. In the future, the flywheel architecture may play a further phase noise cleanup role. Currently, each DSN hydrogen maser has many custom upgrades, including being outfitted with a very expensive quartz oscillator to provide the best phase noise possible. With a dual-loop flywheel architecture (a possible future upgrade to the single loop used here), phase noise cleanup could instead occur with the flywheel oscillator. This may allow the use of COTS hydrogen masers and cleanup of any spurious signals without custom modifications to the maser itself.

With a 100-MHz-based flywheel design, the 5-MHz and 10-MHz reference frequencies are generated by a frequency divider. The low cost of highly reliable digital dividers allows for the improved operability and the reduced complexity of a single-frequency flywheel.

The new reference frequency distribution system design is conceptually shown in Figure 2. The system includes two major hardware subsystems, the selection/switching function known as the Frequency Reference Selection (FRS) assembly and the frequency fan-out function referred to as the Frequency Reference Distribution (FRD) assembly. These assemblies are physically separated from one another. The FRS resides in the well-controlled environment of the standards room. The FRD resides at the heart of the signal processing center for most convenient accessibility.

FREQUENCY REFERENCE SELECTION (FRS)

The Frequency Reference Selection Assembly (FRS) contains five unique subassemblies that provide the switching, flywheel, and frequency divider functions:

1. Selection Switch Assembly
2. Frequency Flywheel Assembly
3. Frequency Divider Assembly
4. Redundant Power System (not shown in Figure 2)
5. Monitor & Control (not shown in Figure 2).

Selection Switch Assembly

The Carrier Select Switch has circuitry which detects the amplitude of each input, and recognizes an alarm imported from the AFS indicating critical conditions such as loss of phase lock. Based on these inputs and a hardwired priority sequence, the switch will select an input according to the following rules:

- If in manual mode, go to selected input, otherwise:
- If standard 1 is OK (input amplitude normal and no imported alarm), use standard 1.
- If standard 1 fails and standard 2 is OK, use standard 2.
- If standard 1 and standard 2 fail and standard 3 is OK, use standard 3.
- If standards 1, 2 and 3 fail, use standard 4 (even if 4 has failed too).

To maintain adequate isolation, switching is implemented by two cascaded electromechanical relays. Isolation of greater than 120 dB, more than adequate to avoid degradation of maser stability, is achieved. The output stage of the carrier select switch has a five-way distribution amplifier to provide multiple redundant outputs in addition to a test port for monitoring signal quality.

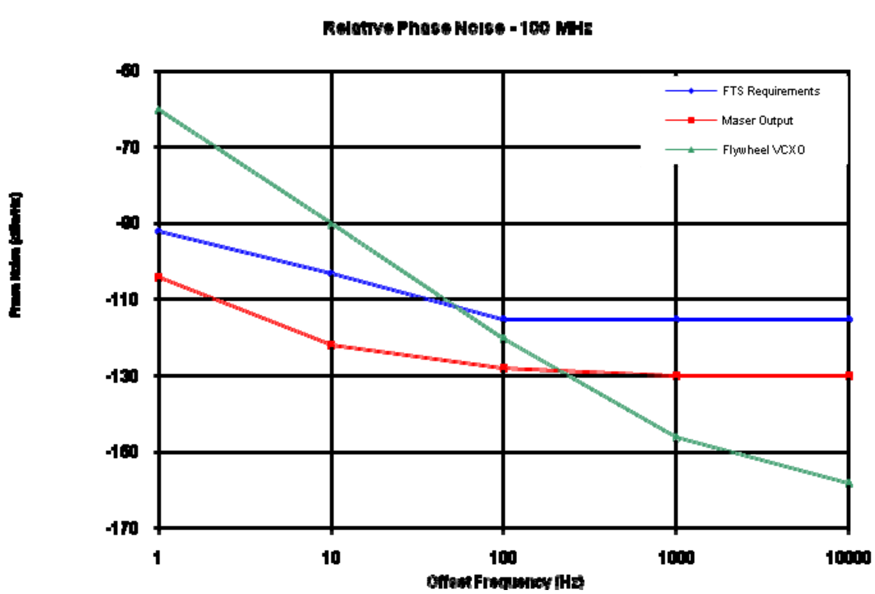

Figure 3. Phase noise output of selected flywheel oscillator locked to incoming maser signal.

