Time and Frequency Equipment Capstone

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The past two years of development, testing and fielding of the Time and Frequency Equipment (TFE) system to Loran stations has one common theme—change. The change was necessary to stay current with the developing architecture of Enhanced Loran. The first fielded version of TFE was installed at Loran Station George, Washington in August of 2003 and is now installed at nine transmitting Loran-C stations across the United States. As the installation team worked diligently to field the system, the development team continued move forward on the second major TFE field release that changed implementation of functions, added versatility and incorporated the latest technology all to increase the ability to move towards Enhanced Loran. The testing of the second version is underway at LSU.

This paper presents the latest TFE system architecture and performance of the second major version. Many of the TFE functions and implementation methods from software to hardware are discussed with respect to Enhanced Loran.

1.0 Introduction

In 1999, the LORAN Support Unit initiated a program to replace the obsolete timing systems at US transmitting LORAN stations with a state-of-the-art system that would not only provide existing timing functionality, but also a platform on which to base future LORAN-C enhancements. This suite of hardware, software, and firmware is called the Time and Frequency Equipment (TFE). The USCG has purchased all of the TFE racks required for the US LORAN transmitting sites and has installed 9 out of 18 sites in CONUS.

Prior to the first TFE installation, the USCG began to expand the capability set for TFE to support Enhanced LORAN. These new functions were added to the lessons learned from the integration of TFE with LORAN-C transmitters and have resulted in a significant second release of TFE. The major capabilities added include Pulse Position Modulation capability for LORAN Data Channel implementation, an advanced timescale algorithm for optimal clock and measurement integration, and an extended (and reconfigurable) Automatic Blink System (ABS).

This paper reviews the original requirements and capabilities of TFE and introduces the new functions. The open architecture dictated in the TFE procurement and applied in the development of the system is revisited as a benefit of the system. By dictating an open, expandable architecture (both physically and functionally), LSU is able to field updates in the system via firmware changes rather than significant hardware modifications. The open architecture gives the USCG the flexibility and capabilities required to field an evolving operational service. This positions the US LORAN-C transmitting stations well for the implementation of Enhanced LORAN.

2.0 TFE Version 1.0

The initial TFE delivery included all the functions necessary to generate, monitor, and control a coherent set of LORAN-C signals to drive a transmitter [1]. The primary timing functions of TFE is to recover UTC(USNO) and create LORAN-C signals such as pulse code interval (PCI), multi-pulse triggers (MPTs) and time-of-coincidence (TOC) with precise timing relationships. In addition to the timing functions, TFE also monitors the transmitted signal (via a ground return feedback loop) for quality and performance against the required tolerances. The system introduces small signal phase corrections to keep the transmitted signal on-time (either to a SAM or to UTC control method). The feedback signal is also used by the automatic blink system (ABS) to alert users of conditions that should preclude the use of LORAN-C from a particular transmitter.

The functions described above are the minimum set of capabilities that were required to replace the obsolete timer equipment at the transmitting LORAN-C stations. In addition to replacing the old signals, new functions were also added with TFE Version 1.0. These new functions included a three clock timescale, sub-nanosecond timing control via frequency changes (rather than phase steps), remote control via IP sockets, and real-time maintenance diagnostics. Figure 1 shows the function set for TFE Version 1.0 as delivered and installed in the field.

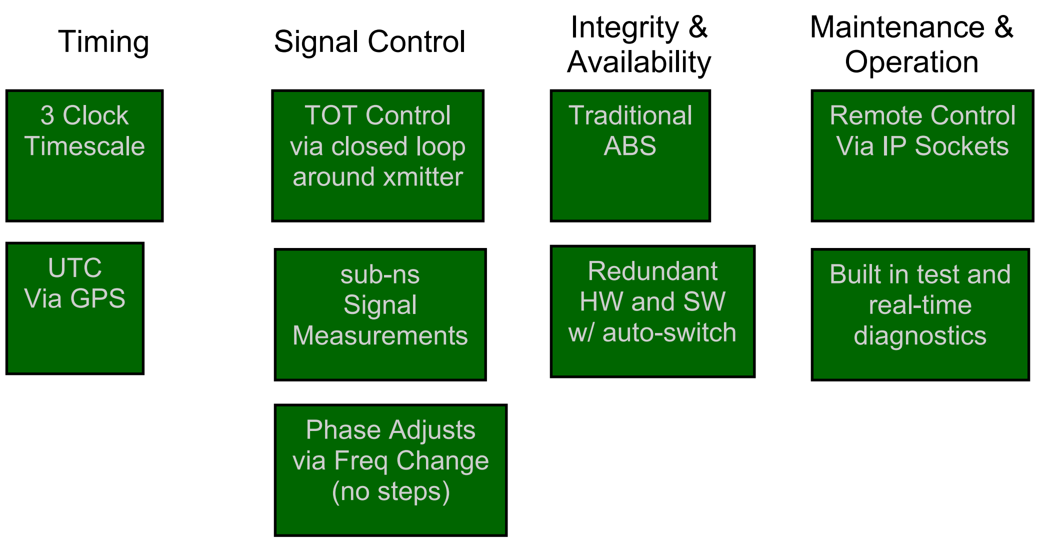

Figure 1: TFE Version 1.0 Function Set

A significant aspect of TFE is the use of a three clock timescale. The USCG has had 3 co-located cesium standards at the transmitting LORAN-C stations for many years. TFE takes advantage of that investment by grouping the clocks into an ensemble that provides many advantages [2] to the USCG including better frequency stability, better holdover performance, and real-time diagnostics based on inter-clock measurements. The three clock timescale is the foundation of TFE and provides the timing and reference signals that control all aspects of LORAN-C transmission.

One of the requirements for TFE Version 1.0 was that the system be designed with an open architecture that would allow for incremental changes without significant re-design. This requirement was satisfied in TFE Version 1.0 by putting as much of the design as possible in digital sections where changes can be made by loading new firmware. Where this was not possible, connectors for additional boards and signals were added for future use. The hardware architecture is also designed to be modular to allow the addition of new cards in the existing chassis that can be easily integrated into the system. The result of this architecture is a re-configurable system that allows the USCG the flexibility required to operate and upgrade a large distributed system. The ability to analyze diagnostic data and install firmware modifications for new functions is a critical tool for remote systems with minimal staffs.

3.0 TFE Version 2.0

Before TFE Version 1.0 was installed at the first LORAN-C transmitting station, the USCG was working with Timing Solutions Corporation to begin a second version with significant new functions. The new functions were a result of the two working groups (LORIPP and LORAPP) that were facilitated by the FAA and the USCG in support of the FAA technical report that was delivered to the Department of Transportation in March 2004. The technical work conducted by these groups resulted in a significant push towards an Enhanced LORAN-C service. Two critical aspects of this new service were the ability to communicate corrections to LORAN-C users and the need to be GPS independent.

LORAN-C's future existence is based on its ability to provide a robust, reliable back-up to GPS for users in the United States. Historically, LORAN-C has performed at levels well below GPS due to the fact that LORAN-C is a ground wave and is affected by propagation effects over the surface of the Earth. Differential corrections (from known sites) can be used to mitigate these propagation effects and allow LORAN-C to meet non-precision approach and harbor entrance requirements for position users. Differential corrections can also be used to provide precise timing users with a GPS backup capable of recovering UTC(USNO) to within 50 ns (RMS) [3]. These corrections must be provided to LORAN-C users and applied to the received data. This is accomplished via the LORAN data channel (LDC) which involves adding a new pulse (ninth for secondary, tenth for masters) that is modulated to provide a data communications channel as part of the LORAN-C signal.