Frequency Flywheel Assembly

The Flywheel Assembly utilizes a 100-MHz VCXO locked to the input reference with a two-pole 200-Hz bandwidth loop. This arrangement follows the excellent phase noise of the maser oscillator close to the carrier, while taking advantage of the lower phase noise of the 100-MHz VCXO at larger offset frequencies. The principal failure risk is loss of phase lock, such as due to the crystal frequency aging beyond its tuning range. To manage this risk, a phase-lock detector is incorporated into the loop. As an early warning of crystal aging, a front panel meter monitors the VCXO tuning voltage, and an early-warning alarm lights if the tuning voltage nears its end limits.

Two identical flywheel assemblies are always active. In the event of a failure of the prime flywheel, the backup one takes over. In the unlikely event of a failure of both flywheels, a bypass cable is selected to maintain signal to the users. This flywheel-select function is accomplished by a second carrier select switch identical to the input switch.

Frequency Divider Assembly

The Frequency Divider Assembly generates 5-MHz and 10-MHz sine-wave outputs from the 100-MHz input from the Flywheel. A 5-bit emitter coupled logic shift register with inverted feedback is used to divide the 100-Hz input by a factor of 10 to generate a 10-MHz square wave. The true 50% duty cycle output has minimal output power at the 2nd harmonic frequency, easing requirements on the reconstruction filter for improved phase stability. A gain stage and five-element temperature-compensated low-pass filter reconstruct a low distortion 10-MHz sine wave. A T-type flip-flop divides the 10-MHz square wave by a factor of 2 to generate a 5-MHz square wave. A gain stage and three-element temperature-compensated low-pass filter reconstruct a low-distortion 5-MHz sine wave.

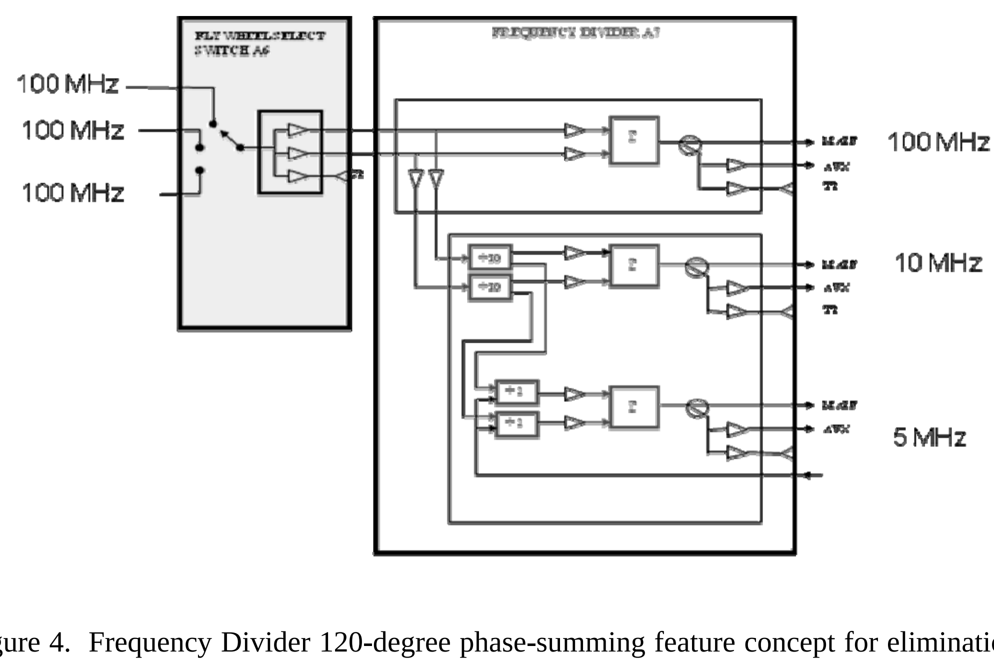

Figure 4. Frequency Divider 120-degree phase-summing feature concept for elimination of single-point failures.

In addition to generating 5 MHz and 10 MHz, the divider chassis also combines the primary 100 MHz with the backup 100 MHz, both originating in the Flywheel Select Switch. The two 100-MHz inputs are combined via a 120-degree power combiner. Unlike in-phase or quadrature summing, the 120-degree combination maintains a constant amplitude 100-MHz output in the event of the loss of either input.

FRS Redundant Power System

The power supply system is fully redundant, beginning with separate power sources. One power supply is powered from an UPS to maintain operation in the event of power mains failure, and a redundant power supply is powered from the mains to maintain operation in the event of an UPS failure. This redundant power arrangement has proven extremely effective for reliable DSN Master Clock operations **[4,5]**. Linear power supplies are used in preference to smaller and more efficient switching types to prevent any possibility of switching spurs contaminating any sensitive equipment in the frequency standards room. Dual redundant power manifolds provide individual voltage regulators for each module. This assures that oscillations or short circuits in one module do not disturb power to the rest of the system. The power manifold contains monitor circuitry to trigger an alarm if any power supply output voltage falls more than 10% below nominal, or if 60-Hz ripple at the power supply output increases above 1vpp. These levels are chosen such that in the event of a graceful degradation over time, the alarm will trigger before the final regulators drop out.

FRS Monitor & Control System

The Remote Control Assembly of the FRS provides operators on the main control floor a reduced set of controls and indicators to operate the frequency standards selection input switch. LEDs representing the four inputs to the switch indicate which inputs are available. An additional set of four LEDs indicate which input is currently selected.

When remote control of the carrier transfer switch is selected (by a front panel switch on the carrier transfer switch in the standards room), an LED on the Remote Control Assembly lights to indicate that remote control is available. Under this condition, the operator can manually select any one of the standards with the Select Input switch, or the automatic selection algorithm can be engaged by selecting standard number zero.

The FRS also includes a simple alarm gathering and reporting interface. The Alarm Interface gathers alarm flags from the eight chassis that make up the FRS. When any of the eight inputs is in an alarm condition, an LED on the front panel lights to indicate which chassis is alarming. This is redundant to the alarm lights on the individual chassis (which are in the same rack). An FRS summary alarm is reported to the FTS Status Summary, which has the capability to log the alarm events. A summary alarm is also reported to the Complex Supervisor (CS), which sounds an audible alarm in the control room. Because the Alarm Interface is a tie point to all of the other FRS chassis as well as other FTS racks, all interconnects are isolated by the use of opto-isolators to avoid introducing ground loops.

FREQUENCY REFERENCE DISTRIBUTION (FRD)

The **Frequency Reference Distribution Assembly (FRD)** is described by dividing the discussion into the following areas:

1. 5, 10, 100 MHz Fan-out Distribution
2. Redundant Power System

3. Monitor System
4. User Interface and Cabling Issues.

5-, 10-, 100-MHz Fan-out Distribution

The frequency reference fan-out distribution is accomplished using commercial distribution amplifiers. The stringent requirements of the DSN call for state-of-the-art low phase noise, very low temperature sensitivity, as well as high isolation. Several vendor products were evaluated for acceptable performance.

The selected amplifiers are composed of one-input five-output distribution modules, with three like-modules mounted in a standard 1U chassis. We opted to use 100-MHz distribution amplifiers and 5-MHz/10-MHz distribution amplifiers with identical outline, mounting and interface. This will facilitate the reassignment of 5-MHz ports to 100 MHz (or vice versa) as older equipment using the lower reference frequency is retired.