3.1 Pulse Position Modulation

TFE produces a set of multi-pulse triggers to initiate the transmission of a LORAN-C pulse set. For each pulse in the MPT set, a corresponding LORAN-C pulse is transmitted. Each MPT pulse is generated with a precise time relationship to UTC(USNO) and is clocked using the 5 MHz from the online cesium and measured against the timescale via the feedback loop. LDC involves adding a new pulse and moving its position based on input data receiver (via RS-232 or Ethernet) from the USCG command network.

The LDC pulse is nominally placed in the ninth time slot (9 ms after the PCI). There are 32 different positions in time that the pulse can appear resulting in the ability to communicate 4 bytes per pulse. The modulation positions are grouped into four sets of eight pulses with approximately 50 microseconds separating the four sets and approximately 1.2 microseconds separating the finer divisions inside the sets. Figure 2 shows the four sets of eight pulses on an oscilloscope trace with 20 microseconds per division. Figure 3 shows a zoomed view of one of the pulse sets from Figure 2 with 2 microseconds per division.

The LDC PPM scheme described above is one of many schemes that can be supported by the TFE hardware (by loading new firmware). The only requirement is that the pulse modulation states be no finer than 200 nanoseconds.

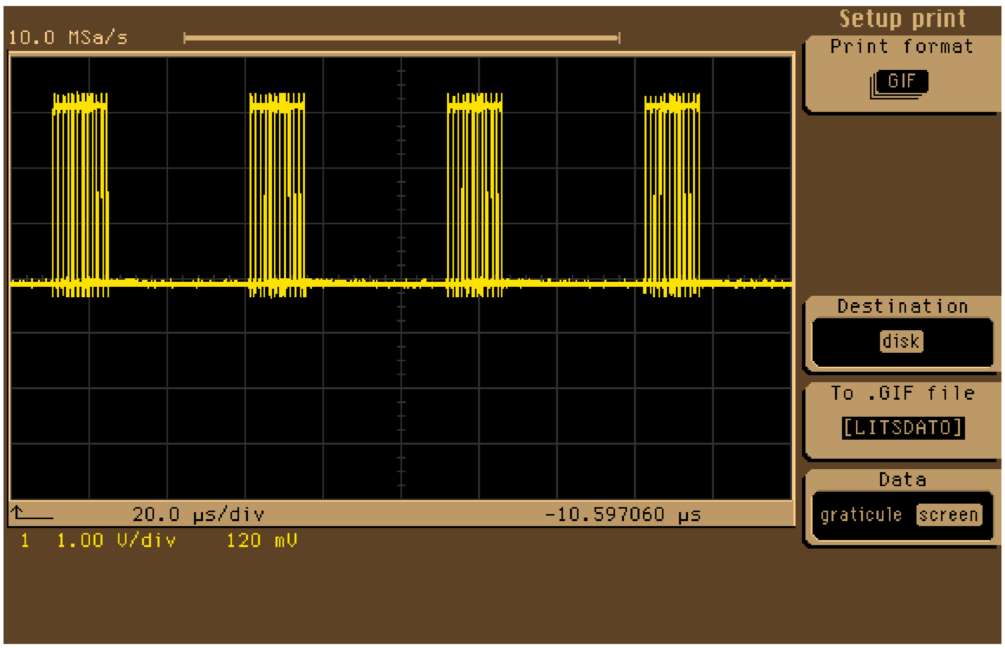

Figure 2: 32 states separated into four groups of eight

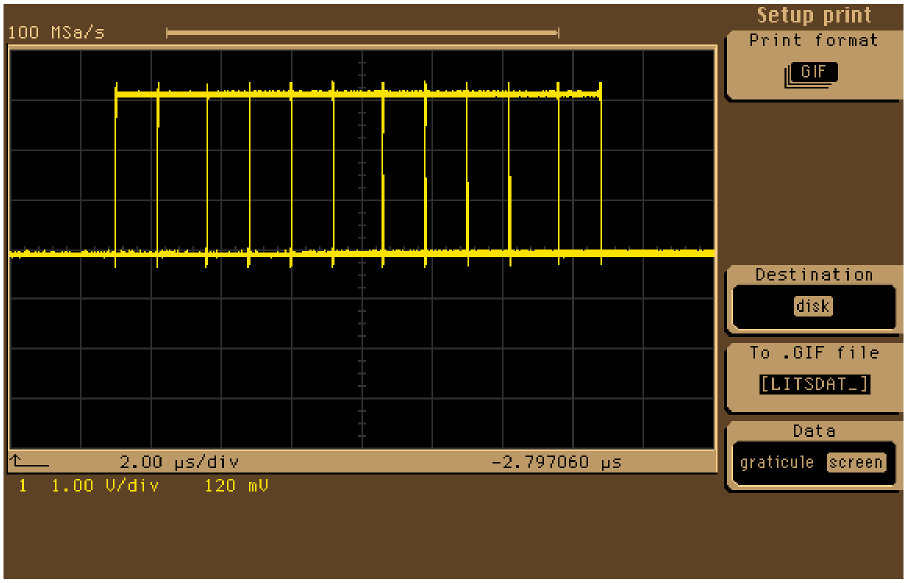

Figure 3: 8 PPS states (zoom on one of the four sets from Figure 2)

3.2 Advanced Timescale

The advanced timescale that is included in TFE Version 2.0 baseline is a significant step forward from the 3 clock timescale in TFE Version 1.0. The timescale in TFE Version 1.0 allows the three cesium standards at a transmitting LORAN-C station to be grouped together in an ensemble and steered to UTC(USNO). The TFE Version 1.0 timescale is limited to 3 clocks and each clock contributes equally to the paper clock solutions.