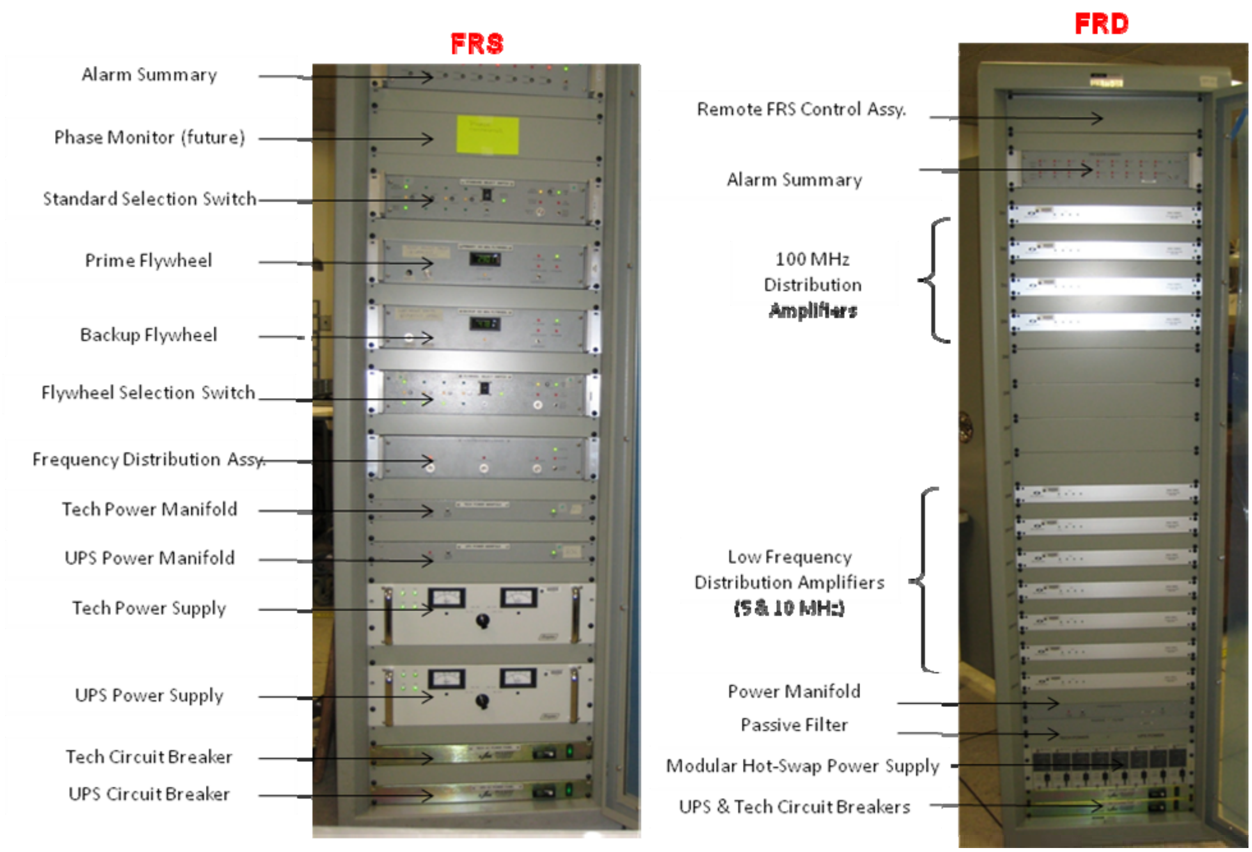

Figure 5. The FRS and FRD Subsystems showing rack layout and assemblies.

Currently, we provide forty-five 100-MHz ports at initial delivery, with a provision for near-term expansion to 95 ports (using all expansion slots for 100 MHz) and ultimately to 120 ports (allowing for the anticipated future retirement of 30 low frequency ports). There are currently sixty-five 10-MHz ports at initial delivery, with a provision for expansion as needed to as many as 110 ports (if all expansion slots are dedicated to 10 MHz and none to other frequencies). We currently provide twenty 5-MHz ports at initial delivery. Although the expansion slots could be used to increase the number of 5-MHz ports if needed, the expectation is that 5-MHz users will decline in number rather than grow.

FRD Redundant Power System

The FRD power supply system is fully redundant, beginning with separate power sources. A single COTS power supply mainframe is used, with eight hot-swappable plug-in modules. Four modules are powered from an UPS to maintain operation in the event of power mains failure, and the other four modules are powered from the mains to maintain operation in the event of an UPS failure. In this instance, switching supplies are used. To keep switching spurs to an acceptable level, we found it necessary to modify the grounding of the COTS chassis, and to add extensive, well-shielded outboard filtering. Dual redundant power manifolds provide individual voltage regulators for each distribution amplifier. This assures that oscillations or short circuits in one module do not disturb power to the rest of the system. The power manifold contains monitor circuitry to trigger an alarm if any power supply output voltage falls more than 10% below nominal. These levels are chosen such that, in the event of a graceful degradation over time, the alarm will trigger before the final regulators drop out.

FRD Monitor System

Built-in monitor circuitry is provided to generate an alarm in the event of hardware failure. Amplitude detectors monitor each output port of the distribution amplifiers. An alarm triggers when the amplitude falls 6 dB below the nominal level. Each power supply module has an alarm to indicate module failure. In addition, the power manifolds monitor the output voltage of each regulator and alarm when the output voltage falls 10% below nominal. This assures that a failed power supply or power manifold will be detected and repaired, even as the backup supply keeps the FRD operating.

The alarm summary panel has an array of indicators to show which chassis has alarmed. The various individual chassis alarms are OR'ed together to develop a high level FRD alarm, which is exported to the FTS Status Summary, and to the control room.

User Interface and Cabling Issues

Despite the low temperature sensitivity of the distribution amplifiers, experience has shown that opening the rack doors in order to cable new users to output ports significantly affects phase stability. To mitigate this effect, we housed the signal processing equipment in one rack, and user cable patch panels in an adjacent rack (not shown). This minimizes the occasions of disturbing the rack airflow and distribution stability.

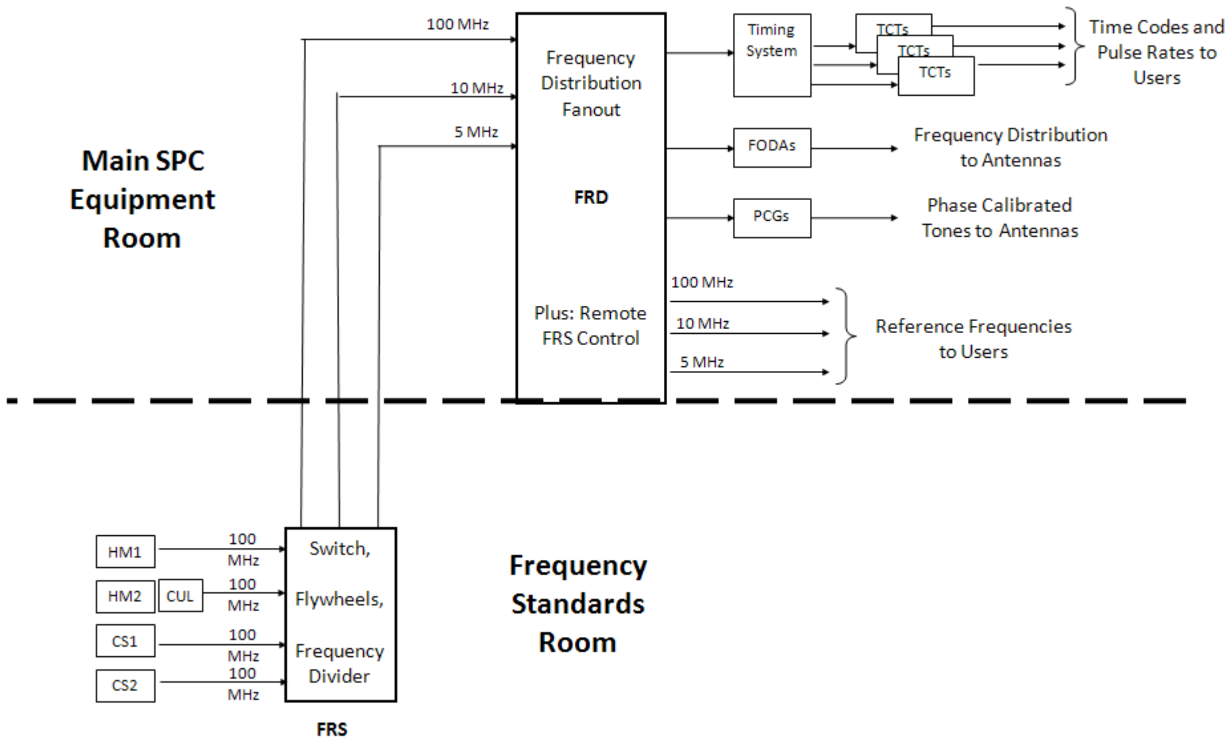

Figure 6. Relative location of the FRS and FRD assembly in the DSN Signal Processing Center (SPC).

SYSTEM PERFORMANCE TESTS

The DSN frequency distribution systems must provide low phase noise and high frequency stability references. One critical user is the FTS Master Clock and timing system, which derives its rate from the online maser through the FRS and FRD system. In addition to phase and frequency stability, low or non-existent spurious signal content must be verified, as well as low component thermal sensitivity, which may affect the long-term stability of distributed frequency and time signals. Switching performance parameters such as the operations limitations imposed by finite switching times and the lock-loop response of the flywheel oscillator are also important.