After the delivery of TFE Version 1.0, Timing Solutions Corporation was funded by DoD sources to continue to development of the KAS-2 timescale to enable real-time parameter estimation, scalability to a network case and redundant data types. Real-time parameter estimation is a technique to determine the noise level of each clock in the ensemble and determine a set of adaptive clock weights. This differs from the equal weights in TFE Version 1.0 in that a set of clocks with differing performance will weight the better clocks higher than the noisier clocks in the timescale calculation. This results in superior timescale performance. The advanced timescale also has two other advantages that enable changes to the future operations of LORAN-C that are significant; scalability to the network case and allowing non-GPS data sources. Scalability to the network case is designed to accommodate a network of nodes that have time sources that can be grouped in a timescale. The original application of such a network was a theater of operations where clocks on board aircraft and/or ships would be grouped together in a timescale using the tactical communication links that exist between theater assets. For LORAN-C, the nodes are the transmitting stations (at a minimum) and the ensemble is a group of approximately 100 cesium standards. The result for the USCG is that TFE has the algorithms required to group the valuable cesium standards into a distributed timescale that can be used to significantly improve frequency stability across the network, provide network based diagnostics where the health of each contributing clock can be measured against the distributed ensemble, and create a LORAN timescale that can backup the GPS timescale should there be a long-term interruption of GPS. The ability to monitor individual clock health also gives the maintainers of the system advance warning of impending clock maintenance before there is an impact on operations.

The inclusion of non-GPS data sources into the timescale is important for LORAN-C to serve as a viable backup to GPS. In the current TFE, GPS receivers are used to recover UTC(USNO) and the GPS data is the external reference for the timescale computation. In order for LORAN-C to be recognized as a true backup to GPS, the system's operation must be sufficiently de-coupled from GPS. By allowing data types in the time scale that are not GPS derived, TFE Version 2.0 is positioned to implement another method of time recovery such as two-way time transfer.