The overall FRS plus FRD system Allan deviation is shown in Figure 7. Also shown is the performance obtained with the old CRG. The stability performance of the replacement system is comparable to the old capability, but was much less expensive to develop, consists of many commercial components, and has a much more reliable system design.

As shown in Figure 6, the FRS resides in the frequency standards room, which is thermally stabilized to better than 0.1 degree C. The residual thermal sensitivity to thermal perturbations is less critical than the FRD, which resides on the main signal processing center area even though stable plenum air flows through the rack. The FRD thermal sensitivity was measured in the JPL Frequency Standards Test Laboratory by cycling the ambient temperature 20 degrees C once per day and measuring the response at

100 MHz. Tests with three cascaded distribution amplifiers measurements showed approximately 0.6 ps/deg C/ per chassis.

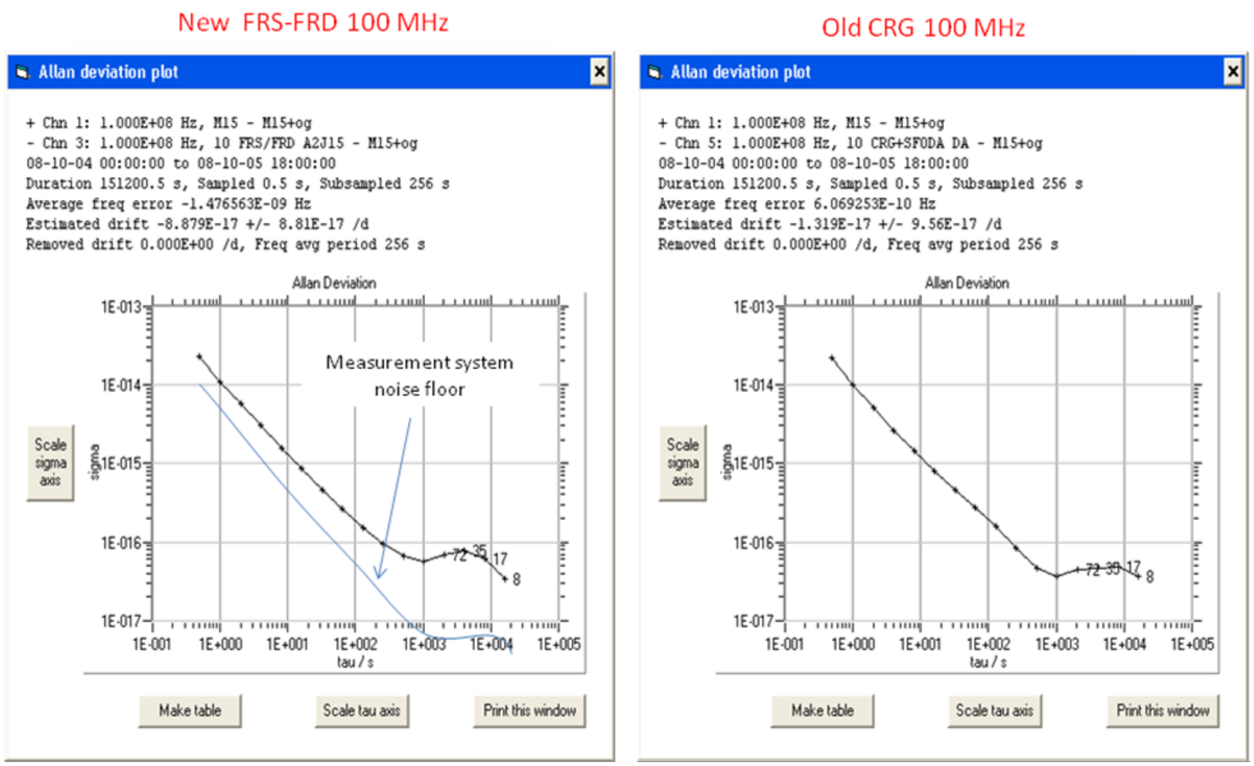

Figure 7. Allan deviation of the new distribution system compared to the old CRG. The FRS/FRD Replacement System has a much more reliable and modular architecture and incorporates COTS hardware where feasible.

Flywheel switching parameters may impact DSN operations when the frequency standard is switched. Figure 8 shows a set of responses as measured with the engineering model. An automatic switchover mode can be selected when a signal dropout threshold is detected or an atomic standard failure is detected. If the frequency standards are phase aligned before being switched, the flywheel output is essentially not perturbed. If the frequency standards are mismatched, the perturbation seen by the DSN users depends on the flywheel oscillator loop response. While constant output amplitude is provided, the flywheel oscillator must move in frequency to accumulate the phase difference between the two inputs.

A design compromise must be made between the magnitude of the frequency excursion compared to the duration of time it is off frequency. Typical switching performance is shown in Figure 8b. Operational tests in the DSN have shown that, while a few of the most sensitive users can detect such an event, their systems stay in lock. This is a dramatic improvement over the previous implementation and means that even in a worst-case scenario of both masers being 180 degrees out of phase, the impact of frequency standard switching is mitigated.

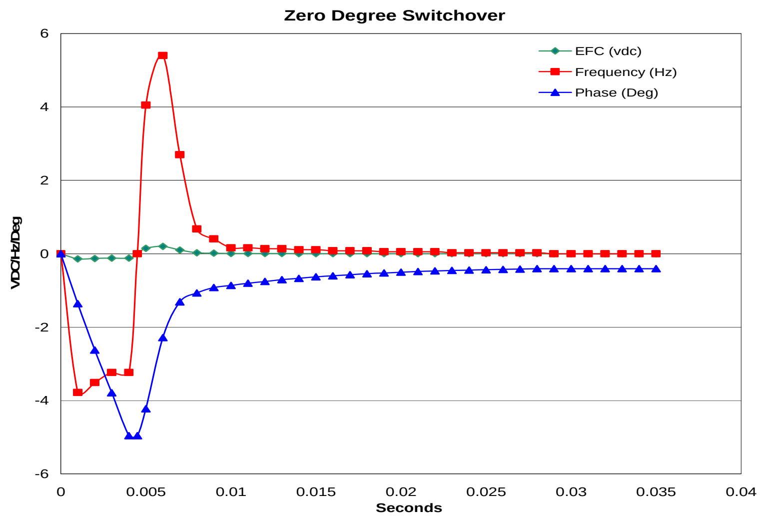

Figure 8a. Flywheel VCXO frequency and phase response to a switchover between phase-aligned standards.

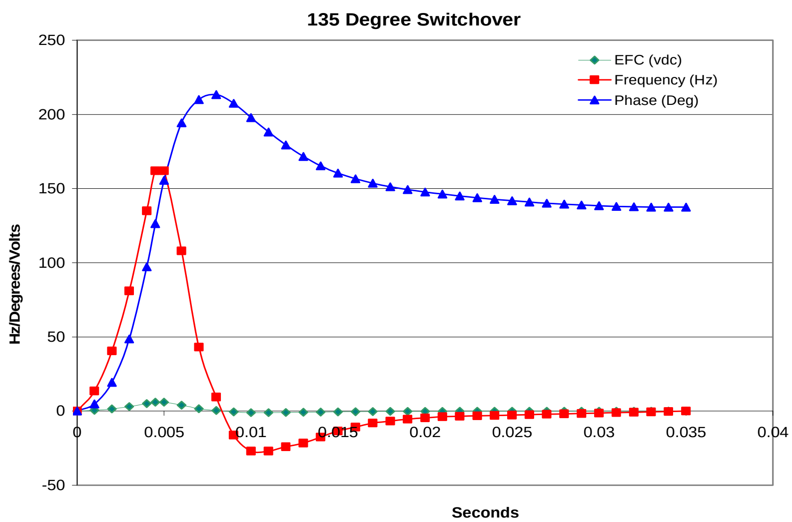

Figure 8b. Flywheel VCXO frequency and phase response to a switchover between standards that are 135 degrees out of phase.

CONCLUSIONS

A new atomic frequency standard selection and frequency distribution system with features and capabilities sufficient to meet the demanding operational needs of the NASA Deep Space Network has been described. The system has been developed and tested, and installation at all DSN complexes is nearly complete. A number of innovative features, including full system redundancy and a frequency flywheel to carry DSN operations through atomic frequency standard switching events, should increase reliability and availability.

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