3.3 Introduction to Two-Way Time Transfer

Two-way time transfer has been used for years over satellite links to measure the relative offset of two clocks at two different sites. The technique involves a two-way time transfer modem at each location simultaneously transmitting a time code through a satellite communications channel. The time between the two clocks is determined by combining the measurements made at each end of the link. When performed using a geo-synchronous satellite as the relay, the propagation delay from one side to the other is determined by the range from each transmitter through the transponder and then down to the receiver. In order for this delay to cancel sufficiently to measure the relative clock offset, the propagation delay difference between the two paths must be small. This translates to a requirement that the radial satellite motion (to each transmitter/receiver pair) must be minimal over the measurement interval. For the case of two static nodes on the earth communicating through a geosynchronous satellite, this is true to the sub-nanosecond level for simultaneous transmission (simultaneity need only be maintained at tens of microseconds for standard orbits)[4]. The propagation delay of the satellite communications channel cancels and the measurement need only be adjusted for measurement effects and differences in equipment delay.

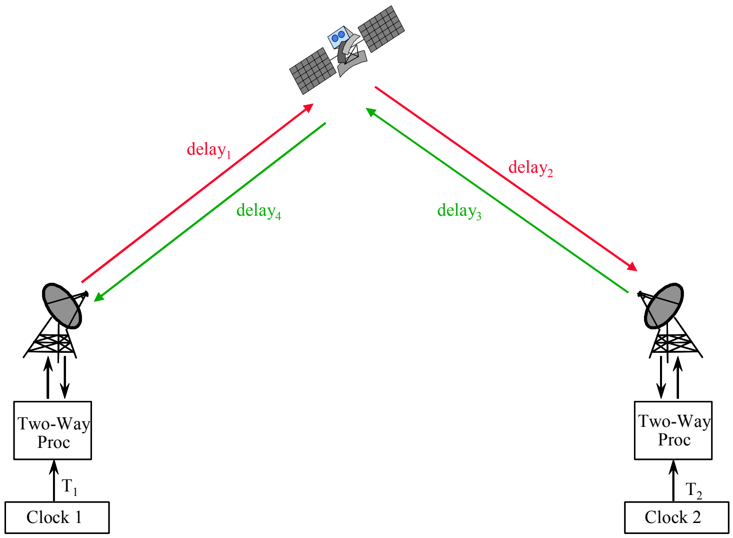

Figure 4: Static Two-Way Time Transfer

The two-way equations for the static case involve two measurements (made at each side of the link) between two clocks. The measurement configuration for the static two-way calculation (satellite relay case) is depicted in Figure 4 . The measurements that are made by the two-way processor at each end of the link are:

$$Meas_1 = T_1 - (T_2 + delay_3 + delay_4 + Sagnac_{12}) \qquad (1)$$
$$Meas_2 = T_2 - (T_1 + delay_1 + delay_2 + Sagnac_{21}) \qquad (2)$$

where,
T_1 = Time of clock 1
T_2 = Time of clock 2
$delay_1$ = delay from Clock 1 site to satellite during time of transmission
$delay_2$ = delay from satellite to Clock 2 site during time of transmission
$delay_3$ = delay from Clock 2 site to satellite during time of transmission
$delay_4$ = delay from satellite to Clock 1 site during time of transmission
$Sagnac_{12}$ = Sagnac time-of-flight correction from node 1 to node 2, and
$Sagnac_{21}$ = Sagnac time-of-flight correction from node 2 to node 1.

Subtracting (1) from (2) yields,
$$Meas_2 - Meas_1 = 2*(T_2 - T_1) + (delay_1 - delay_4) + (delay_2 - delay_3) + \Delta Sagnac \quad (3)$$

where,
$\Delta Sagnac = Sagnac_{21} - Sagnac_{12}$
and
$$T_2 - T_1 = .5*[(Meas_2 - Meas_1) - (delay_1 - delay_4) - (delay_2 - delay_3) + \Delta Sagnac] \quad (4)$$

For time transfer between two fixed ground sites, $delay_1 \approx delay_4$ and, $delay_2 \approx delay_3$ over the measurement interval. In this case, (4) reduces to

$$T_2 - T_1 = .5*[(Meas_2 - Meas_1) + \Delta Sagnac]. \qquad (5)$$

For the static case, ΔSagnac is a constant.

3.4 Conceptual LORAN-C Two-Way Time Transfer Network

A two-way time transfer network for LORAN-C transmitting sites must be designed with connectivity to all of the transmitting stations and with links to UTC(USNO). By utilizing the existing control centers at Alexandria, VA and Petaluma, CA, a two-way network can be constructed for inter-site timing between the transmitting stations. Figure 5 shows a cross-site measurement network that could be constructed using the existing USCG facilities with additional external links to UTC(USNO) and UTC(USNO-AMC). Two-way links would be facilitated between the two control stations and their LORSTAs using transponder bandwidth on commercial satellites. Each control station would also have a two-way link to a USNO station; USNO for the east coast stations and USNO-AMC for the west coast stations. Data would be shared between the two control stations with each control station computing a timescale for the entire network.

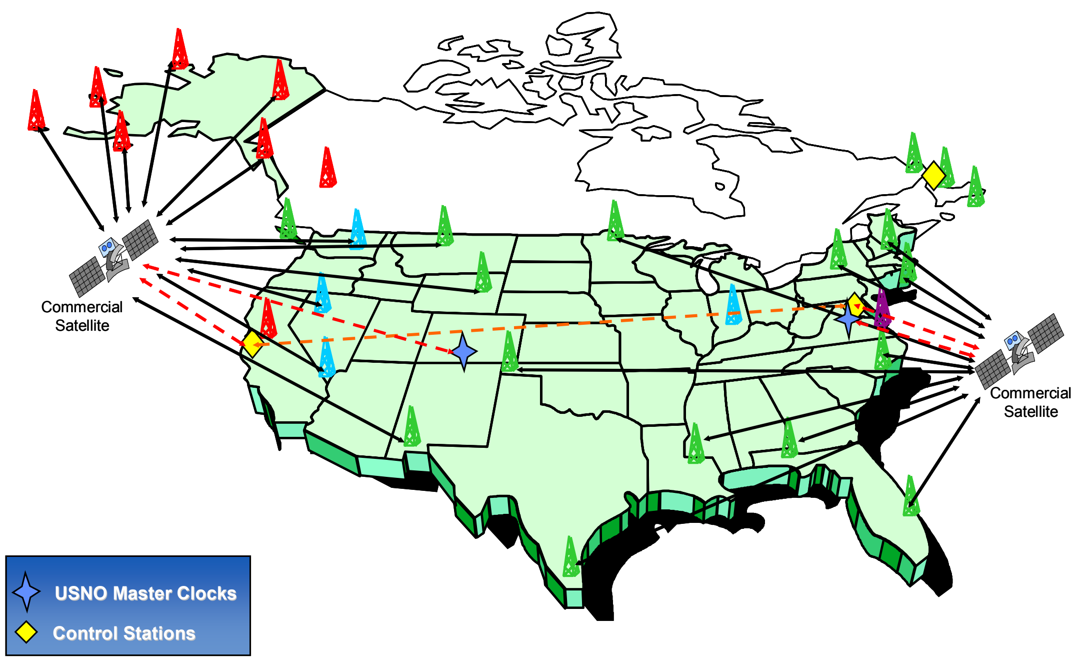

Figure 5: Conceptual Two-Way Network

There are multiple advantages to this architecture. First, the two-way network mirrors the existing LORAN control network which keeps the timing task consistent with current operations. Second, there is no single point of failure in the system, including USNO. Finally, all of the data exists at both controlling stations (Alexandria and Petaluma) so the entire timescale is available if a control station is not available.

3.5 Summary of Capabilities

TFE Version 2.0 has important new functionality that positions the USCG LORAN-C network well for implementation of Enhanced LORAN concepts. Figure 6 shows the new functions (in yellow) listed with the existing functions (in green). In addition to the new capabilities detailed in sections 4.1 through 4.4, there are other capability extensions that have arisen from the continuous improvement process that is a function of the installation and integration of TFE with the new or existing transmitters. One example of this is the Automatic Blink System (ABS). In TFE Version 1.0, ABS was simply a newer implementation of the same concepts that have been used for years in LORAN-C. The system would go into blink based on out of tolerance conditions. As TFE was integrated with the transmitters and the LSU knowledge base grew, there were opportunities to update ABS to take on more responsibility and serve the users better. One example of this is the change to base the ABS timing verification on all transmitted pulses, not just the standard zero crossing of the first pulse. Another example is to make the ABS system on the redundant (off-air) half of TFE cognizant that errors in the transmitted signals do not originate in the off-air chassis and there is no need to blink. This enables the transmitted signal to be switched to the off-air chassis without entering a blink condition. These are just two examples of the many small additions that have been made to TFE as a result of the continuous improvement process.

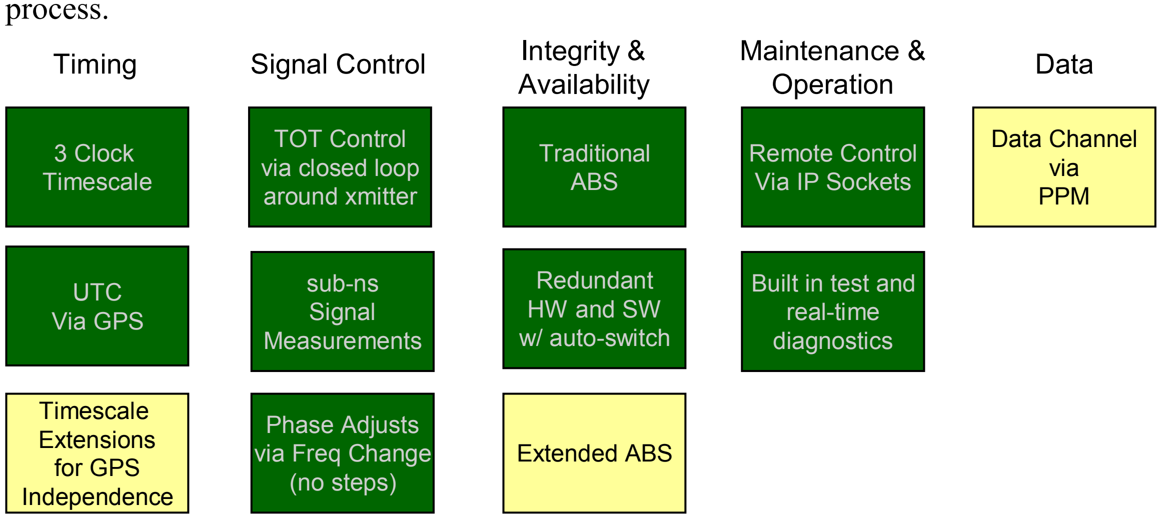

Figure 6: TFE Version 2.0 Function Set

4.0 Conclusion

The LORAN-C Time and Frequency Equipment Suite is being installed aggressively at LORAN-C stations in the United States. During the last year, 9 of the 18 CONUS stations have received TFE and the system has been in 24/7 operation with no significant maintenance. During this period, the TFE baseline has evolved with a new version released and under test at LSU. The new version has an extended capability set that provides the infrastructure for critical aspects of Enhanced LORAN such as GPS independence and data modulation. All of the changes to date have been accomplished with no changes to the TFE hardware baseline. As a result of the open architecture that relies on digital firmware, the new TFE version requires no hardware changes, only firmware changes in the main controller and the signal generation chassis. This significantly reduces life-cycle improvement costs and simplifies the upgrade process for the USCG.

References

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(2) S. Stein. "The New LORAN-C Timescale and Possibilities for Future Enhancements". *Proceedings of the ILA-31 Convention &Technical Symposium.* Washington, D.C., October 2002.

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(4) R.A. Nelson, *Handbook on Relativistic Time Transfer* (September 2002).

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